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Vehicle Safety
Research Integration
Symposium

Presented By:
RESEARCH INSTITUTE'S
OFFICE OF OPERATING SYSTEMS RESEARCH
OFFICE OF VEHICLE STRUCTURES

Chairmen:
LYNN L. BRADFORD
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Foreword

The proceedings of the Vehicle Safety Research Integration Symposium consist of Introduction, Opening Address, Technical Papers, and Closing Remarks. The Technical Papers were solicited by the Office of Operating Systems Research and the Office of Vehicle Structures Research. The staff members in these Offices ably assisted in coordinating the program and in conducting the Symposium. The contents of the papers were the opinions of the authors and not necessarily those of the U.S. Government. Any oral discussions which took place during the Symposium were transcribed and included herein. Because of some transcription difficulties, some editing was required.
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Lynn L. Bradford
Good Morning, Ladies and Gentlemen

On behalf of the Office of Operating Systems Research and the Office of Vehicle Structures Research, it is a pleasure to welcome you to Washington and this symposium.

I have long felt that our collective efforts have not received the recognition they deserve. Rarely does research receive the good publicity it deserves and on occasion it is cast as the culprit. And sometimes contractors may fail to acknowledge that work they have accomplished was in fact done for the Department of Transportation.

For several years we have initiated research projects in an interrelated and integrated manner. In a continuing process the field of vehicle safety is reviewed in depth to identify specific items and subjects which need research and analysis. These items are then listed in priority order and resource requirements are estimated. Projects are funded as a function of the priority list and the amount of funds made available by Congress.

In the past, however, we made only a partial effort to tie these many projects and contracts back together after the research was completed. We state in subsequent contracts that previous work and reports must be reviewed so as to place present and future research into context with earlier results. We reflect the completion of project and program milestones in revisions to future program plans and resource requirements. In these ways we relate previous research with future planning.

With this symposium we would like to take the obvious next step. We thought it was important to have several of our contractors and other individuals working in safety related fields to present the current state-of-the-art in vehicle safety research. This is not to establish an overall baseline, but rather to review the achievements to date. Many become engrossed with their specific area of concern and lose sight of the overall research picture. Therefore, we chose to hold this symposium as a single session rather than to have split sessions as a function of research discipline. In this way, we may all view our own work, and the work conducted by others, in a slightly broader context.

I would like each of you in the next two days to keep in mind the terms integration and interrelationship. We have organized this symposium and called you together to focus attention on the need to concentrate more effort on tying the various areas of vehicle safety together. The existence of many interrelationships will be made clear in the following presentations. However, I believe that we have only scratched the surface in identifying and defining how these many areas tie together. The primary purpose of this symposium is to reaffirm our desire to reestablish
the need to conduct vehicle safety research as an integrated and balanced process.

To officially open the symposium, I'd like to introduce the Associate Administrator for Research and Development, Research Institute. In December 1972, Dr. Gene Mannella became the Associate Administrator for Research and Development of the National Highway Traffic Safety Administration. Obviously the last few months have been very busy for him since the early part of each year is the height of the procurement cycle and also the time of congressional hearings. However, he has taken time in his busy schedule to be with us today. At this time it is my pleasure to introduce Dr. Mannella.
Opening Address

Gene G. Mannella
U.S. Department of Transportation
National Highway Traffic Safety Administration

Thank you very much, Brad. First of all, let me bid you all a good morning and a welcome. We certainly are gratified by the turn out that this symposium has engendered. As a matter of fact, you might say that for the past few days we've been overly gratified by the turn out that this symposium was apparently going to trigger since I've been getting a number of irate phone calls from people within NHTSA, within DOT, and outside of DOT demanding to know why they weren't invited or couldn't come or couldn't send "X" people and why only "25X" was allocated to them. I think that this is a very good indicator of the strong interest that exists in the vehicle research area. Within NHTSA it is one of the top priority programs. We accorded a very high level of effort in terms of resources and we look to it to help us solve a very large share of the mission—to contribute to solving the problem of reduced highway fatalities. To paraphrase just briefly some of the things which Brad said in his opening remarks, I think we look to this symposium to contribute a number of things. One of them is to afford the opportunity for many of you to see the Vehicle Research Program in its complete breadth, in its totality, and perhaps to afford you some opportunity to see the interrelationship between the area that you're addressing and some of the other work that is going on. Secondly, in keeping with the sort of traditional aims and goals of a research symposium, we look to an interchange of technical ideas, cross fertilization, to use a common term, and thirdly and perhaps most importantly, we look to this as a model of communications in which many of the groups which are interested not only in vehicle research per se but improved highway safety can communicate with each other about their activities and their goals and their aims. And I hope that by tomorrow afternoon all of us will be of the opinion that in the preceding two days we have seen progress towards attaining all three of these goals. With that, I wish you good luck.
Modeling and Simulation as Applied to Vehicle Structures and Exteriors

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ABSTRACT

In recent years a number of investigators have developed computer simulation programs to model the structural response during vehicle impact. In the present paper these programs are reviewed relative to the simulation needs of the National Highway Traffic Safety Administration. A simulation spectrum of sufficient breadth to cover these needs is defined. Through a discussion of their capabilities and limitations, current modelling concepts are related to this spectrum. Although qualitatively meaningful simulations are well established, it is concluded that only minimal quantitative results are achievable within the current state-of-the-art. Considerable potential exists, however, for the development of advanced simulations. An approach to advanced simulations is suggested and needed research areas are identified.

INTRODUCTION

The major mission of the National Highway Traffic Safety Administration (NHTSA) is to set reasonable and cost effective standards with respect to vehicle safety. Structural crashworthiness obviously plays a major role in this mission. The increasing concern with crashworthiness of automobiles has imposed the need for much greater understanding of vehicle structures in the crash environment. This is a formidable task requiring a dynamic analysis of a complex configuration undergoing large plastic deformations. In response to this need a number of investigators have developed computer simulation programs to model the structural response during vehicle impact. In the present paper these programs are reviewed relative to the simulation needs of NHTSA's crashworthiness effort. Attention is restricted to modeling concepts applicable to large plastic deformations of realistic vehicle structures.

In carrying out its basic mission NHTSA has many different simulation needs with wide variation in the required level of sophistication. In the next section we define a simulation spectrum of sufficient breadth to cover these needs. The spectrum is typified by five levels of simulation from simple qualitative models (Level 1) to quantitative models giving complete pointwise time histories (Level 5). On this scale Level 4 simulation is the minimum sophistication required to correlate structural behavior with detailed occupant injury criteria.

In this paper currently available simulation programs are discussed. These include qualitative spring-mass models, colinear lumped mass models employing generalized resistance members, and a variety of frame models based on both plastic hinge and finite element concepts. The capabilities and limitations are delineated, and the programs are related to the defined simulation spectrum. The remaining sections of the paper consider the potential for advancing the state-of-the-art. A number of basic problem areas requiring further research are identified. Finally the
requirements and feasibility of developing advanced level simulations are delineated.

SIMULATION SPECTRUM

Computer simulation of the structural response during vehicle impact is a necessary research tool for many of the functions performed by NHTSA. Figure 1 shows a selected number of these functions correlated with specific uses of computer simulation. The required level of sophistication varies widely for the various simulation uses. It is clear, for example, that the model used for a parameter study to ascertain the effect of mass-stiffness ratio on vehicle compatibility need not have the capability of a simulation program for verification of compliance with standards. The required sophistication of the simulation applications shown in Figure 1 has been examined by McIvor (Ref. 1). This study led to the definition of a simulation spectrum defined by five levels of increasing sophistication.

Level 1 simulations are models with up to five or six degrees of freedom, the variables representing displacements and possibly rotations of lumped masses. Typically the model involves two-three lumped masses and a

![Diagram](image-url)

*Figure 1. Selected NHTSA functions and associated use of computer simulations*
few (less than ten) generalized resistances. Detailed geometry and material behavior is not modeled. Geometry and the generalized resistances are defined by a small set of parameters. There is no attempt to relate the resistances to specific vehicle components, but rather they represent overall vehicle characteristics. The limited variables restrict results to overall gross displacements and average rigid body accelerations. The modeling is restricted to a specific loading situation. Level 1 simulation is designed for qualitative studies.

Level 2 simulations are models with up to twenty degrees of freedom, the variables again representing displacements and rotations of lumped masses. The number of masses and generalized resistances may be greater than Level 1 simulation, but geometry and resistances are still defined by relatively few parameters. At this level, however, the generalized resistances represent specific vehicle components. The greater number of variables permit obtaining relative displacements between components. Generalized resistances are now related directly to force deformation characteristics of components, but the limited parameters permit modeling only the gross features. The modeling is restricted to a specific loading situation. Level 2 simulation is again qualitative but for a wider range of variables including the effect of specific components.

Level 3 simulations also include models with up to twenty degrees of freedom. The essential difference is the increase in sophistication in modeling component behavior. The force deformation behavior of the generalized resistances is obtained either from experimental tests or detailed static modeling of specific components. At this level the component tests or modeling will be for specific load conditions which restrict the simulation to similar loading situations. Level 3 simulations give quantitative results which correlate with experimental data for relative displacements and average rigid body accelerations of the lumped masses. Generality of the results is restricted by the limited model variables.

Level 4 simulations will have on the order of one to two hundred degrees of freedom. This level permits the dynamic modeling of major components including inertia and strain rate effects under reasonably general loading conditions. Other vehicle components will be modeled with less sophistication. The number of variables employed should permit sufficient detail to obtain displacement and acceleration time histories of a number of significant points in the vehicle including the occupant compartment for three dimensional motions. Level 4 simulations give accurate quantitative results for displacement and acceleration histories for the model variables employed.

Level 5 simulation is a modeling of the vehicle structure in sufficient detail to give pointwise results for the displacement and acceleration histories throughout the vehicle. Probably in excess of one thousand degrees of freedom will be required. Modeling is based on material stress-strain behavior and detailed geometry of components. The modeling includes joint eccentricities, joint efficiency and local deformation effects. This level of simulation will give the displacement and acceleration environment of the occupant compartment in complete detail with accuracy of all variables within the confidence level of the input data.

Thus the simulation spectrum spans the range from simple qualitative models to general simulations capable of predicting pointwise response. This spectrum is summarized in Figure 2. Also indicated in the Figure are applications appropriate for the different levels. The introduction of this spectrum provides a measure for evaluating current modeling efforts and required future developments.

CURRENT MODELING CONCEPTS
Simplified Spring-Mass Models

In general we define simplified models as those having two-three lumped masses and less than ten degrees of freedom. The masses are connected by generalized resistances
<table>
<thead>
<tr>
<th>Simulation Level</th>
<th>Degrees of Freedom</th>
<th>Modeling Detail</th>
<th>Nature of Loading and Response</th>
<th>Confidence Level</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>Overall vehicle stiffness</td>
<td>Each model specialized for particular load, gross vehicle deformation and acceleration</td>
<td>Qualitative</td>
<td>Parameter and sensitivity studies</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>Limited parameters for gross modeling of component force-deformation</td>
<td>Model specialized for loading relative displacements for limited variables, rigid body accelerations</td>
<td>Qualitative</td>
<td>Identify basic phenomenon, parameter and sensitivity studies, component compatibility</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>Detailed modeling of major components by approximate methods or experiments</td>
<td>Model specialized for loading relative displacements for limited variables, rigid body accelerations</td>
<td>Accurate relative displacements of major components and average rigid body accelerations</td>
<td>Predict occupant compartment behavior, identify basic phenomenon, interpret exp. data, component compatibility</td>
</tr>
<tr>
<td>4</td>
<td>100 to 200</td>
<td>Accurate modeling of major components Approximate modeling of sub-components</td>
<td>General loading three-dimensional response-limited detail occupant compartment acceleration</td>
<td>Accurate displacements and accelerations of model variables</td>
<td>Predict occupant compartment behavior, identify basic phenomenon, interpret exp. data, component compatibility</td>
</tr>
<tr>
<td>5</td>
<td>Greater than 1000</td>
<td>Detailed modeling from geometry and material behavior including joints and local effects</td>
<td>General loading pointwise response</td>
<td>Accurate displacement and accelerations for all points</td>
<td>Predict occupant compartment behavior, interpret exp. data, compliance verification</td>
</tr>
</tbody>
</table>

Figure 2. Simulation spectrum

which represent gross structural properties and are not specifically identified with particular vehicle components. There is a variety of such models in the published literature. Typical examples are given in Refs. 2, 3, 4 which serve as a basis of discussion here. The three models range from a single mass and spring to a three mass model with eight generalized resistances.

All three authors claim reasonable agreement between calculated results using the model and experimental results. It is noted, however, that agreement of displacement variables is considerably better than decelerations. Although peak deceleration may be quite close in the examples cited, the deceleration time curve is matched only in its gross features. This is more a function of judicious choice of parameters than a measure of model confidence. There is a high degree of arbitrariness in the definition of the generalized resistances employed in the model. All the authors employ piecewise linear force-deformation curves representing a plastic yielding structure. Each resistance represents a gross structural characteristic. For example, in Ref. 4 two of the resistances are defined as "front end upper member" and "front end lower member." The determination of the parameters characterizing the resistance is even more vague, as illustrated by a typical quote from Ref. 3, "The load-deformation characteristics of each nonlinear spring were determined by both presumptive calculations and experiments."

Thus, we conclude that agreement between model predictions and experiment represents a high degree of intuitive judgment by the investigator with a strong element of empirical curve fitting. This, of course, is not without merit. It demonstrates that simple models can describe qualitatively those features of vehicle impact which are compatible with the limited variables of the model. On the other hand, a high level of confidence cannot be ascribed to quantitative results except for the experimental conditions (and possibly even more significant, the exact experimental procedure) to which the model was "tuned." Thus simplified models are not useful as a predictive tool in a quantitative sense, but rather as a qualitative measure of general behavior.

With these limitations it is futile to pursue the question of the "best" model. Rather, model selection should be based on choosing
variables appropriate for the particular study. Vehicle parameters must be “tuned” by the investigator for the specific application based on experience and experiment. With this, any number of simplified models will serve as Level 1 simulations. Typical examples of appropriate uses of such models for parameter and sensitivity studies may be found in the reports by Carter (Ref. 5) and Spencer (Ref. 6).

BCL Simulation Program

Battelle Columbus Laboratories (BCL) has developed a computer simulation program for collinear car/car and car/barrier collisions (Ref. 7). This program is based on a mathematical model with 4 masses and up to 35 individual nonlinear resistances. The masses are restricted to unidirectional motion.

Since the focus of BCL’s study was to develop a flexible computer program, each mass or nonlinear resistance of the mathematical model does not represent any specific part or member of the vehicle. The determination of the candidate mass and resistance assignments are left to the user. He can leave these as blank, i.e., simplify the model, but he can not change the basic configuration. For a proper choice of masses and resistance, however, BCL’s program can be applied to front, side, and rear collinear impact.

In the program the characteristics of the resistance members can be classified into six different types, each being represented by a program subroutine. They are:

1. A model of elastic-plastic “spring” capable of transmitting compression force only.
3. A model of an elastic-plastic “spring” which has both tension and compression capability.
4. A generalized model for elastic-plastic springs with tension and/or compression capability which may be described by a set of force versus deflection points and a representative unloading spring rate.

5. A model of variable-stroke, variable-orifice hydraulic cylinder.
6. A model of damping element which produces force proportional to velocity.

These various options for generalized resistances permit the representation of a wide variety of hypothetical force deformation relations. Thus with relatively simple input a broad range of component behavior can be modeled. With this capability the program meets all the requirements of a Level 2 simulation subject only to the restriction of collinear impact.

Its use as a Level 3 simulation, i.e., a simulation capable of quantitatively predicting crash results for a specific vehicle, remains to be verified. The basic difficulty is that there is no systematic way to determine the parameters of the hypothetical generalized resistances from the geometric and material properties of actual physical components. In principle they could be obtained from fitting the various options to experimental crush data. In fact, using option 4, experimentally determined curves can be used directly. In either case its use as a predictive tool requires experimental crush data for each component. The limitations of such “hybrid” models are discussed in the next section. To date, the use of the BCL program in this manner and comparison of computed results with actual crash tests have not been reported.

Finally it should be noted that the BCL program has an option to incorporate a dynamic correction factor to component force-deformation data. It has the form

\[ F_{dynamic} = C_v \cdot F_{static} \]

where

\[ C_v = A + B \log_{10} V_0 \]

in which \( V_0 \) is the impact velocity. \( A \) and \( B \) are chosen to give \( C_v = 1.3 \) at an impact velocity of 30 MPH. Such an overall magnification factor must be considered empirical and should be used with caution. This point is discussed in more detail in the next section.
Hybrid Simulation*

At the present time, hybrid simulation based on the work of Kamal (Ref. 8) has been the most successful approach to predictive capability for vehicle impact. Its use has wide acceptance within the automotive industry. To our knowledge there are two operating programs in use, the Kamal program at General Motors and the CSS program employed by Autosafety Engineering Corporation (Ref. 9). Both are considered proprietary in detail, but their general features and application to specific problems are available.

The present programs are basically three lumped masses with eight resistances. The resistances are identified with specific vehicle components or subassemblies. The force deformation curve for each resistance is determined experimentally from static crush tests and supplied to the program in digitized tabular form. Dynamic resistances are accounted for by an empirical "strain rate factor." The programs are limited to collinear front or rear impact.

The demonstrated results for frontal impact are good. Accurate values for the relative deformation of components and overall vehicle crush are obtained. The energy dissipated in each component is also obtained and the total energy accounted for within a few percent. The computed rigid body accelerations are less satisfactory but sufficient to make engineering judgment on design. Typically experimental results for accelerations show high frequency oscillations about an average value. The high frequency peaks are not obtained in simulation, but the average value is predicted with engineering accuracy.

In evaluating the present programs there are two major problems that limit their general use. The first is the dynamic correction factor. Although there is considerable information on dynamic stress-strain curves for common metallic materials, equivalent information for structural force deformation curves is not known. The basic difficulty is that the strain rate may vary spatially over the structure with local strain rates differing by order of magnitude from the average rate. Thus, at the present time the dynamic factor is set empirically. This requires considerable judgment and experience. There is evidence that different factors may be required for different structural configurations.

The second problem is the care that must be exercised in conducting the static crush tests. Correct simulation depends upon the static deformation mode coinciding with the dynamic mode. The crush test must be carried out to insure this similarity. This may require special constraints and/or loading procedures. Again considerable judgment and experience must be exercised in the design of the tests. These problems in general reduce the confidence level of the simulation in the absence of experimental confirmation for a particular run. This is due to the difficulty of objectively measuring the judgment factors involved, and reliance must be placed on subjective evaluation of the experience of the investigator.

There are also some difficult problems in generalizing the present simulations to other crash environments. Even a relatively simple situation as an unsymmetric pole test presents major difficulties. The crucial problem is to define the experimental information required which is consistent for a given model. When the only degrees of freedom are unidirectional translational displacements, the required force-deformation curve is relatively easy to define. When other displacement and rotational degrees of freedom are introduced which is necessary for any type of unsymmetric loading—the problem is much more difficult. For the large plastic deformations of interest, the force and moments transmitted to the lumped mass will depend upon all the degree of freedom variables. How to define a series of tests to experimentally determine this function of several variables is not obvious. Further the correlation between analytically defined degrees of freedom and

*We use the term "hybrid" to denote simulations requiring experimental crush data for components as program input.
physical measurements is difficult in the three-dimensional situation. Finally insuring the appropriate deformation mode presents additional difficulties.

We conclude that currently used hybrid models provide Level 3 simulation capability within the restriction of collinear impact. Their use, however, requires experience and judgment in obtaining appropriate experimental crash data. Finally the potential for generalizing hybrid models to higher level simulations is small.

Frame Models

Recently a number of investigators have independently developed more general programs directed towards Level 4 and Level 5 simulations. Although a variety of structural techniques have been employed, they all model the vehicle as an assemblage of frame members interconnected at discrete nodes. The frame members are taken as straight beams with a uniform cross section between nodes. Inertial modeling consists of lumped point or rigid body masses at the nodes. With one exception the simulations are three-dimensional and allow for general loading conditions. In the following paragraphs we briefly review these programs.

The first approach is the dynamic elastic-plastic response of planar frames presented by Shieh (Ref. 10). The basic simplifying assumption is the structural concept of a plastic hinge. The analysis permits large changes in structural geometry, but assumes that plastic deformation occurs only at the nodes. The deformation between nodes is taken as elastic and hence is assumed small. The location of all potential plastic hinges must be specified a priori. The method of assigning lumped masses at the nodes is left to the judgment of the user.

A number of approximations and assumptions are inherent in introducing the concept of a plastic hinge. In addition to assuming that the extent of the plastic zone is small, it also neglects any elastic-plastic bending at the cross section. Thus the cross section is considered either fully elastic or fully plastic as determined by the yield condition. In the present study the effect of axial force on the yield condition is neglected. Thus a hinge is introduced whenever the bending moment at the node reaches a critical specified value. The moment is then specified to be constant until the rate of plastic work becomes negative at which time the section is again considered to be elastic.

The simulation is reasonable within the framework of these assumptions. Correlation with experiments has been demonstrated for specialized frame structures with respect to overall deformation and average accelerations. Detailed correlation has not been demonstrated.

The results obtained, however, have demonstrated the usefulness of the plastic hinge formulation for crashworthiness studies. The current restriction to planer frames, of course, limits its use as an overall vehicle simulation. Even for symmetric loadings, bi-axial bending and torsion will be induced in typical automotive frame structures. It should also be noted that the assumptions inherent in the concept are too restrictive for predicting the detailed response associated with Level 5 simulation. This follows from the fact that realistic relationships between the stress-resultants and the deformation cannot be established without detailed consideration of the stress distribution on the cross section. As established in Section 2, however, there is a need for a cost-effective Level 4 simulation. The Shieh program has considerable potential for this purpose.

Recently a different approach has been employed by Wittlin and Gamon (Ref. 11) in their simulation program "KRASH." This program was developed for aircraft type structures. In principle, however, it is applicable to vehicle impact. In concept it is a three-dimensional extension of the BCL model consisting of masses connected by straight line one-dimensional "beam" elements. Each mass now has six degrees of freedom, three translational and three rotational. The model equations are obtained writing the equations of motion for each mass.
by summing the forces and moments acting on the mass from the generalized beam resistances. The program includes occupant masses that may be coupled to the structure.

In treating the generalized resistances, however, the program is essentially a frame model. Each "beam" element transfers a general force (three components) and general moment (three components). Thus the structure is replaced by an equivalent three-dimensional frame. The large deformation is treated by piecewise linearization. In each time step, the forces and moments are determined from a linear stiffness matrix (the elastic stiffness matrix) which is adjusted for plasticity by multiplying by a stiffness reduction factor. The stiffness reduction factor is experimentally determined from overall force (moment)-displacement (rotation) curves obtained from static crush data. In this respect it is a generalization of the "Kamal" model.

Although the KRASH program appears to have potential as a general three-dimensional Level 3 simulation, there are serious questions about the feasibility of the procedure. The stiffness reduction factor concept employed in the program is theoretically incorrect in three-dimensional problems. The procedure employed implies that each element of the plastic stiffness matrix depends upon the current value of only a single deformation variable, whereas in general they depend upon the entire deformation history. Thus it is impossible to define a unique "load-stroke" curve for the experimental determination of the reduction factor as postulated by the KRASH formulation.

We conclude that experimentally determined stiffness reduction factors are meaningful only if the component test closely duplicates the dynamic deformation experienced in the actual vehicle impact. It is questionable whether this is experimentally feasible for general three-dimensional response except possibly under very special loading conditions. In addition the experimental difficulties discussed above in connection with extending the Kamal model are relevant here.

Thus it is likely that KRASH can be used as a Level 3 simulation only under restricted circumstances. It may prove useful as a three-dimensional Level 2 simulation where hypothetical reduction factors can be chosen based on experience and judgment for a particular qualitative study.

A more general finite element frame model has been developed by Young (Ref. 12) in the simulation program CRASH. The program is three-dimensional and considers both geometric and material nonlinearities. Material behavior is limited to plasticity theory. The basic beam element has uniform properties, but nodes may be specified arbitrarily. No prior assumption on location of plastic zones is required. Inertial modeling is accomplished by lumped masses at the nodes, the assignment of masses being left to the judgment of the user. Moments and forces at the nodes are computed by numerical integration of the stress distribution over the cross section. Thus the actual stress-strain behavior of the material may be used directly at the expense of monitoring the stress state at locations across the cross section.

The formulation of the CRASH simulation is analytically sound and does not rely on simplifying assumptions in its treatment of plasticity. Its present applicability to general vehicle simulation, however, is questionable. The CRASH program has been used by Melosh (Ref. 13) to model the vehicle to barrier impact of a Mustang. The simulation was not successful. The model was much too stiff. Passenger compartment acceleration peaks occurred earlier and were of higher duration than the test results.

It is unlikely that these results could be improved significantly by using more elements. The basic difficulty is the inadequacy of the frame concept to model the entire vehicle. At the present time there is no rational way to choose cross-sectional properties so that a beam is equivalent to many actual structural components. Another source of modeling error are the structural joints. In the Melosh simulation the joints are treated as frame nodes which essentially neglects any
effect of joint inefficiency. Also local deformation of the cross section is not considered.

The final frame program to be discussed has recently been developed by Thompson (Ref. 14). The program is proprietary, but a general description is given in the reference cited. Basically the program is a finite element frame program with nonlinear geometry and plastic deformation capability. Although differing in some key respects, it is similar in size and concept to CRASH. It is considerably more flexible in treating cross-sectional properties and is thus more adaptable to vehicle modeling. (As with all frame models, of course, the basic modeling problem of replacing actual components with equivalent beams remains). It is also more general in material properties including strain rate sensitivity.

It also differs in another important respect. Rather than derive a plastic stiffness matrix which must be recomputed at each time step, the program employs an elastic stiffness matrix and a stiffness reduction factor. Unlike KRASH, where the reduction factor is postulated as being known from experiment, the present program computes this factor at each time step by taking the ratio of the actual moment about the neutral axis to the fully elastic moment. This requires pointwise integration across the cross section and an iterative procedure for converging to the plastic stress-strain curve at each point. This is computationally a major task. Relative efficiency between this and the CRASH formulation is not known, but they are probably computationally of the same order of magnitude.

Although the Thompson reduction factor accounts for deformation history, it still may be criticized on theoretical grounds. The procedure is valid for symmetric bending, but in general is not correct. The range of loading conditions for which the procedure will give reasonable results is speculative. We believe, however, that reasonable results can be expected, provided the resultant moment vector has small deviation from the neutral axis and torsion and axial effects are not significant.

In Ref. 14 correlation between results of simulation and tests was demonstrated for two experiments. The first was a dynamically loaded beam, and the second was a side impact study. In both cases the program was used to predict the time-varying nodal forces when the experimental nodal displacements were used as input at each time step. This is quite different, of course, than predicting the dynamic response from initial conditions. Thus on the basis of published results, the Thompson model cannot be considered as fully validated.

STATE-OF-THE-ART SUMMARY

In the section we have discussed the capabilities and limitations of currently available simulation models. The discussion is summarized in Figure 3. An assessment of the current state-of-the-art based on this summary leads to the following conclusions:

1. Level 1 and Level 2 simulation needs of NHTSA are adequately met by available simulation programs.
2. Within the restriction of collinear impact, Level 3 simulation may be obtained with hybrid models. Experimental crush data for components in the appropriate dynamic deformation mode is required.
3. No currently available simulation based on a frame model has been qualified as a vehicle simulation.

An assessment of the current state-of-the-art should include the potential for future development. In this respect we have reached the following conclusions:

1. To extend hybrid simulations to three-dimensional capability or higher level simulations presents major experimental difficulties. Thus the potential for such extension is low.
2. The frame program KRASH has major deficiencies for use as a Level 3 or higher simulation. The restrictions on the quantitative validity of the stiffness reduction factor again imposes major experimental difficulties.
<table>
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<th>Program</th>
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<td>BCL</td>
<td>Spring-mass, general configuration</td>
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<td>KAMAL</td>
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<td>CRASH</td>
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<td>Ideal frame elements</td>
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<td>—</td>
<td>Ideal frame elements, reduction factor</td>
<td>Level 5</td>
<td>Local deformation and joint behavior, generalize reduction factor</td>
</tr>
</tbody>
</table>

Figure 3. Summary of current simulation programs

3. The other frame simulation programs have considerable potential for use in advanced simulations in conjunction with the development of other modeling concepts.

The most striking feature of the current state-of-the-art is the success of hybrid models for quantitative prediction when to date there are no published reports of qualified vehicle simulations using the more analytically sophisticated frame models. There are two major factors that account for this situation. Despite their apparent greater modeling detail, no current frame simulation accounts for local deformation of the cross section. Further joint efficiencies* and eccentricities are not taken into account. Both effects play a significant role in the energy dissipated by the structure and are inherently accounted for in experimental crush data. The second factor is that the single force deformation curve required for collinear impact can be obtained experimentally for non-frame components like exterior sheet metal, fire wall, unitized forestructure, motor mounts, etc. In contrast there is no rational way to choose the cross section properties of an equivalent beam element to use in a frame model. Thus the evidence strongly suggests that a purely frame model is inadequate for a complete vehicle simulation. In addition advanced simulations cannot be realized without including effects of local deformation and joint behavior.

Nevertheless the frame simulation programs have considerable potential for advancing the state-of-the-art by serving as accurate modeling techniques for actual frame components of the vehicle structure. Thus the merit of such simulations is for use as a major "module" in the overall vehicle simulation.

With respect to the potential of specific simulations, the Shieh program is the most limited. It was noted in the discussion that the plastic hinge concept itself is too restric-

*The Thompson model incorporates an empirical joint efficiency factor but the choice and use of this factor was not discussed.
tive for use in Level 5 simulation. It does, however, have merit for use as a module in Level 4 simulation if it is generalized to three-dimensional deformation. The program CRASH and the finite element program of Thompson both consider the detailed elastic-plastic stress distribution over the cross section. This computational complexity precludes their use for Level 4 simulation, but will be required in a Level 5 frame module. For both levels of simulation the degree of sophistication and method of incorporating local deformation and joint behavior are unresolved.

RECOMMENDATIONS FOR FUTURE DEVELOPMENTS

Development of Advanced Simulations

As concluded above, Level 4 and Level 5 simulations are not achievable within the current state-of-the-art. Moreover, no current simulation program has the potential to achieve these levels without additional modeling concepts. In the near future, however, there will be increasing need for advanced simulations to match our increasing knowledge of biomechanics in the crash environment. Level 4 simulation will be the minimum required to relate structural response to occupant injury.

In assessing the feasibility of developing advanced simulations there are two distinct considerations, potential modeling concepts and the feasibility of the associated numerical computation. This paper is directed towards the first consideration. Even without detailed examination, however, it is increasingly clear (see, for example, Ref. 15) that numerical computation is not the limiting factor. With current progress in automatic generation of input data and computer capability, it can be anticipated that exercising models with one or two thousand degrees of freedom will be cost effective with respect to full scale testing. Thus the limiting factor is the development of modeling concepts with a level of confidence equivalent to testing.

Here we briefly suggest an approach to advanced simulations based on the development of a number of self-contained mechanical simulation modules representing sub-assemblies of the vehicle. Some modules would be general purpose like a frame module or rigid body module. Others would represent specific sub-assemblies like a drive train or suspension module. Even for advanced simulations a module which can be defined by empirical test data is likely to be required.

For each module we define a discrete set of "external nodes" as the points where it interacts with other modules. Enforcing compatibility and dynamic equilibrium of the nodes gives the overall system equations. This is identical to assembling the global equations in a finite element method where the simulation modules are analogous to "super elements."

This modular development has a number of advantages. It permits employment of a variety of modeling techniques that are appropriate for specific components. It also permits freedom within one program for assembling quite different models for particular situations, thus minimizing the number of degrees of freedom employed. This is controlled by input data specifying the numbering and initial location of the external nodes of the appropriate modules chosen from a module library. The program system will then generate the equations governing the overall response. The organization of input data would be simplified, each module having its own format compatible with the modeling technique employed.

In developing the individual modules, the choice of modeling technique would be based on the most efficient method compatible with the detail and accuracy required for a specific component relative to its role in the overall vehicle response. Level 4 and Level 5 simulations would be accomplished within the same framework, the only difference being in the number and modeling sophistication of the modules employed. For example, a frame module based on the plastic hinge concept might be employed in Level 4 simulation.
whereas a finite element frame module would be required for Level 5.

To effect this modular approach will require an intensive effort directed towards component definition and modeling. Some areas such as frame structure components are already well advanced. The development of a two-dimensional finite element module for sheet metal components is currently feasible. Due to computational complexity, however, its use will be limited to Level 5 simulation. An approach to its counterpart for Level 4 simulation is not yet defined. For both levels of simulation a major effort in joint behavior and local deformation is required.

### Recommended Research Areas

In addition to the general need to develop component modeling techniques, we can identify a number of more basic topics that require investigation in support of the modeling effort. Here we suggest five areas that are crucial to the development of advanced simulations. They are:

1. **Joint Behavior**
   
   A major factor in the geometric complexity of automotive structures is the complicated joints and material attachments used in standard manufacturing practice. There is a need for a systematic study of joint behavior under various load conditions. At the present time there even remain basic questions on how to characterize joint behavior. For example, the concept of joint efficiency introduced for elastic joints is not well defined for plastically deforming joints.

2. **Local Deformation**
   
   For the large deformations experienced in crashworthiness applications there are significant changes in cross-sectional shapes of structural frame members. It is conceptually possible to model this behavior with three-dimensional finite elements. In practice, however, this is likely to add a prohibitive number of degrees of freedom. Moreover we are not interested in the details of the local deformation but only its effect on the overall load transmission and energy absorbing characteristics of the structure. A rational way to incorporate these effects is needed.

3. **Strain Rate Sensitivity**
   
   Although considerable information is known about material strain rate effects, the realistic incorporation of such effects in structural theories is not well understood. At the present time most simulations use an average strain rate either as an empirical correction factor or to choose a single dynamic stress-strain curve. In general, however, there are large spatial variations in strain rate throughout the structure. The effect of such variations is now known.

4. **Load Transmission Characteristics**
   
   For Level 4 and the minor components of Level 5 simulations, restrictions on the total degrees of freedom prohibit using two and three-dimensional finite elements for modeling all non-frame members. Thus there is a strong need for understanding how two-dimensional structural elements transmit various loadings in order to rationally define an equivalent frame member.

5. **Numerical Error Control**
   
   Although a discussion of the numerical methods employed by current simulation programs is beyond the scope of this paper, they in general require considerable judgment and numerical experiments to choose a time step and/or error measure. There is a strong need for systematic study of the effect of local error bounds on accuracy and efficiency. Related questions are the appropriate definition for the error measure and the choice of error weight functions.
Acknowledgements

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References


Questions & Answers

ROBERT MELOSH, VIRGINIA POLYTECHNIC INSTITUTE:
Do you have any idea from your study how many degrees of freedom are really needed to find a satisfactory correlation between the test and analysis?

The answer, Bob, is I think no, but based on our study we believe that it's realistic to think that we can do this with one to two thousand degrees of freedom if we can develop the right kind of modeling concept. If you go much beyond that, I'm not sure that my statement about cost effectiveness and so on still remains valid.

LLOYD CARLSOn, AGBABIAN ASSOCIATES:
Do you feel that it's possible to achieve the kind of correlation we need without a 3D finite element approach to the problem?

Yes, I think so. But certainly we're going to require a two D finite element type approach to the problem for some components. There is also going to be a need to develop quite different modeling concepts for some components. I'm not sure that for the drive train assembly, for example, you're ever going to model finite elements; that's going to remain some kind of spring mass simulation of that particular component in the overall simulation. That's why we talk about a modular development. So I think there's a variety of type elements that we need to derive, not all of them in the classical finite element sense.

JOHN HERRIDGE, BATTELLE COLUMBUS LABORATORIES:
I was wondering if you could expand a little bit on what you thought the gap areas were in the strain rate sensitivity area?

I think the biggest difficulty is while we know a great deal about the strain rate behavior in terms of the stress-strain curves of materials, we really don't know its influence on force deformation characteristics. All of the current models that use experimental crush data scale the static test curve to a dynamic curve by strain rate correction factor, a dynamic correction factor. Now that's based on some kind of average strain rate, and in the actual structural response, the strain rates in areas of very rapid yielding, the area of hinges, is quite different than the average strain rate. How important this is, we at the moment really don't know.

GEORGE ABRAHAMSON, STANFORD RESEARCH INSTITUTE:
I want to thank you, Ivor, for an excellent summary of all that material. It really looked like a complicated thing to tackle. In choosing these various levels of sophistication and so on, you did a good job. I wanted to point out another aspect of simulation, though. You've been talking here about the entire vehicle, and if one is willing to concentrate on a small part of the vehicle, you can indeed get quantitative simulation with something that's extremely simple. So if one is willing to take one part of the vehicle, you simply can do a very precise job.

I think that's a valid comment, George. Again, I think that's why if you want to do overall vehicle simulation, the technique is to develop a number of these sub-modeling concepts, some of which will have to be quite refined and some of which can be quite simple, into some overall simulation.

E. H. LEE, STANFORD UNIVERSITY:
You mention the need to study error control. Do you consider this is likely to be done by direct numerical analysis approach or what do you think of the idea of some standard problems which people could then try their programs on to assess overall accuracy?

I think there's a lot of merit to comparative testing of various specific programs on standard problems. This has been done in the structures area in nonlinear shell programs, and I think it's been quite revealing. I think a similar type work in this area eventually would be worthwhile.
Hardware Development and Production Feasibility as Related to Vehicle Structures and Exteriors Research

Patrick M. Miller
Calspan Corporation

ABSTRACT

Automobile structures directly influence three aspects of automobile crashworthiness, (1) capacity for providing protection to car occupants, (2) behavior of other automobiles, and (3) interaction with pedestrians during various types of accidents. Current automobile structural crashworthiness research is primarily concerned with occupant protection with a secondary interest on the effect automobile structures have on other vehicles. Only limited effort is being directed towards vehicle-pedestrian accidents. Research priorities are based on available accident statistics where it is apparent that side and rollover type accidents result in as many serious injuries as frontal collisions with rear impacts a relatively unimportant factor.

Extensive crash data for current production automobiles have been developed to (1) define current levels of structural performance and (2) identify areas where improvements are needed. Motor vehicles of various weight classes (luxury, full size, compact and subcompact) have been subjected to fixed object (pole and flat barriers) and intervehicular tests simulating loading conditions of severe real-world type accidents.

Major effort has been directed towards development of crashworthy structures for full size automobiles. Reasonable passenger compartment integrity (occupant survival space) and accelerations have been obtained in extremely severe collisions. These protective measures are being incorporated into fully operational vehicles using typical automotive prototype fabrication techniques.

Crashworthy techniques developed for full size vehicles are being extended to other vehicle classes (e.g., compacts and subcompacts). Greater emphasis is being placed on establishment of performance requirements within the overall motor vehicle population mix, resulting in the need for advancement of more efficient energy managing structures and devices.

Although not a major consideration in present structural research, future effort must place greater emphasis on pedestrian protection. Work in this area has been retarded by a lack of problem definition and repeatable, meaningful test procedures.

INTRODUCTION

This report attempts to present in a very general way a review of various NHTSA programs related to vehicle structural crashworthiness research. This type of research has been actively pursued and supported by NHTSA as well as most automobile manufacturers during the last four or five years. Consequently, considerable data, test results, design goals, philosophies, etc. are now emerging. Nevertheless, because automobile safety design frequently represents a number of trade-offs or a series of compromises between conflicting requirements, the role of vehicle structures in providing optimum automobile crashworthiness is not yet well defined.

The term “crashworthiness” has evolved from aviation safety usage and has been generally used in reference to the capacity of a vehicle for providing protection to occupants during potentially survival accident exposures. In more recent years, this concept has been extended to motor vehicles and widely applied in reference to their performance during various kinds of highway acci-
idents. Because of the nature of these accidents, the crashworthiness of an automobile must be viewed in a much broader context than just a consideration of potential protection for its occupants. That is, emphasis must be placed on the way the vehicle interacts with other automobiles and pedestrians.

Of the different elements (e.g., restraints, interior surfaces, exterior structures, etc.) that characterize the total measure of automobile crashworthiness, the vehicle structure is unique in the sense that it directly influences automobile crashworthy performance in all of these areas. As a minimum, potential changes in structural performance must be investigated in relation to possible effects on, (1) vehicle occupants, (2) other motor vehicles, and (3) pedestrians. Because of these overlapping and somewhat conflicting requirements, development of crashworthy automobile structures is extremely complicated and, if not divided into logical categories for investigation, could result in an overwhelming situation.

Recognizing this fact, the NHTSA undertook an automobile structural crashworthiness study in the latter part of 1968 with both immediate and longer range objectives. Immediate goals were placed on energy management and the implications such structures might have on properly restrained car occupants during severe single vehicle accidents. After encouraging results were obtained, investigations were implemented to consider the behavior of such structures in the overall population mix of automobiles. This paper attempts to present the underlying rationale and results from these basic studies.

The vehicle-pedestrian problem is the most complicated aspect of automobile crashworthiness due to a number of factors; (1) multiple impacts usually occur (both pedestrian-vehicle and pedestrian-roadway contacts), (2) lack of repeatable and meaningful test procedures, and (3) a need for more definitive recommendations concerning potential avenues for vehicle changes which might result in improvement. Perhaps because of these reasons, to date, only limited effort (in relation to that directed towards car occupants) has been expended in this research area. Nevertheless, the magnitude of the problem suggests that major effort must eventually be directed towards possible solutions to this critical problem.

Automobile structural design must recognize the nature of vehicle attrition from the highway system and commitment to automotive production volume capacity. Hence, changes in automobile structural performance can be expected to occur in an evolutionary manner in relation to the overall system. Therefore, the initial objective in improving structural crashworthiness is to establish a datum condition of representative real-world performance under a multitude of impact conditions. Once this is established (within a particular segment of the problem) consideration is given to development of possible improved performance. Generally, improvement is assumed to constitute an extension of crash energy control to higher impact speeds and/or more severe loading conditions.

Because of a lack of precise human tolerance criteria and a clear understanding of accident exposures, "improved" performance is generally defined in relation to measured deviations between conventional and modified (prototype) vehicle performance. Simultaneous reductions in maximum passenger compartment (and occupant) decelerations and intrusions are usually accepted as improvements. But, it is also recognized that some limited intrusion could constitute potential benefit to occupants. For example, side wall intrusion during lateral collisions or steering column rearward displacement during frontal collisions under restrictive conditions could actually be beneficial to occupants if this tends to enhance ride down.

Naturally, a more desirable evaluation method would be definition of acceptable human tolerance criteria. But advances here are plagued by notable gaps in existing knowledge in the relationship between simulated occupant exposures (anthropomorphic devices) and actual human injury. Nevertheless, limited injury criteria are available and fre-
quently used to define acceptable performance levels.

Thus, highly repeatable test techniques and conditions are mandatory. Advances in highway safety experimental techniques and equipment have been made in recent years, and from a structural viewpoint, reasonable conditions are available to simulate numerous types of real world accidents. Critical deficiencies do, however, still exist in the simulation of realistic rollover and pedestrian-vehicle accidents. This has contributed to the somewhat retarded progress in developing a clearer understanding of the function of vehicle design in relation to these accident types.

ESTABLISHMENT OF PRIORITIES

Since its inception, NHTSA has supported a wide range of programs encompassing the different types of structural involvement, but resources mandated that some ordering of priorities be established. A major factor in setting priorities is, naturally, expected accident exposures. Other influencing factors are areas where more immediate payoff appears evident, the performance of conventional vehicles, expected trends in the automobile population, etc. For example, even though rollover collisions are widely recognized as an important contributor to serious injuries and fatalities, the lack of realistic, repeatable test conditions has tended to reduce the attractiveness of this area as one where potential improvement could readily be established.

In 1967 existing ACIR (Automotive Crash Injury Research) data representing nearly 25,000 predominantly rural, injury causing accidents were tabulated and analyzed to determine patterns of dangerous and fatal injuries to car occupants (Ref. 1). Data from that study were condensed and are presented in Figure 1 showing distributions for both vehicle impact direction and injuries (dangerous and fatal) to drivers. Also presented in Figure 1 are data from the RECAT (Cumulative Regulatory Effects on the Cost of Automotive Transportation Costs, Ref. 2) which is derived from a sample (also circa 1967) representing all accident types (i.e., not limited to rural, injury causing accidents). The two studies show differences in impact distribution (probably as a result of sampling variation) but reasonable similarity is evident between injury distributions. That is, nearly one-half of all occupant fatalities result during frontal collisions. The remaining occur predominantly during side and rollover accidents. Rear collisions appear to be an insignificant factor (in relation to the other accident types) in terms of dangerous or fatal injuries. Analysis of more recently collected data has tended to support these general findings (see Ref. 3).

These data have had a direct bearing on crashworthiness research. As an accident type, major attention has been focused on frontal collisions. If, however, side and rollover collisions are lumped together, then this area deserves as much attention as frontal collisions. This categorization, side and rollover, is appropriate because both types generally require similar structural performance, i.e., maintenance of structural integrity during direct passenger compartment loadings. It should also be noted that the side structure as contrasted with the front structure does not have the potential for being aggressive and its effect on occupants of other vehicles is not a major factor. Other than for specific items such as fuel tank integrity, there appears to be no justification for directing effort to rear structural performance (seating and interiors may, however, require attention).

In addition-to-accident type, impact speed distribution is critical in terms of defining structural performance goals. It must be recognized that accurate, reliable impact speeds are difficult to establish; nevertheless, efforts have been made, based on observed

![Figure 1. Estimated collision involvements, dangerous and fatal injury distributions](image-url)
vehicle damage, to determine fatalities as a function of equivalent barrier speed. Shown in Figure 2 are distributions derived from three different studies, performed by NHTSA, General Motors Corp. and Ford Motor Co., of frontal collisions (Ref. 4). Although there are divergencies between the studies after 40 MPH equivalent barrier speed, it is apparent that 90% of car occupant fatalities in frontal collisions occur at speeds below approximately 50 MPH.

As a result of crashworthiness research, considerable data now exists on the performance of conventional automobiles undergoing various types of collisions. Early in the research effort, it was recognized that major reliance on flat barrier impacts was inherently inappropriate because a number of the more severe accidents are such that concentrated, localized loadings are produced on the automobile. A pole barrier (essentially a commercially available pipe filled with concrete) was selected to augment flat barrier rigid obstacle tests. Representative full size domestic automobiles (1966 Fords) were subjected to six different fixed object experiments (Refs. 5 and 6). These included frontal impacts into both flat and pole barriers at both head-on and oblique vehicle orientations, at impact speeds between 40 MPH and 60 MPH, as well as a lateral impact into the pole barrier at 20 MPH. These data constituted the initial basis for assessing the structural performance characteristics of full size automobiles.

More recently, the scope of conventional vehicle test data has been broadened to include different vehicle sizes and/or impact obstacles. DeLays, et al. (Ref. 7) report on a number of tests where different size automobiles were impacted into partial flat barriers which simulated a rigid heavy vehicle underride. Later, similar vehicles were impacted into prototype heavy vehicle underride guards (Ref. 8). These tests were such that only part of the vehicle structure engaged the impact obstacle and, although intended for use in automobile/heavy vehicle underride, provide an indication of vehicle performance when underride of a different nature occurs (e.g., collisions with other automobiles, roadside obstacles, etc.).

A series of intervehicular frontal collisions involving different size automobiles were performed in 1970 (Ref. 9). In this study, full size 1968 Fords were impacted into each other and into two popular foreign small cars, Volkswagen and Opel, at closing speeds in excess of 80 MPH (40 MPH each vehicle). This effort was followed by a series of similar tests where a 1969 Ford was impacted into a larger vehicle, 1968 Buick, and two smaller vehicles, 1968 Nova and 1971 Vega (Ref. 10). These experiments provide a general indication of vehicle performance where a typical (or most popular size) automobile is involved in a severe frontal collision with similar and much smaller vehicles where the mass ratio approaches a factor of two.

The results of eight different side impact tests were recently reported by Greene (Ref. 11). The study considered full size 1968 Fords in perpendicular front-to-side impacts.

![Figure 2. Comparison of fatality distribution data frontal collisions (Ref. 4)](TAKEN FROM DOT HS 810197)
at speeds ranging from 15 MPH to 45 MPH. An oblique (45°) test was also performed at 45 MPH. To address car size and structural design, 1968 Fords were impacted perpendicularly into a 1969 Plymouth (unitized body), a 1968 Nova, and a 1971 Vega. The full size 1968 Ford was also impacted laterally into a pole barrier. The performance of full size, four-door hardtops (1969 Chevrolets) while striking a pole barrier and being impacted laterally by a 1968 Ford and a 1967 Plymouth Valiant is reported in Ref. 12.

Finally, a series of rear structure collisions are reported in Ref. 13. In this case, 1968 Fords were impacted rearward at 40 MPH into a flat SAE barrier and colinear (front-to-rear) at a closing speed of 40 MPH (struck car stationary). In the barrier test, the rear structure collapsed to the C-pillar. No major passenger compartment intrusion occurred, but the fuel tank was crushed.

The results for conventional full size automobiles indicate that these structures are adequate for frontal fixed object collisions not exceeding 35 MPH to 40 MPH, side impacts with narrow objects in the range of 10 MPH to 15 MPH, front-to-side intervehicular in the range of 25 MPH to 30 MPH, and rear collisions into fixed objects between 30 MPH and 40 MPH. Structural adequacy implies that the passenger compartment accelerations were within tolerable limits (assuming ride down) and structural integrity was maintained (i.e., excessive intrusion did not occur, doors remained closed, but tempered glass sometimes shattered resulting in potential ejection for occupants). Conversely, dummy occupant accelerations indicated that vehicle interiors (restraints and surfaces) are not always adequate throughout these speed ranges. Thus, potential benefits of current full size automobile structures are not being fully exploited because of present inadequate restraints and interior surface characteristics.

Naturally, the performance of small cars (compact and subcompact types) shows some degradation from that of the large vehicle. This is particularly noticeable in the vehicle-to-vehicle collisions between large and small cars. A collision type is becoming more important as economic factors are resulting in a greater relative number of small vehicles. Furthermore, the population mix is such that for the small car, the greatest likelihood is involvement with a larger mass car during intervehicular collisions.

It is noteworthy that these tests have uncovered certain deficiencies in current automobile front structures which deserve attention and possible correction. The “pros” on fenders, hoods, and bumpers, produce concentrated loads on the sides of other automobiles, during front-to-side collisions, resulting in excessive vehicle intrusion. The forward swept hood section also buckles in such a way as to become a target for heads of occupants of cars which are struck on the side. During forward collisions, swept rear hood sections (hidden windshield wiper region) intrude into the windshield becoming a potential target for front seat occupants.

DEVELOPMENT OF FULL SIZE AUTOMOBILE CRASHWORTHY STRUCTURES

As a consequence of both accident statistical and conventional automobile structural performance data, major emphasis should be placed on front, side, and rollover type collisions where impact speeds exceed the limits of current structural adequacy. Because of their popularity, initial effort was focused on full size automobiles. Early tests (circa 1969) with structurally modified automobiles concentrated in the range of 40 MPH to 60 MPH for frontal collisions and 20 MPH for lateral collisions with fixed objects (Refs. 5, 6, 14, 15, 16, 17). The results of this initial study, Basic Research in Crashworthiness I (NHTSA Contract No. FH-11-6918), were encouraging regarding the potential for better control of energy management during structural deformation.

More recently, NHTSA has sponsored programs which have led to the development of operational, full size automobiles having improved crashworthiness structures. These are the Experimental Safety Vehicle (ESV)
and Basic Research in Crashworthiness II (NHTSA Contract No. FH-11-7622) programs. In a follow-on to the Crashworthiness program, two fully operational automobiles, modified for front, side, rear, and rollover protection are under development in the Production Feasibility-Crashworthiness Structures, Full Size Cars Program (NHTSA Contract DOT-HS-053-2-487). In addition, side structural changes for hardtop automobiles are reported in Ref. 18 while a rear structural concept is considered in Ref. 13. As a result of these efforts, considerable data is presently available on the potential for improving structural crashworthiness of full size automobiles.

It is not possible to review the results of all of these programs in this report. Also, it should be noted that the basic objectives of these two activities were different. The ESV's were developed in an attempt to satisfy rigid specifications on acceptable passenger compartment acceleration-time histories, intrusion, etc., during various kinds of tests. The most critical conditions were 50 MPH frontal (pole and flat) barrier and 15 MPH lateral pole barrier impacts. On the other hand, research under the Crashworthiness programs is more basic and greater flexibility in attempting to define rational bases for trade-off between performance, feasibility, production, etc., throughout a wide range of possible impact conditions is permitted. Thus, precise limits of impact speeds, compartment decelerations, time-histories, intrusion, etc., are not specified in an absolute sense. Nevertheless, both efforts have contributed to a much better understanding of the problem of improving structural crashworthiness performance.

The results from the ESV program are well documented and presented in the proceedings from a series of International ESV Conferences (Refs. 19 and 20). Certainly, these sources must be consulted to obtain an adequate review of the progress made in developing ESV's. Four different full size vehicles were developed and the most notable differences in these vehicle designs are the various methods of dissipating energy during frontal collisions. Both the AMF, Incorporated (Ref. 21) and Fairchild Industries (Ref. 22) ESV's provide for energy dissipation through hydraulic systems. The General Motors (Refs. 23, 24) and Ford (Ref. 25) ESV's dissipate energy through combinations of hydraulic systems (low speed) and collapsing metal structures (higher speed).

Structural designs intended to improve crash performance during lateral collisions have generally followed traditional practice. That is, door beam panels have been developed and installed within existing door geometry. Passenger compartments are also strengthened through modifications to pillars and sills. An exception to this approach is considered in Ref. 18 where "bumper like" extensions were installed on the outside doors of a 1969 Chevrolet. In this case an attempt was made to dissipate most of the kinetic energy outside of the periphery of the original door contour. A similar approach was proposed and adapted to full size automobile rear structures (Ref. 13).

In the following, the general scheme developed under the Basic Research in Crashworthiness program is discussed. This discussion is not intended to indicate uniqueness but rather a general illustration of the type of structural alterations and resulting performance changes that are readily being incorporated into a full size automobile. Certainly, this approach is not unique and other structural changes could be made to achieve similar performance objectives.

Shown in Figure 3 are schematic illustrations of the major structural changes developed for full size, 1972 Ford automobiles under Contracts FH-11-7622 and DOT-HS-053-2-487 (Refs. 25, 26 and 27). Front and rear low speed energy dissipation is provided through urethane foam encased in the front and rear bumper face bars. Bumpers are supported by the 1st and 5th frame cross members which are placed at the leading and trailing ends of the frame. For higher speed frontal collisions, the 2nd and 3rd frame cross members have been redesigned to augment the energy dissipated by the original outside
frame side rails. In addition, the 3rd cross member has been strategically relocated to greatly improve frame performance during lateral collisions.

Body modifications for frontal collisions include a load distributing grille and an energy absorbing inner fender structure attached directly to the fire wall. The original fire wall is replaced with a sandwich panel design which, in addition to keeping engine house components from intruding into the passenger compartment, redirects the engine relative to

(a) FRAME MODIFICATIONS

(b) BODY MODIFICATIONS

*Figure 3. Illustration of structural changes incorporated into full size production automobile*
the passenger compartment. The remaining passenger compartment modifications are intended primarily for side collisions, i.e., door beams, pillars, etc., but also provide improved longitudinal compartment strength during frontal collisions.

Important features for lateral protection are sandwich panel door beams which are attached directly to the side pillars through the hinge and latch mechanisms. The B-pillars have been strengthened and are designed so the lower end overlaps the frame side rails. Thus, even though the front structure of other vehicles will tend to override the frame side rails, participation of these side rails during intervehicular collisions is assured because of the lower B-pillar design. Additional lateral strength is provided by the 3rd frame cross member and the roll bar attached at the upper ends of the B-pillars. This structure also provides potential benefit during rollover collisions.

Furthermore, the existing tempered glass side windows are replaced with laminated energy absorbing glazing. In these vehicles, the crashworthiness function of glazing is twofold, (1) to prevent ejection, and (2) to control head acceleration. Interior surfaces are covered with a two-stage energy absorbing structure which is a composite made from layers of foam urethane and crushable honeycomb. The foam urethane is intended to dissipate occupant energy during impacts up to 10 MPH, while the honeycomb will collapse at higher speeds.

The overall structure has been developed and tested in over forty tests involving various fixed objects and intervehicular collisions. Shown in Figure 4 are post-test photographs of a conventional 1972 Ford and a modified vehicle after comparable 58 MPH frontal collisions with a pole barrier. Passenger compartment longitudinal data for these two tests are shown in Figure 5. Major changes in structural performance for the two vehicles occurs during the first 0.040 sec. of the collision where energy dissipation has been substantially increased as a result of the structural modifications.

Figure 4. Exterior views of conventional and modified full size automobiles after comparable high speed collisions with pole barrier

The change in energy management had a major effect on passenger compartment intrusion. The engine was displaced into the center of the front seat in the 1972 Ford while fire wall, toe pan rearward displacement was limited to less than one inch in the modified vehicle. It should be noted that, as a result of longitudinal compartment forces, the doors were jammed shut in the modified vehicle but all windows were operable.

Shown in Figure 6 are post-test photographs of conventional and modified vehicles after a 21.5 MPH collision with a pole obstacle. Significant improvement in occupant protection is evident in Figure 7 which shows passenger compartment and occupant exposure data for each of these vehicle tests. Equally impressive changes have been demon-
Figure 5. Comparisons of passenger compartment longitudinal kinematic data for conventional and modified full size vehicles during comparable high speed frontal collisions with pole barrier (see Figure 4).

strated in other collision modes (see, for example, Refs. 26, 27, and 28).

This basic concept is now under final refinement where careful attention is being placed on the production feasibility aspects of improving current vehicle performance. For this purpose, two 1973 Ford sedans are under modification with prototype tooling and fabrication methods being employed. These vehicles should be available for testing this fall.

Figure 6. Exterior view of conventional and modified vehicles after 21 MPH lateral impact with pole barrier
PARAMETER
LOCATION OF DUMMY IN STRUCK VEHICLE
RESTRAINT SYSTEM
HEAD SEVERITY INDEX
PEAK HEAD RESULTANT ACCELERATION (g's) *
PEAK CHEST RESULTANT ACCELERATION (g's)**
PEAK PELVIS RESULTANT ACCELERATION (g's)**
HEAD CONTACT SURFACE

<table>
<thead>
<tr>
<th>TEST NO 49 MOD 3E3, 21.5 mph</th>
<th>TEST NO 46 1968 FORD, 21.3 mph</th>
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<tr>
<td>RIGHT FRONT SEAT (IMPACT SIDE)</td>
<td>RIGHT FRONT SEAT (IMPACT SIDE)</td>
</tr>
<tr>
<td>NONE</td>
<td>NONE</td>
</tr>
<tr>
<td>480</td>
<td>1520</td>
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<td>55</td>
<td>107</td>
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<td>39</td>
<td>70</td>
</tr>
<tr>
<td>58</td>
<td>97</td>
</tr>
<tr>
<td>EA LAMINATE (0.050 sec)</td>
<td>WINDOW-SILL NEAR B-PILLAR (0.093 sec)</td>
</tr>
<tr>
<td>ROOF HEADER (0.066 sec)</td>
<td></td>
</tr>
</tbody>
</table>

* FOR 0.003 sec DURATION, SAE J211, CLASS 1000 FILTER  
** FOR 0.003 sec DURATION, SAE J211, CLASS 180 FILTER

* Figure 7. Comparison of vehicle and dummy data for modified and conventional vehicles (see Figure 6)

REFINEMENT OF MODIFIED DESIGN TO OPERATIONAL, PROTOTYPE MODIFIED VEHICLES

Structural crashworthiness research has progressed to the point with full size automobiles where the remaining problems are essentially related to manufacturing, weight control, and operational performance aspects of the overall problem. Of these, weight appears to be the most difficult part and here it should be noted that part of the weight increases result because prototype vehicles have been essentially direct modifications to existing full size vehicles. Thus, compromises in vehicle geometry have not been permitted and complete flexibility in vehicle design might result in weight changes which are within normal year-to-year weight adjustments for a particular automobile type.

Continued use of mild steel need not result in a change in current manufacturing
technology. But, modified vehicles have consistently employed welding methods (much of it continuous rather than spot) which is a factor that must be considered. Furthermore, limited use of higher strength steels, with static yield stresses in the 70,000 to 90,000 psi range, particularly in passenger compartment reinforcements, would have a direct impact on manufacturing requirements.

Weight increases have plagued all structural crushworthiness research. The weight changes for the structural design of Figure 3 have been carefully recorded. Based on test results and weight changes of these modifications, vehicles which will allow acceptable passenger compartment acceleration (40 g to 50 g maximum) and passenger compartment integrity during 50 MPH collisions with either flat or pole barriers, and 20 MPH lateral collisions with a pole barrier, can be developed with a weight change of about 360 lbs. over conventional 1972 Ford weights (3850 lbs.). Such vehicles would also provide added structural protection during rollover collisions, but the degree of change has not yet been established.

These weight increments are shown in Figure 8 for the various vehicle structural components involved in the modification. To place such a weight penalty in perspective, it should be noted that energy managing potential of the structure would be increased by a factor between 2.0 and 2.5. Thus, in this context, the weight change is considerably more favorable and indicates that within modest changes in vehicle dimensions, current vehicle weights could be maintained with highly significant changes in energy management capability.

Experiments with automobiles developed within the Crashworthiness and ESV projects have demonstrated that the structural changes have only minor effects on vehicle dynamics (performance, handling and ride). The more important factors appear to be the accessibility of existing components and subsequent effect on maintenance. However, this part of the problem has not been explored and it is quite probable that careful vehicle packaging can mitigate some of the restrictions evident in the modified vehicle.

**CRASHWORTHY STRUCTURES FOR OTHER VEHICLE SIZES**

Limited research has been directed towards front structure development for other size automobiles. These have included luxury, compact and subcompact automobiles. Buick Electra 225 series automobiles were modified and tested under high speed frontal collisions (Ref. 29). Similar efforts were also performed with compact (Nova) and subcompact (Vega) automobiles (Refs. 30 and 31). Clearly, the luxury automobile does not present a problem distinctly different from that of the full size automobile. That is, the vehicles are generally very similar in structure. The added weight for the luxury automobile tends to result from additional features (non-structural) which are related to additional

<table>
<thead>
<tr>
<th>STRUCTURAL COMPONENT</th>
<th>NET WEIGHT INCREASE (lbs)</th>
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<tr>
<td>FRAME</td>
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<tr>
<td>1st X-Member</td>
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<tr>
<td>S-Extension</td>
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<td>2nd X-Member</td>
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<td>Side Rails</td>
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<td>BUMPER</td>
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<td>Bar</td>
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<td>5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
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</tr>
<tr>
<td>PASSENGER COMPARTMENT</td>
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<tr>
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<tr>
<td>C-Pillars (2)</td>
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</tr>
<tr>
<td>Front Doors (2)</td>
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</tr>
<tr>
<td>Rear Doors (2)</td>
<td>12</td>
</tr>
<tr>
<td>Roll Bar</td>
<td>8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>173</strong></td>
</tr>
<tr>
<td>FENDERS &amp; GRILLE</td>
<td>50</td>
</tr>
<tr>
<td>DEFLECTOR (Engine &amp; Transmission)</td>
<td>12</td>
</tr>
</tbody>
</table>

*Figure 8. Structural weight changes resulting from modification of vehicle components*
comfort, convenience, etc. On the other hand, the small automobile, particularly the subcompact, is a distinctly different vehicle than its large size counterparts. This difference is represented in both accident patterns and vehicle design.

Exterior photographs of a conventional and a modified Vega after 60 MPH impacts with a pole obstacle are shown in Figure 9. Passenger compartment deceleration data are shown in Figure 10. Similar modified Vegas were also tested in front-to-front collisions with conventional full size automobiles (Ref. 31). Although impressive performance was demonstrated, considerable refinement in the design is required before it would be feasible for incorporation into operational, prototype vehicles.

Currently, a program—Frontal and Side Impact Crashworthiness, Compact Cars—is underway to develop fully modified structures for compact automobiles (NHTSA Contract DOT-HS-257-2-461). No reports have yet been issued on this program, but some tests have been performed with the base line vehicle, an AMC Hornet. Completion of the program is expected near the end of 1973.

In the present mix of automobiles, small vehicles (subcompact and compact) represent a small percentage of the total population. Even though their market share is growing, it will be years (if ever) before their numbers are comparable to full size automobiles. Thus, because these vehicles operate within the same system as larger vehicles, it is apparent that their greatest vehicle-to-vehicle exposure potential is with a larger size automobile. Differences in mass clearly place the small vehicle at a distinct disadvantage and this disadvantage being fundamental cannot be corrected through vehicle design. That is, in large-small car accidents, the smaller vehicle will always experience the greatest velocity change. Therefore, equal protection for occupants of small and large cars can be obtained only if the small car is designed to provide protection throughout a greater speed range than the larger car. Because of other constraints, it is unlikely that this will occur, and consequently, occupants of small cars must accept a greater risk than occupants of larger cars.

Small cars are designed considerably different than large cars. However, it is sometimes expedient to think of small automobiles as scaled versions of their larger counterparts. And, with respect to certain aspects of the vehicle, this is reasonable. For example, mass ratios between small and large cars can approach a factor of two; likewise, respective engine power plant outputs are usually near this ratio. On the other hand, overall vehicle geometry is not even near the mass ratio where, for example, vehicle widths vary about 12 in. from 66 in. and 78 in., and consequently, structural properties are considerably different.
Bumper face bars provide an illustrative example. Prior to 1973 models, when bumper standards went into effect, typical face bar weights for large cars were in the order of 50 lbs. while counterpart weights for small cars were about 15 lbs. Thus, efforts to improve bumper performance on the small car will have a much greater relative effect on the small vehicle than on the larger vehicles.

Small vehicles have a major compensating factor when involved in single vehicle accidents. That is, the energy absorption requirements are reduced in direct proportion to the vehicle weight. Furthermore, because comparable metal thickness are used in small and large vehicles, present small vehicles tend to dissipate energy somewhat more efficiently than larger cars. To a certain extent this tends to compensate for their reduced physical dimensions. That is, for a fixed object test, small cars do not demonstrate markedly different structural performance, in terms of compartment integrity, than larger vehicles.

For these reasons, the small car structural problem in the American highway system is definitely related to its involvement with other, principally larger cars. This problem is also recognized as being extremely pertinent to the current trends and constitutes a major area for future research.

FUTURE RESEARCH

Automobile structural crashworthiness progress must be viewed as a demonstration that changes in structural performance can be made which have the potential for greatly improving occupant protection, provided adequate measures are also taken to upgrade present restraint system performance and usage. Such structural changes are feasible within present automobile manufacturing technology, but further developments could permit more efficient incorporation of such performance into production automobiles. The problem of vehicle mix has not yet been
fully addressed, and the effect front structural changes would have on other vehicles must be determined.

There is a natural tendency to assume that increasing front structure energy capacity will automatically have a disastrous effect on other conventional and/or smaller cars. But, recent results (see Ref. 26) with full size modified vehicles impacting full size conventional automobiles do not indicate that degradation of conventional vehicle performance need accompany changes in front structure performance. Indeed, if the foremost part of the structure is properly designed in relation to load distributing surfaces (frontal contours) and force-deflection characteristics, it appears the potential exists for reducing current full size vehicle “aggressivity” while at the same time improving potential protection for its occupants.

The intervehicular interface, or collapsing structure region, between two automobiles is extremely complicated when two structures having different properties are simultaneously collapsing. This situation is not tractable through simplified lumped-mass model analysis. Quite likely, projections based on such analyses are subject to considerable error. Therefore, this problem requires more sophisticated study before a total assessment of potential vehicle aggressivity can be made. Such investigations must rely on both experimental and analytical structural approaches.

Research on structures and accident data indicate that increases in energy absorption capacity by a factor between two and three over current vehicles is needed. This would place impact speed limits near those of the original ESV specifications. Much of the past effort has been directed towards adding devices to existing automobiles rather than a more fundamental approach to the problem. Not surprising, excessively heavy vehicles have emerged with somewhat discouraging assessments of the potential for improvement. It is believed, however, that with more emphasis on basic automobile structural characteristics, such changes are achievable with only modest weight (less than 10 percent of gross vehicle weight) adjustments to large automobiles and somewhat larger (slightly greater than 10 percent) adjustments to small vehicles. The major improvement must come from two factors, (1) redesign of existing vehicle structures, and (2) improved manufacturing techniques.

Present automobile structures have evolved from designs which were not basically intended to provide high energy management control. However, mild steels, because of their relative ease of formability, have been widely used in automobile structures. These materials, having modest strengths, high ductility, superior strain-rate properties, etc., are ideal for energy absorption. Hence, the major effort in designing automobiles to improve energy absorption should be placed on the design of structural components and methods of manufacturers rather than seeking drastic alternatives to present material usage.

An example is provided by present hoods of full size automobiles which weigh about 80 lbs. and are hinged and latched so that energy dissipation is low during post buckling collapse. Multiple latches located at the midspan can increase hood energy absorption by a factor between 2 and 3. Furthermore, rigifying the outside hood sheet metal skin by direct attachment to internal reinforcement sections could increase the hood energy absorption by factors between 5 and 10. Structural adhesives may be ideal for this purpose.

Similar advances are likely possible with other structural components. If structural adhesives could be used to attach reinforcement members to outside door sheet metal skins, present door beams could be replaced by lighter, more efficient structural composites. In this instance, performance would be improved while at the same time reducing gross vehicle weight. Likewise, there are numerous other candidates for similar consideration within conventional automobile structures. It should be emphasized that development of such technology requires further research before being widely applied to automobile production, but these avenues warrant further exploration.
The major requirement in developing improved structural design is further progress in improved analytical capability. This means that structural analysis methods which predict post collapse behavior of structures are needed. An example of this type of computational capability is provided in Refs. 31 thru 34, where efforts to analyze frame structures are reported. These computer programs have been used to redesign the frame structure originally developed for the full size vehicle modifications. The program was utilized in the Production Feasibility-Full Size Automobiles Program (NHTSA Contract DOT-HS-053-2-487). In this case, the energy dissipation capacity of the frame was improved while, at the same time, 40 lbs. of material was removed from the structure.

Similar programs are needed to analyze sheet metal structures. Such effort would be primarily related to determining properties of reinforcement members which are intended to stabilize unitized structures. In this case, the structure must be stabilized throughout collapse rather than just up to impending large deformations as is normally done with present structural designs.

As indicated earlier, the pedestrian problem has not been given sufficient attention. To provide potential benefits to pedestrians, rather drastic changes in vehicle structures may be required. Indeed, from a research viewpoint, it might be reasonable to consider developing automobiles which have extremely soft peripheral structures. These vehicles would then be subjected to test conditions to determine differences between base line and prototype vehicle performances. Such an approach would define limits of potential pedestrian improvement. Then, if encouraging results were obtained, the next major goal would be directed towards incorporation of such performance characteristics into practical vehicle structures without at the same time greatly compromising crashworthiness performance in other areas.

Trade-off studies in front structure performance must be undertaken. In this effort, major consideration should be given to the collapse characteristics of the foremost section of the vehicle. Its potential effect on pedestrians and other cars (primarily during side collisions) points towards a lower force collapsing structure while frontal collisions with fixed objects and other similar size (or larger) vehicles require higher force levels. In addition, restraint system performance may be affected by initial force structure stiffness properties. Clearly, optimum performance within the overall scope of possible involvement will require compromises in the area where performance requirements conflict.

Finally, distinctly different accident patterns are evident in urban and rural areas. Present automotive structural design does not consider potential areas of usage. However, as safer automobiles are required, it may be reasonable in terms of overall economics to consider vehicle design in relation to expected type of usage and exposure. In any event, this would appear to be a fruitful avenue for consideration in relation to overall economics, practicality, etc.

References


SUMNER MEISELMAN, AMERICAN AUTOMOBILE ASSOCIATION:
I have been quite impressed by the increase in performance though the modified frame weighs only 360 lbs. in excess of OE frame. Does this 360 lb. increase in weight give due consideration to the redistribution of weight in the vehicle frame, the change in the center of gravity, the increase in suspension components and tire size to carry the additional load?

CARL NASH, PUBLIC INTEREST RESEARCH GROUP:
How does the performance of the Calspan Ford compare with the Ford ESV or any of the other large ESV's that have been produced for the Department of Transportation?

We have not attempted to compare the results of this program with the ESV for a number of reasons; the most important one is that ESV was built to rather rigid specifications concerning intrusion, concerning the wave-form of the passenger compartment acceleration, particularly peak-G as a function of vehicle speed. These were areas in our program that we had been attempting to ascertain as to whether they were important or not. So I don't think it's quite fair to take the vehicle which we developed—which was developed to quite different specifications—and compare it directly to the ESV program development. That is the reason we haven't tried to compare them. We're working towards different specifications. In that sense, I don't think it's reasonable to compare the two directly. I do think, though, that we can provide, at the higher speed range, reasonable passenger compartment decelerations, and if we can find a restraint system that will do the job, then we can talk about survivability in that case.

DON FRIEDMAN, MINICARS, INC.:
You mentioned the characteristics of impact of the dummies with the vehicle interior structures. In frontal impact, can you indicate or estimate the probable survival in those impacts with the structural modification?

The problem here is that we do not have a restraint system that appears to permit the occupant to take advantage of riding down the structure. We did do something on this program. Although it's not reported in the paper, it is reported in one of the references. We put in some rearward facing rear seat occupants to determine what the response would be where the occupant did directly benefit from the ride-down—and this is a 57 or 58 MPH collision with a full obstacle. Those rearward facing occupants would, I think, generally satisfy existing 208 requirements. But we're not recommending people ride around backwards. This was a research effort to see what the effect would be if the occupant could directly benefit from the structure itself.
Again, we have to define what we mean by aggressivity or how critical it is in the overall mix, and I contend that that has not been done yet, so it's very difficult to say what force deflection characteristics need be to satisfy the matter of aggressivity. I don't really see why we have to be locked into one concept or another, that is, the collapsing metal structure or hydraulic systems just because of aggressivity. I think what has been demonstrated here is that we can take a collapsing metal type structure and tailor the force deflection characteristics to suit some ideal curve that we might want. Now, if we can define what that curve is, I think you can do it with collapsing metal structure. You may have to add a little length to the front of the car to do it, or you can probably do it with hydraulic systems. My own personal opinion would be that in terms of economics, at the present time, the collapsing metal structures would probably be more economical. Now, what should happen in the future in terms of methods for manufacturing hydraulic systems, I'm not sure, but at least at the present I would tend to think that the economics would favor collapsing metal structure itself.
Testing and Evaluation as Applied to Vehicle Structures and Exteriors

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Frederick E. Arndt
Ralph A. Rockow
Dynamic Science
A Division of Ultrasystems, Inc.

ABSTRACT

The techniques used for testing and evaluation of surface vehicles have been significantly improved in recent years as a result of the emphasis placed on vehicular safety by the National Highway Traffic Safety Administration. The automotive industry and independent test laboratories have incorporated the latest test techniques available in order to assure that meaningful data are evolving from the millions of dollars currently being expended on improving the safety of the surface vehicles. This paper presents a summary of testing and evaluation techniques currently being used in the area of vehicle structures and exteriors research. Support functions such as facility design, data acquisition and data processing are discussed.

The paper reflects the latest in the state-of-the-art of test techniques as presented in public documents and reviews the merits and limitations of certain techniques.

INTRODUCTION

With the increased emphasis on automotive safety resulting from the implementation of Federal Motor Vehicle Safety Standards and vehicle safety research, a need for improved auto test facilities has evolved. Several years ago, automotive test facilities were primarily confined to the automotive industry with a few independent laboratories available to handle specialized component testing. In nearly all cases, the test work was focused on overall vehicle operational performance under a range of highway operating conditions. Little effort was focused on the performance of the vehicle during an accident mode; namely, determining the structural crashworthiness of the vehicle.

The theme of this paper is to discuss several test techniques that have played an important role in making it possible to measure the crashworthiness performance of an automotive structure. No attempt is made here to cover all of the techniques that are currently available; only the more significant are discussed and illustrated.

The complexity of the automotive structure is increasingly apparent when one attempts to predict its performance under high loading at rapid rates of onset. Correspondingly, the need for developing data collection techniques to measure structural performance is also readily evident. Fortunately, many of the test and evaluation techniques and data acquisition systems developed during our space program are directly applicable to the automotive test field.

An appreciation for the data acquisition challenge is apparent when one considers that the impact pulse during a collision lasts for approximately 200 milliseconds. A complex array of structural performance data must be collected during this period of time. Superimpose the problem of accurately controlling the energy equivalent to nearly 5,000 horsepower for a standard car impacting the barrier at 60 MPH and it soon becomes clear that the
study and design of automotive structures under crash conditions is not that straightforward for the inexperienced. It requires the most sophisticated design and test tools which can be brought to bear on the problem.

**SUB-SCALE AND COMPONENT TESTING**

The engineering and economic payoffs of sub-scale and component tests are many. Sub-scale models usually represent specially designed structures that have been analyzed beforehand to focus on specific design characteristics of full-scale systems. As a result, data obtained from sub-scale testing normally have to be conditioned through analytical scaling laws to predict the full-scale performance. Component testing includes evaluation of individual elements of a structure as well as complete subsystems. A large and usually timely data base can be derived from component and sub-scale testing. These tests can provide fundamental engineering information early in the structural development cycle.

Component and sub-scale testing approaches are used to specifically:

- Evaluate basic concepts and materials
- Establish basic failure modes
- Establish dynamic load amplification
- Establish force-deflection characteristics
- Establish velocity sensitivity
- Provide design trade-off data
- Verify computer models.

Component and sub-scale tests provide the engineer and designer with the tools to study the basic structural behavior at a level and in an environment where the fundamental physics of the problem can be seen and better understood. Furthermore, test conditions can usually be controlled with a higher degree of accuracy in a variety of component and subsystem tests. Thus, the performance of a given design can be precisely examined and accurate trade-off decisions made. In addition, there are significant economic advantages in performing work at these levels as costs of test hardware, test setup, test conduct, and data reduction can generally be greatly reduced. It has been Dynamic Science's experience that component and subsystem testing methods are powerful approaches to the development cycle and should be exploited to the fullest extent possible to maximize the return on the total dollar being invested in the overall test program.

**Sub-Scale Testing**

Sub-scale test techniques are attractive approaches to obtaining large volumes of data, particularly in support of analytical models of complex structures which, if pursued on a full-scale level, would involve excessive expense. One should always remember, however, that in sub-scale testing there are several shortcomings. For example, if inadequate attention is paid to the initial design of the sub-scale test specimen (particularly as related to scaling laws), the resulting data can be misleading. Usually, at best, the sub-scale technique provides trends to guide the designer when designing the full-scale vehicle. Other inadequacies associated with sub-scale testing are that material shapes, thicknesses, interfaces, and joint effectiveness problems do exist and are not readily represented by a sub-scale model. For example, the inability to properly represent a structural joint can produce an erroneous result because the overall influence of a joint is much more predominant in the sub-scale model than the same joint would be in a full-scale test. Care must be taken to study the interface between instrumentation and the sub-scale model because, here again, the size of the instrumentation itself can affect the performance of the model. The fact that sub-scale models are usually small (1/10-1/4 scale) and thus cannot be instrumented as completely as the full-scale vehicle also tends to be a shortcoming.

Subsystems testing techniques were used rather extensively and effectively under National Highway Traffic Safety Administration contracts for rear end structural crashworthiness improvement and side structure crashworthiness improvements for standard size hardtop vehicles (Contracts DOT-HS-
046-2-264 and DOT-HS-046-1-209). Results shown in Figure 1 illustrate data obtained from half-scale component tests of energy absorbers which were being evaluated for improved rear end structural crashworthiness.

Component Testing

Structural component tests can include tests of either individual components or elements of the automotive structure as well as the complete subsystems. Advantages of testing specific components and/or subsystems of a structure are:

- Lower costs when compared with total-system test costs
- Usually quicker test turnaround than in full-scale testing; thus, an efficient development tool
- Usually able to control test conditions rather closely
- Testing is conducted at the full-scale level; thus, analytical scale factors used in sub-scale testing are not required
- Ability to evaluate the influence of production fabrication processes.

Probably the most significant item above is the fact that when testing components and/or subsystems of an automotive structure, the engineer is obtaining data directly from the actual part that is being considered in the final structure.

The primary disadvantage of testing components and/or subsystems is that it is difficult to simulate the interaction between the components and the total system. This problem has caused many researchers to develop subsystems which, when they eventually integrate them into a total system, do not perform as predicted. This is directly attributable to the inability of being able to simulate the interaction forces of the total system when subjecting the component to simulated operating environments.

Test facilities normally used for component structural testing can be grouped into sleds/catapults, drop towers, pendulum systems, and static crushers. The tests are conducted under either static or dynamic test conditions.

STATIC COMPONENT TESTS

In recent years, the large-scale static crusher has become more popular as a means for statically evaluating the crush performance of the total structure. A typical static crusher is shown in Figure 2.

Like all devices of the static type, extreme care and thought must be taken to assure that

Figure 1. Comparison of crush characteristics for one-half scale component tests

Figure 2. Heavy-duty static crusher
the load paths are representative of the actual crash environment that is experienced on the highway. Experience has shown that correlating static data to the dynamic environment is extremely difficult; small changes in structural design can make significant changes in structural performance under dynamic conditions that had not been observable beforehand when studying the performance of the structure under static conditions. Considerable effort is currently being employed to develop static crush capabilities at several facilities in the country, and there is little doubt that as we understand this test technique better in future years it can and will prove to be a valuable design tool.

DYNAMIC TESTS

Drop towers, sleds, pendulums, and bogey vehicles are the most popular test facilities used to evaluate vehicle components under dynamic impact conditions.

Drop Tower

Figure 3 shows the drop tower configuration where the test item is a modified side structure of a vehicle. In this particular test series the test specimen was held stationary and was impacted by a contoured weight simulating the front structure of a modified vehicle. These examples, of course, are of relatively simple structures; the drop tower can just as easily be used for complex subsystem evaluations. Experience has shown good test repeatability when employing this relatively inexpensive test technique.

Impact Sled

The impact sled is another device for dynamically testing structural components and subsystems. An impact sled can be accelerated by using a number of techniques including a falling mass, solid propellant thrusters, or pneumatics of hydraulics. The desired deceleration pulse to which the sled is subjected is obtained by impacting the sled against a shaped stack of crushable material or hydraulic buffers. Experience has shown good reproducibility with this test technique. Many tests can be run in this manner at a very economical per-test cost.

An example of the type of test that is conveniently conducted on a sled facility is the development of a crashworthy retention system for gas storage vessels mounted in automotive vehicles equipped with dual-fuel systems. Figure 4 shows a typical test setup for evaluating the performance of the gas storage vessel installation. The test bed in this case was a body buck mounted to the sled structure. The body buck orientation was pitched down to achieve the target vertical acceleration levels. Sled deceleration was controlled by means of a crushable paper honeycomb stack backed by a concrete buttress.

![Figure 3. Side view of side structure in drop test](image1)

![Figure 4. Typical pre-test sled setup](image2)
Pendulum

Another popular method for subjecting components to high-impact impulses is the pendulum technique. This technique has been used for several years by European and other foreign manufacturers to evaluate the performance of specific components on heavy-duty vehicles. It is now being employed as a requirement for evaluating automotive bumpers of the future. Although a valuable test apparatus for economically conducting tests, the pendulum test setup has a definite drawback in that extreme care must be taken to properly locate the test specimen relative to the impacting pendulum weight. The fact that the pendulum moves through an arc means that the force application has both horizontal and vertical components; a parallelogram pendulum ensures that the impacting force of the striking mass remains in fixed orientation with respect to the impacted vehicle.

Bogey Vehicles

Another technique that is gaining popularity is the use of bogey vehicles to conduct dynamic structural performance tests. The bogey vehicle is defined here as a workhorse-type test bed which is used for multiple crash tests into a barrier, and thus eliminates the expense of using a destructible vehicle for each impact test. Components and subsystems are attached directly to the bogey vehicle and it is propelled into the impact zone by a towing mechanism similar to those discussed later in this paper.

FULL-SCALE TESTS

The term full-scale testing is used here to mean the evaluation of the complete system. The following discussion places emphasis on the advantages and disadvantages of testing at the full-scale level and provides an evaluation of the various types of full-scale tests currently being conducted.

The primary advantage of full-scale system testing lies in the fact that the complete structural system is evaluated. The interrelationship between the structural components or subsystems can be determined when the complete vehicle is tested. Full-scale tests also allow a closer simulation of the actual accident conditions which are to be encountered.

The major disadvantage with full-scale testing is the associated high costs. Not only is the testing itself expensive but the test specimens are usually fairly complex and expensive to build. Test frequency is reduced because of time associated with modifying and/or building new full-scale prototype components as well as the added time required to prepare the vehicle for test. And finally, test facility requirements are greater and the sophistication of data acquisition, as well as special operational problems associated with running a complex facility, are more difficult.

Types of Full-Scale Tests

Figure 5 depicts in schematic form the many types of crash situations which may be realized in the real-world of automotive accidents. It will be observed from this figure that the load application can be classed as follows:

- Concentrated load
- Uniformly distributed load
- Other load applications.

Impact directions are from the front, side, rear, roof, and rollover.

Concentrated loads are those usually associated with high structure intrusion potential. Typical examples of the concentrated loads are pole, bridge abutment, oblique vehicle, and off-center vehicle impacts. Uniformly distributed loads are associated with head-on, front-to-rear, front-to-side, and full-area roof-loading-type impacts. Other types of impacts include the underride of the striking vehicle as it impacts a truck or larger vehicle, such as a bus, and roll-over impacts where both lateral and oblique loading are provided into either the side or the front corner of the roof structure.

It becomes readily apparent that many test techniques are required to evaluate the real-world accident situation. The following full-scale test modes represent a summary of
<table>
<thead>
<tr>
<th>LOAD</th>
<th>IMPACT</th>
<th>OBSTACLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>BACKWARD</td>
<td>DISTRIBUTED</td>
<td><strong>HEAD ON</strong></td>
</tr>
<tr>
<td></td>
<td><strong>FRONT END, OFFSET</strong></td>
<td><strong>SIDE, 90°</strong></td>
</tr>
<tr>
<td></td>
<td><strong>WEDGING OF PASSENGER CAR UNDER TRUCK</strong></td>
<td><strong>SIDE, OBIQUE</strong></td>
</tr>
<tr>
<td></td>
<td><strong>TRUCK CAB FRONT END PANEL, HEAD ON</strong></td>
<td><strong>SIDE SKID AGAINST TREE, POLE, ETC.</strong></td>
</tr>
<tr>
<td>CONCENTRATED</td>
<td>DISTRIBUTED</td>
<td><strong>REAR END, FULL ON</strong></td>
</tr>
<tr>
<td></td>
<td><strong>FORWARD DISPLACEMENT OF BULKY GOODS OR LOOSE GRAVEL, ETC.</strong></td>
<td><strong>FULL AREA, ROOF PANEL</strong></td>
</tr>
<tr>
<td>FORWARD</td>
<td>DISTRIBUTED</td>
<td><strong>SIDE EDGE, ROOF PANEL</strong></td>
</tr>
<tr>
<td>CONCENTRATED</td>
<td><strong>REAR END, OFFSET</strong></td>
<td><strong>END EDGE, ROOF PANEL</strong></td>
</tr>
<tr>
<td></td>
<td><strong>FORWARD DISPLACEMENT OF LOGS, POLES, ETC.</strong></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 5. Types of crash situations*
test types which have been used in the past and are available today:

- Rigid flat barrier tests
- Rigid oblique barrier tests
- Rigid pole barrier tests
- Vehicle-to-vehicle tests
- Rigid bogey vehicle-to-vehicle tests
- Roll-over tests.

Each of the above test configurations involves impacting the test vehicle with another object that is usually rigid at the impact face. In the real-world situation, the impacted object also yields, particularly in vehicle-to-vehicle tests. Thus, it is apparent that a real need exists for test barriers that yield in a programmed manner. Two test types are presently under development to achieve these results. They are:

- Variable rigidity barrier tests
- Variable rigidity bogey-to-vehicle tests.

These two test types are new developments that recognize the need for more realistic vehicle simulation techniques. They have evolved from a rather sophisticated crashworthiness methodology research effort.

**FLAT BARRIER**

Until recently, the flat barrier impact has been the primary test mode for evaluating frontal and rear structural crashworthiness improvements. A typical flat barrier impact is shown in Figure 6. The barrier has been used as a development tool and as a design verification tool. It provides a distributed load to the front or rear of the vehicle. The major problem with rigid barrier impacts lies with the inability to adequately define the barrier equivalent test energy levels (barrier equivalent speed) which might be involved in other crash situations.

**OBLIQUE BARRIER**

An oblique barrier is essentially a variation of the flat barrier. It is used to simulate angular inputs from either the front or rear and, like the flat barrier, it provides a repeatable test scheme for evaluating the structural response of the vehicle with concentrated load inputs. A major advantage of the oblique barrier is that it allows the vehicle to be tracked along its longitudinal centerline into the impact as shown in Figure 7, as contrasted to mounting a vehicle on casters as shown in Figure 8 and then tracking the vehicle at some oblique angle relative to the vehicle centerline. Thus, the overall vehicle dynamics are retained during the crash simulation.

**RIGID POLE**

A rigid pole has been used extensively to test vehicles for concentrated and intruding load conditions during structural crashworthiness research and development activities. This particular test approach, while being extremely severe, is probably more closely in line with real-world collision situations than any other rigid barrier test modes. It represents, with a fair degree of accuracy, front or side collisions with trees, poles, and sharp bridge abutments (Figure 9).

**VEHICLE-TO-VEHICLE**

Vehicle-to-vehicle impacts can be of several types including front-to-front, front-to-rear, and front-to-side. These impacts include the range of angles from normal to highly oblique and hence represent both distributed load impacts as well as concentrated load impacts.
Vehicle-to-vehicle impacts represent the most direct approach to evaluating structural response in accidents where two vehicles are involved. In these tests, the actual resultant structural interactions are obtained.

The major disadvantage of the vehicle-to-vehicle test lies with its increased complexity and hence increased costs. However, the element of realism in the test and the subtle effects of the overall interaction of two vehicles require that this kind of testing be performed.

**BOGEY VEHICLE-TO-VEHICLE**

Some cost benefit can be derived by using a bogey vehicle which has attached to its front various fixed barrier configurations such as a flat barrier, an oblique barrier, or a pole barrier. These moving barriers have some of the same reproducibility advantages of the rigid barrier configuration. However, an added advantage is offered in that better simulation of the total system energy and momentum exchange is achieved because of the two-mass system. The bogeys are rigid, usually nondestructible, and have the ability to change the mass ratio system.

**ROLL-OVER SIMULATION**

Historically, the lack of repeatability is one of the primary drawbacks of the roll-over test technique. Many techniques have been evaluated to induce vehicle roll-over. These are:

- Driver induced
- Ramp roll
- Inclined sled
- Roof crush
- Roof drop.

The latter two are designed to evaluate the crush strength of the roof only, while the first three types provide a dynamic situation where both the structural behavior of the vehicle as well as the occupant ejection probabilities can be evaluated. The ramp roll method and the sled roll method are the only methods that have merited any serious consideration as a basic test tool for structural evaluations.
Lack of repeatability is a primary drawback of the ramp roll technique. It does provide a forward velocity component, however, which relates, in some cases, to a more realistic real-world crash situation. It is a good test for occupant ejection as well as for overall structural strength. However, its proven record of nonrepeatability and unreliability outweighs its usefulness as an acceptable test tool.

The sled roll technique, as conceived and perfected by Mercedes-Benz, has shown repeatability and ease from a test implementation point of view. It allows for evaluation of the roof structure and also provides a measure for evaluating occupant ejection. Its major disadvantage lies with the fact that no forward velocity component is present during the test.

VARIABLE RIGIDITY BARRIERS AND BOGEY VEHICLES

As part of a front end structural crashworthiness program presently being conducted by Dynamic Science for the National Highway Traffic Safety Administration (Contract DOT-HS-046-2-468), a new family of test vehicles and barriers are being developed which have variable force buffers attached to them. Two of these test devices, commonly referred to as variable rigidity barriers or variable rigidity bogeys, are shown in Figures 10 and 11, respectively. The buffers yield in a programmed manner upon impact with the striking vehicle. One device is termed a fixed-force system because crushable materials are used to establish the force response. This fixed-force system is actually passive in that the crushable material, most often aluminum honeycomb, is configured to provide the desired pulse shape. A complete family of fixed-force pulses can be obtained. The second force system uses hydraulics. Two hydraulic systems are available. These are the AMF Inc. ESV hydraulic buffer system which is used on the bogey vehicle and another hydraulic buffer system which is used on the barrier. The latter system uses a set of replaceable orifices to program the crush response desired for a particular test. The hydraulic system obviously offers much flexibility over the fixed-force system as these replaceable orifices can easily be designed to simulate far more complex crush responses than can be obtained with the fixed-force systems.

These variable rigidity systems represent the most advanced energy management test tools available today. It is readily apparent that they offer a major bridge in the gap between the realism of vehicle-to-vehicle impacts and the simplicity of barrier impacts. A very significant advantage of the variable rigidity bogey vehicle is that it is of "workhorse configuration," and can be ballasted to easily allow the study of mass ratio effects as
well as other aggressiveness effects. These aggressiveness effects can be in terms of either bumper mass or structural stiffness as programmed into the variable rigidity portion of the buffers. These bogeys require relatively simple instrumentation as they are rigid (one lump mass) and only a few accelerometers are needed to adequately define the response of the vehicle. As a better understanding evolves from tests conducted using these test tools, a second generation of more sophisticated bogey vehicles will naturally follow.

FULL-SCALE VEHICLE TEST FACILITIES

The following text describes some of the basic elements of test facilities as they exist throughout the industry today. The automotive industry and independent research and development laboratories generally have vehicle crash test facilities which include the six essential elements listed below:

- Barrier/impact area
- Guidance and roadways
- Propulsion/tow system
- Test abort systems
- Data acquisition/instrumentation
- Test control systems.

Barrier/Impact Areas

Three types of barrier/impact areas exist at most facilities. These are fixed barriers which include the flat barrier, the fixed pole, and the angular flat barriers. An area is usually provided for vehicle-to-vehicle impacts where either both vehicles can be moving at the time of impact or one vehicle is stationary and impacted by another vehicle. An area may also be provided for vehicle roll-over testing which may or may not be an integral part of the basic test facility.

Camera pits are usually provided in the barrier and vehicle-to-vehicle impact areas.

Guidance and Roadways

Guidance is normally achieved by means of a monorail system although tension cable systems and radio control have been used. The monorail concept provides for a sliding shoe which rides on the rail, is attached to the vehicle, and provides vehicle directional control as the vehicle rolls along the roadway into the impact area.

The tensioned cable concept for guiding the vehicle is not used very often because it is not capable of providing any significant lateral restraint. As contrasted to the monorail system, the cable tension guidance system does not have any application to rearward taws. The radio control concept has been perfected to a high degree of sophistication by the Fiat Motor Company. Its main disadvantage is that a receiver and steering system must be located within the car, thus adding to an already complex test setup and generally high test weight conditions.

The barrier approach roadways usually consist of smooth and level asphaltic concrete or cement surfaces. Typically, these surfaces have a dry skid number of 75. The outer edges of the roadway are prepared in a variety of ways to minimize the abrasion which might occur to trailing umbilicals which relay data signals from the vehicle to central data acquisition stations.

Propulsion/Tow Systems

A variety of propulsion systems are being used to tow test vehicles into the impact area. The most popular forms of propulsion are:

- Stationary power plant systems
- Tow vehicle systems
- Test vehicle power systems.

The most common system in use today involves stationary power plants consisting of either two or three high-power internal combustion engines which tow the vehicle into the impact situation by means of a cable.

Variation does exist, however, in the cable towing devices. Two basic approaches are used: single-ended cable systems and continuous-cable systems. The single-ended system simply winds the tow cable onto a drive drum which is connected to the engine either through a transmission or gear box arrangement whereas a continuous-cable system is exactly what it implies, a continuous cable
which is driven by means of a winch drum system connected to the engines through either a gear box or transmission. At Dynamic Science, a continuous-cable system is used whereby the cable is pulled up one side of the guidance rail and is returned down the other side of the guidance rail by means of a return sheave. This system has several major advantages, one of which is that vehicle-to-vehicle tests can be easily accomplished by towing vehicles into each other by means of the same cable, thus ensuring precise control of the impact point. Other continuous-cable systems simply return the cable by means of a remote routing course away from the basic test monorail system (the General Motors system, for example). When employing a continuous cable system, a scheme for maintaining cable loading on the slack side of the cable must be provided.

Some single-ended cable systems employ a tow vehicle as the primary propulsion system, i.e., a high-powered tow vehicle pulls the test vehicle into the impact zone. The greatest disadvantage of the tow vehicle is usually the lack of sufficient drawbar horsepower which is required for high-load, high-speed impact tests. This system can also suffer from impact speed control problems because of its inherent underpowered condition.

Test vehicle power is used only in a limited number of cases. This approach usually requires a significantly longer roadway prior to impact, or it is limited to relatively low-speed impacts if the availability of space is a problem. Vehicle impact speed control is definitely a problem with this system. The other obvious drawback is that the test vehicle must be operational and have fuel on board, creating still another problem associated with test safety.

Test Abort System

The test abort system is probably one of the most important elements of the crash test facility. The ability to make last-second “go/no-go” decisions and confidently stop the test vehicle prior to impact is an absolute require-

ment. Three basic concepts have been used to achieve test abort. These are:

- Trailing cable/drag drum abort system
- On-board abort system
- External abort system.

TRAILING CABLE/DRAG DRUM SYSTEM

The drag drum system is not greatly different from the single-ended cable tow system in that a cable wrapped on a drum is played out and trailed behind the vehicle during acceleration and tow-in to the test impact. Should an abort be required, power is cut and the drag drum is braked to provide the retarding force to the towed vehicle. This system is used in several instances and provides good abort force capability. It can of course be used in conjunction with the on-board vehicle braking system to supplement the abort brake capability and hence achieve high abort braking capability.

ON-BOARD ABORT SYSTEM

The on-board abort system uses the vehicle’s service brakes to achieve the abort function. This system has some limitations in that the maximum stopping capability of the vehicle is limited by the stopping power of the brake system. With normal-size sedans, maximum effort braking on the order of .8g is a limit (giving a stopping distance from 60 MPH of slightly less than 190 feet). The consequence of this relatively long stopping distance lies with the fact that the final abort decisions must be made at a considerable distance from impact (>200 feet) and hence, greater variations in impact speed are realized.

TRAILING ABORT SYSTEM

The trailing abort system concept utilizes a braking device (shoe) which rides on the monorail guidance system and is attached to the rear of the test vehicle with cables. Braking force is achieved by clamping onto the guide rail and transmitting this force to the test vehicle. The system is capable of delivering extremely high abort force levels—levels as
high as 3g can be achieved, depending upon the weight of the test vehicle. This allows the test vehicle to be stopped in very short distances (well under 100 feet from 60 MPH, again depending upon the weight of the vehicle). Hence, overall system and vehicle readiness can be checked later in the vehicle run-out and less time is available for speed variation at the impact point. This latter condition is of particular importance when performing compliance tests and other testing associated with the Experimental Safety Vehicles where competitive performance decisions are being made.

Data Acquisition

A reliable data acquisition system which includes sensing, transmitting, and recording of the data is of key importance to any test facility conducting vehicle structure tests. The test data requirements basically dictate the type of instrumentation and data acquisition system which must be employed. Table 1 illustrates in a general form the typical data requirements for a given full-scale dynamic test and also indicates the method of acquiring such data. Instrumentation divides into basically two categories; namely, electronic and photographic. These records are supplemented by a test log and observation of the test phenomena. Electronic data fall into a variety of categories, as listed below:

- Accelerations
- Loads
- Displacements
- Pressures
- Strains.

The basic electronic instrument used to evaluate the structural crashworthiness of vehicles is the accelerometer. Instrumentation of this type is in a high state of development, i.e., accuracy and reliability are good and all instruments are easy and straightforward to calibrate.

A key element of the test instrumentation is high-speed photography which is generally used to study structural and occupant dynamics during the impact. Many brands of high-speed cameras are available on the market today. These can be used in either a fixed ground location or on board the vehicle. Normally, framing speeds are set at 1,000 frames/sec for close-up structural or dummy dynamics work, whereas 500 frames/sec coverage is generally adequate for overall structural observations for current test speeds. The high-speed photographic coverage is supplemented with normal-speed framing cameras for overall test documentation and stop-action still cameras for sequence action shots.

Written observation is generally limited to overall comments about vehicle performance, vehicle rebound, yes-and-no criteria, post-test static crush information, and any other pertinent test observations.

DATA ACQUISITION AND TRANSMISSION

Three schemes for recording data exist today. These are:

- Trailing wire umbilical/ground-based recording
- Radio transmission/ground-based recording
- On-board recording

Virtually all recording is performed in either FM or FM multiplex form. Very advanced pulse code modulation techniques are becoming available; however, to the knowledge of the authors, these have not yet been applied to automotive crash testing. The on-board data recording technique has not been perfected sufficiently because of lack of reliable crashworthy tape recorders.

The trailing wire umbilical system offers a good and reliable technique. The size of the umbilical can be a problem, depending upon whether on-board or ground-based signal conditioning is used. Data formatting can also affect umbilical size.

A schematic of a typical data acquisition and transmission system is shown in Figure 12. The system utilizes a trailing umbilical system as well as a backup radio transmission link. The basic elements of this system are similar to most systems in use today. As
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement Method</th>
<th>Application Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic Vehicle</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact Time</td>
<td>Contact switch signal impressed on millisecond time base.</td>
<td>X</td>
</tr>
<tr>
<td>Approach Velocity</td>
<td>Fifth wheel and low cable velocity sensor. Differentiate to obtain approach acceleration.</td>
<td>X</td>
</tr>
<tr>
<td>Impact Velocity</td>
<td>Fifth wheel and speed trap. Entrance and exit signals from speed trap are used to gate a counter.</td>
<td>X (1)</td>
</tr>
<tr>
<td>Rebound Distance</td>
<td>Direct post-test linear measurement. Also determine from high-speed film data.</td>
<td>X</td>
</tr>
<tr>
<td>Rebound Velocity</td>
<td>Calculated from integrated barrier force measurements, mass of vehicle, and impact velocity. Thus: ( V_0 - V_1 = F/m ). Crosscheck with acceleration data and high-speed film data.</td>
<td>X</td>
</tr>
<tr>
<td>Impact Angle</td>
<td>Analysis of impact on overhead high-speed camera film using vehicle and pad reference marks.</td>
<td>X</td>
</tr>
<tr>
<td>Acceleration Measurements at Various Locations on Vehicle</td>
<td>Accelerometers, unbonded strain gage type.</td>
<td>X</td>
</tr>
<tr>
<td>Force Versus Distance Response</td>
<td>Measured force versus time cross-plotted with distance versus time. Distance obtained by double integration of acceleration data. Force may also be computed from acceleration data if ( m ) if the mass involved can be identified. Displacement also crosschecked with high-speed film results.</td>
<td>X</td>
</tr>
<tr>
<td>Net Crush</td>
<td>Direct linear measurement. Verified with high-speed film results.</td>
<td>X</td>
</tr>
<tr>
<td>Crush Versus Time for Various Members</td>
<td>Equivalent to distance versus time. Computed by double integration of acceleration data. Also by analysis of high-speed film for visible components.</td>
<td>X</td>
</tr>
<tr>
<td>Steering Column Displacement</td>
<td>Analysis of high-speed film.</td>
<td>X</td>
</tr>
<tr>
<td>Fuel Loss</td>
<td>Leak rate measurement by collecting timed samples.</td>
<td>X</td>
</tr>
<tr>
<td>Vehicle Weight by Wheel Performance</td>
<td>Direct pre-test measurement using balance scales.</td>
<td>X</td>
</tr>
<tr>
<td>Vehicle Attitude During Impact: Roll, Pitch, Yaw, Displacement</td>
<td>Engineering observation and Voltage Measurements.</td>
<td>X</td>
</tr>
<tr>
<td>Vehicle/Restraint System</td>
<td>Analysis of high-speed film.</td>
<td>X</td>
</tr>
<tr>
<td>IORS Triggering Time and Supply Voltage</td>
<td>Signal from impact sensor impressed on millisecond time base.</td>
<td>X</td>
</tr>
<tr>
<td>Sound Level and DC Pressure Level in Occupant Compartment</td>
<td>Transduced voltage measurement.</td>
<td>X</td>
</tr>
<tr>
<td><strong>Barrier</strong></td>
<td>Microphone for db levels. Pressure transducers for DC levels.</td>
<td>X</td>
</tr>
<tr>
<td>Fixed Flat Barrier Force</td>
<td>Load Cells.</td>
<td>X</td>
</tr>
<tr>
<td>Dummy Dynamics</td>
<td>Triaxial acceleration.</td>
<td>X</td>
</tr>
<tr>
<td>Accelarations: Head, Chest, Pelvis</td>
<td>Doubly integrated acceleration data, film data.</td>
<td>X</td>
</tr>
<tr>
<td>Velocity: Head, Chest, Pelvis</td>
<td>Doubly integrated acceleration data, film data.</td>
<td>X</td>
</tr>
<tr>
<td>Displacement: Head, Chest, Pelvis</td>
<td>Differentiation of initial acceleration data.</td>
<td>X</td>
</tr>
<tr>
<td>Rate of Onset: Head, Chest, Pelvis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Femur Loads</td>
<td>Load Cells.</td>
<td>X</td>
</tr>
<tr>
<td>Head Laceration Index</td>
<td>Observation of chamois skin. (3)</td>
<td></td>
</tr>
</tbody>
</table>

(1) Fifth wheel only.
(2) Combined elastic and plastic deflection of a given point on vehicle.
(3) According to the Wayne Laceration Severity Index procedure as discussed in SAE Paper No. 700,427 and 700,428 of the 1970 SAE International Automobile Safety Conference Compendium.
indicated in the schematic, on-board signal conditioning units which consist of on-board power, on-board calibration circuits, and on-board FM multiplexing are also utilized. This particular approach allows the trailing umbilicals to be significantly smaller, and hence lighter, than systems using off-board signal conditioning and calibration control circuits. The disadvantage of the system is that it tends to be heavier than off-board signal conditioning systems. An advantage of the RF link is readily obvious in that the trailing wire umbilical is eliminated from the test setup.

CALIBRATION

To ensure reliable and accurate test results, all elements of the data acquisition system and instrumentation must be calibrated. Rigorous calibration procedures must be established and performed. These include use of traceable calibration standards as well as a rigorous plan of maintenance and scheduled instrument and equipment calibration.

DATA REDUCTION

Converting the measured information to hard engineering numbers represents the successful culmination of a test activity. Data recorded on tape are usually processed in the manner indicated in the schematic of Figure 13. The first scheme is simply to play the data back in time format via an oscillograph recorder. This process usually represents the first of a two-step operation in handling data and provides the first look at the test results in a relatively short period following the test. Typically, data in this format tell something of the quality of the information obtained during the test, general signal levels, and time durations. The second process of the data reduction scheme consists of analog-to-digital conversion of the signals, followed by processing of this digital information by means of a high-speed digital computer. Outputs from the computer generally consist of hard copy printouts of the basic parameters versus time. Normally, acceleration information is integrated once to obtain velocity response and twice to obtain displacement response of the vehicle. These data then can be used to obtain crush characteristics (G versus displacement) of the structure being evaluated. When occupants (dummies) are on board the vehicle, the data may be further processed to obtain
information on injury criteria such as the head severity index, acceleration levels, and time durations above preset acceleration levels. The computer is also then used to generate plots of all the output information for subsequent engineering analysis.

Test Control

Once all facilities and equipment and instrumentation are in readiness, the test must follow. The key operation during this phase of the effort is close monitoring and control of the test. Monitoring and control consists of the following basic elements:

- Vehicle speed control
- Facility readiness status
- Instrumentation readiness status
- Data acquisition readiness status.

Monitoring of all of these parameters during the vehicle roll-out and subsequent period prior to impact requires close vigilance on the part of the key test operations personnel. Predetermined criteria must be established for satisfactory operation of each of the above-mentioned parameters and any deviation from these should result in test abort. Basic system readiness is usually monitored visually while velocity abort is generally automatic. Totally automatic abort systems are operational today at those facilities involved in compliance and competitive evaluation type testing where very tight and precise test control and test performance parameters are required.

In spite of the fact that automatic velocity control systems have evolved, the use of highly accurate and precise speed traps for determining vehicle speed remains a basic requirement for the type of crash testing that has been discussed in this paper. Manual speed control still remains the most prevalent scheme for controlling the impact velocity of the test vehicle. This generally works well but the need for automatic speed control systems is highly desirable. Unfortunately, the cost-effectiveness trade-off for fully automatic control systems has not been sufficient to justify the complete system.

CONCLUSIONS

This paper has focused on presenting a discussion of the more common techniques currently used to test and evaluate vehicle
structures and exteriors. Several conclusions can be made as a result of preparing this paper.

1. Test and evaluation techniques for studying the performance of vehicle structures and exteriors have improved significantly in recent years. The uses of data acquisition and data reduction systems have greatly improved the accuracy of test data.

2. New test techniques are being considered to more closely simulate the real-world environment of automobile accidents. The use of bogey vehicles promises to become a valuable technique for studying the performance of automotive structures under controlled conditions.

3. The importance of studying the performance of the total system rather than just specific components is increasingly apparent. Sophisticated test techniques are required to properly evaluate the performance of the total system.

4. The significant cost savings when performing sub-scale and component tests is the prime mover to challenge the R&D communities to make better use of this mode of testing.

The authors feel that the discussion presented in this paper is only the beginning of the sophistication which will evolve as engineers attack the structural safety problems that will exist in future modes of transportation.
Development of Advanced Deployable Restraints and Interiors

Donald Friedman
Minicars, Incorporated

ABSTRACT

Motor vehicle accident statistics are tabulated by the impacted object, the impacting area, and the approximate force/deflection characteristics of each. The relationship between this data and injury criteria determines restraint requirements. These are quantified for existing and modified structures of 2000 lb. and 4000 lb. vehicles.

In this paper, types and fixtures of deployable restraint and interior components are briefly discussed including sensors, igniters, inflators, inflatables, bolsters, and cushioning. These are related to head, thorax, and femur energy absorption and in turn to occupant kinematics via computer simulation and high speed sled tests and development.

The expected performance of assembled restraint systems is estimated for various compartment sizes and occupant locations and the current status is outlined. Problem areas and future limitations are summarized.

When, in conjunction with a recent proposal effort, Minicars first turned from the study of deployable occupant restraints in full size cars to the study of deployable restraints in sub-compact cars, it was with a sense of enthusiastic interest, but also with a sense of foreboding because of the challenging extremity of the crash phenomenon in small cars. Newton’s inexorable laws seem to guarantee that the crash of a two-ton-or-more object into a one-ton object will always be very, very bad for the one-ton object and anything inside it. It was felt that, given this unfavorable elementary situation, advantage would have to be taken of every resource available in occupant restraint systems, and this meant achieving a truly realistic, un-impressionistic understanding of the operation of restraint systems.

Our study ultimately brought us a clearer understanding of the crash situation, not just for sub-compacts, but for all cars, and indeed of what to do about the situation for all cars. Some of the things learned, once recognized, seem obvious, for instance, that a restraint system and the structure of the car in which it operates actually work together as a complete system to save the occupant. Other things were more surprising. For example, our vision of cars crashing square-on into flat barriers or rigid poles at high speeds had to be given over—not only because such accidents are exceedingly rare, as everyone always knew, but because cars designed to be less dangerous in such crash modes might be more dangerous in the far more common lower-speed car-to-car modes.

In fact, because the great majority of present-day accidents produces no significant injuries, any random change in cars will probably hurt more people than it will save, and any change in cars will be “random” (in effect), no matter how rationally and deliberately it is made, if it is not made in full light of the real nature of accidents, the relationship between restraint performance and structural performance, etc.
To over-simplify a little, saving the occupant in a crash with the use of a deployable restraint depends on having enough total crush stroke (i.e., crushing of the car or cars, plus interior stroke, or distance inside the car over which the restraint can work). The less the car crushes, the more stroke must be available inside the car, and vice versa. If the sum of these two distances is too small, then, unless our human tolerance estimates are in gross error, no restraint can save the occupant. If it is a certain minimum amount, then a very fast-deploying restraint will be necessary to save the occupant. Increase the sum of crush plus interior stroke more, and the restraint can deploy more slowly. Another factor in this complex relationship is the “efficiency” of the restraint, which is defined as the comparison of the theoretical minimum distance over which the restraint could stop the occupant and the distance over which it actually does. No restraint can be 100% efficient in this sense; but the closer a restraint comes to 100%, the less crush stroke plus interior stroke is required. The third factor in the relationship concerns the nature of the load distribution provided by the restraint system. Generally, the better the load distribution, the higher the loads that can be safely applied to the occupant. Higher load, of course, means higher occupant decelerations which, in turn, means that stopping distances can be shortened.

Analysis of these factors in the case of large cars shows that more than enough crush stroke plus interior stroke is available to save the occupant in, say, a crash into a barrier using an advanced deployable restraint possessing good load distribution properties and of 80% efficiency.

In the case of the small car, however, there is not enough crush stroke plus interior stroke available for conventionally-structured passenger air bag restraint systems to work successfully in a relatively high-speed front-to-front crash with a larger car (though such a restraint would offer protection in a small car at lower impact speeds). Increasing the efficiency of the restraint has the effect of raising the top limit of survivable impact speed, and that now seems the most promising avenue of development. The following pages demonstrate how these conclusions were derived and present them in greater detail.

In development, half of the difficulty lies in understanding the problem. In order to optimize restraint performance and thereby minimize casualties, it is necessary to: 1) characterize accidents as they are in the real world; 2) optimize structural compatibility between cars; 3) define the relationship between structural performance and restraint performance; 4) determine how much can be spent on restraint and structural changes, based on the benefits derived. These factors will be analyzed in the first half of the paper in order to determine the design requirements for a successful advanced deployable restraint. The resulting restraint system will be discussed in the second half of the paper.

Each year in the United States, 28.5 million vehicles are involved in accidents (Figure 1), with 42 million (mostly unrestrained) occupants involved. Yet only 2.1 million injuries that are “disabling beyond the day of the accident” result.

A better understanding of human tolerance levels has fostered improved safety glass, recessed controls, adequate padding, and frangible protrusions, and has made the modern passenger car a relatively safe environment for unrestrained occupants in impacts of 20 to 30

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<tr>
<th>1971 ACCIDENTS, DEATH AND INJURIES CONSIDERED*</th>
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<td>INVOLVING FATALITIES</td>
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<td>INVOLVING DISABLING INJURY</td>
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<td>INVOLVING PROPERTY DAMAGE (INCLUDING MINOR INJURY)</td>
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<td>TOTAL</td>
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Figure 1. 1971 accidents, death and injuries considered
fps. Analysis of accident statistics reveals that most accidents occur at these rather low speeds (about 26 million of the involvements). Furthermore, most cars run into another car, rather than into anything resembling a flat or pole barrier. And finally, most impacts are not co-linear (e.g., "head-on"). These three facts are responsible for the low percentage of significant injuries and fatalities (see Figure 2).

Let us consider in detail these three important severity-influencing aspects: impact velocity (or rather, "barrier equivalent velocity" or BEV, the velocity of a crash into a barrier that produces the same deformation as that of a given non-barrier crash); the nature of car-to-car crashes; and the nature of non-co-linear ("oblique") crashes.

Your chance of impacting or being impacted by another vehicle, as opposed to any other object, is approximately 89%. Of that 89%, there is a 22% chance of impacting another vehicle with the front end of your vehicle. Most of these front end collisions turn out to be relatively low barrier equivalent velocity impacts. In fact, in all categories, including the 11.26% of "other" impacts (fixed objects, etc.), less than 3% are likely to be centerline-to-centerline collisions with high BEV's, the most severe and publicized type. It can be seen from these statistics that the preponderance of actual collisions involve angular loading of at least one front end and very often both; i.e., most accidents occur in an oblique or angular mode. Later, it will be shown that cars have different structural

### MAJOR FACTORS REDUCING SEVERITY

**WITHIN FATAL OR DISABLING ACCIDENTS**

1. **IMPACT TYPE** 89% CAR-TO-CAR
2. **DIRECTION** 97% ANGULAR IMPACT
3. **LOW SPEED** 90% below 30 MPH BEV

*Figure 2. Major factors reducing severity (within fatal or disabling accidents)*

### ESTIMATED CHANCES OF IMPACTING

**WITHIN FATAL OR DISABLING ACCIDENTS**

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<tr>
<td>ANOTHER CAR</td>
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<tr>
<td>YOUR FRONT</td>
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<tr>
<td>HIS RT., LFT., OR CTR. REAR</td>
<td>14.00</td>
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<td>HIS RT., OR LFT. SIDE</td>
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<td>HIS FRONT</td>
<td>1.60</td>
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<tr>
<td>OTHER</td>
<td>1.40</td>
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<td>YOUR RIGHT FRONT</td>
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<td>YOUR LEFT REAR</td>
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<td>YOUR LEFT FRONT</td>
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<td>OTHER</td>
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<td><strong>TOTAL</strong></td>
<td>11.26%</td>
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*Figure 3. Estimated chances of impacting (within fatal or disabling accidents)*

performance characteristics in these modes which radically affect restraint design.

In Figure 4, the number of casualties in various accident modes is characterized as a function of BEV's above and below 35 MPH. The societal costs of the casualties are illustrated on the vertical axis. The total cost of

*Figure 4. Estimated 1971 societal costs of 2.13 million casualties*
all categories is about 22 billion dollars, about half of which results from frontal impacts. Note in particular that the number of casualties is predominant in the "below 35 MPH" category, while the severity (indicated by the huge societal cost per incident) is predominant in the "above 35 MPH" category. It is clear that with current restraint systems, the large bulk of casualties can be substantially eliminated, but the 15 billion dollar cost of the more severe 150,000 casualties will remain.

The degree to which these casualties can be reduced depends on the barrier equivalent velocity above 35 MPH to which the modified structure and advanced restraint combination can protect the occupant. Figure 5 estimates the BEV distribution for sub-compact and full size car accidents within the 2.1 million casualties. If, for instance, the survivable BEV can be increased to 50 MPH, the percentage of fatalities eliminated increases from 94% to 98.5% for the full size car. This would account for an additional savings of 100,000 casualties and a concomitant societal cost savings of 4.7 billion dollars. However, as the number and percent of small cars in the U.S. grow, protection for their occupants equal to that afforded full size car occupants will require substantially higher speed performance from the small car's structure and restraints.

Since America's existing traffic mix consists of approximately 25% small (2000 lb. range) and 75% large (4000 lb. range) cars, it is fairly well agreed that two-car compatibility should exist between cars of different masses. One way this can be achieved is by modifying the vehicles so that a common force level exists to which all cars will resist an impact. Figure 6 illustrates the desired force/deflection characteristic proposed by NHTSA for high speed compatibility in two-car frontal impacts in 2000 and 4000 lb. vehicles. These structural characteristics will be used throughout the remainder of the discussion.

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**Figure 5.** Cumulative percent of frontal collision accidents within the equivalent test speed ranges (BEV)

**Figure 6.** Structural performance
Note that oblique force/deflection characteristics of the vehicles have been added which are significantly different than those of frontal barrier impacts, particularly for full size cars. These were derived from a parametric analysis of the structural performance maximizing the compatible velocity of unequal mass car-to-car collisions as indicated by the accident analysis. They are further justified because cars exhibit such asymmetrical loading properties and such loading often occurs, and, because the velocity to which the occupant can be protected is dependent on the sum of the resulting deflections.

Figure 7 illustrates the structural deformation of a full size car in frontal and oblique barrier tests at 38 MPH and compares them to the desired performance. These tests indicate, at least to that speed and particularly in oblique impacts, that conventional full size cars approximate the desired performance and require only the modification necessary to adjust the peak forces so as to remain below the established common force level. (In Figure 7, the 100,000 lb. force level suggested previously is characterized for a 4000 lb. sedan as a 25 g's maximum deceleration.) Therefore, there seems to be good evidence that the proposed structural compatibility between small and large cars will not involve as much modification as might have been expected.

Now that we have established some structural characteristics (see Figure 6), what about the restraint?

Although many biomechanical limitations of the human body, such as head injury criteria, maximum femur loads, chest severity index, etc., are significant, in large measure the restraint performance can be based on biomechanical estimates of whole-body deceleration which will produce no injury. As a result, a substantial reduction in deaths and injuries can be effected with a high degree of confidence if a restraint installation with characteristics as shown in Figure 8 is postulated. It should be noted that it has been assumed that the restraint system in question distributes loads in such a manner as to justify the high (50-60 g) assumed tolerable g-level. It remains to relate these structural and restraint characteristics to each other in order to determine the required deployment time and other factors by first considering a sub-compact barrier collision.

The solid lines in Figure 9 are a plot of the distance traveled by the occupant compartment* of a sub-compact car possessing the restructure characteristics of Figure 6b in a barrier collision as a function of the initial impact velocity. Two solid lines, for frontal and oblique impacts, are shown. For example, frontal crushing in a barrier impact at 60 fps (about 41 MPH) would cause the

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*Includes the motion of the center of mass inside the compartment.
car's center of mass to travel approximately 30".

The dotted lines are the minimum required travel of the center of mass of the occupant to avoid injury as defined by the previously-mentioned injury criteria (Figure 8). Dotted lines are shown for different restraint deployment times. In effect, the dotted lines define the minimum distance over which the center of mass of the torso must travel during deceleration. If the occupant travels further, the injury criteria may not be exceeded, but if he travels less, they certainly will be. Now the difference between the distance traveled by the occupant compartment and the center of mass of the occupant is the minimum interior stroke over which the restraint must operate in order for the occupant to survive. The analysis for a big car is similar and the results are easier to implement, but since it is desired that all cars be compatible, it is the problem for the little car at the highest practical speed that must be solved.

It is noted that, in a sub-compact car, the 35 ms deployment time of current front passenger air bag systems is too slow to prevent injury at high speed. About 12" of interior stroke is available, yet the interior stroke at a barrier impact velocity of 60 fps for an injury-free frontal impact would have to be 19" as a minimum, assuming that the restraint can be made to operate with 100% efficiency (right at the limit of, but not exceeding, the injury criteria).

Actually, present passenger air bag restraint systems operate at about 50% efficiency, where efficiency is defined as the ratio of the ideal distance over which the occupant could be decelerated safely to the actual distance traveled during deceleration. A 50% efficiency means these restraints produce forces, on the average, which are less than ideal, and therefore require more interior stroke. The interior stroke is also affected by variations in restraint performance over the anthropometric range. These factors tend to make current sub-compact car passenger air bag restraint performance effective for most
of the population only at speeds below 35 MPH.

Obviously, injury could be avoided at much higher speeds if a 25 ms or 15 ms deployment time and the idealized restraint performance specified earlier (see Figure 8) could be achieved. But even then, a 50 MPH barrier impact for a sub-compact is not as severe as a collision with a full size car which is also traveling at that velocity.

Looking at that case—a sub-compact car impacting a full size car—the effect of the unequal masses on the distances traveled by the occupant compartment of the sub-compact car and its occupants, as a function of the velocity with which each vehicle enters the impacts, becomes clear. Figure 10 displays the distance traveled by the compartment of a sub-compact car in frontal impact with the front and oblique structure of a full size car with the foreshortening characteristic of Figures 6a & b. At a traveling speed of 60 fps, the sub-compact car occupant, even with a restraint having a 25 ms deployment time and ideal characteristics, would still require an interior stroke of 18” if the 4000 lb. car impacts with its front, but only 7” if it impacts obliquely. Obviously, higher compatible velocities are possible in the oblique mode, which, as pointed out earlier, is the predominant impact mode.

In order to determine how much cost can be added to each vehicle to reduce the casualties in the more severe accidents, i.e., those over 35 MPH BEV, it is necessary to calculate the societal savings associated with implementing a current effective restraint system without any structural modification to existing conventional cars. A comparison of these reductions with the original costs is illustrated in Figure 11. The total savings of 7 billion dollars divided by an annual production of 10 million cars provides a benefit/cost ratio of 4:1, even if the restraints cost $175.

It should be noted that these reductions in the societal costs of injuries and deaths below 35 MPH BEV result from restraints alone; this is due to the fact that there is very little structural intrusion below 35 MPH, at least in frontal collisions.

Now the remaining $15 billion in societal costs are, in turn, the benefits which can be achieved by reducing casualties even more through further improvements in structure and restraints.

![Figure 10. Deceleration distances of a 2000 lb car in frontal impact with a frontal or oblique 4000 lb car](image)

![Figure 11. Original and remaining 1971 societal costs of 2.13 million casualties assuming the installation of current passive restraints](image)
Figure 12 illustrates how these societal costs may be related to the allowable investment in dollars per car as a function of the resulting percentage reductions of fatalities and injuries. It shows clearly the value of improving frontal accident protection above 35 MPH BEV. On the other hand, note that reducing fatalities and injuries by an additional 75% in frontal collisions above 35 MPH (corresponding roughly to 50 MPH BEV protection) is, in a benefit/cost sense, only worth about $120 per car.

Obviously, the funds must be split between that required for improving restraint performance and those required for modifications that 1) maximize the deceleration distance of the car and 2) insure that the occupant’s interior stroking distance is not intruded upon at design impact velocities (see Figures 9 and 10). In this regard, however, it should be noted that in order to further reduce casualties in the most severe few percent of accidents, the relationship between structure and restraint becomes more critical, and progress in one must be coupled to the other by more than a specification and independent component development.

The present analysis has thus far dealt with some of the problems of structure and the relationship between the occupant/restraint and that structure in real world accidents. The results clearly indicate the design requirements for a high performance deployable restraint.

Those requirements in restraint terminology from the point of view of the toughest problem, protecting the occupant in the sub-compact car, are the subject of the following discussion.

Figure 13 shows the effects of varying the deployment time of the restraint system on the interior stroke required to decelerate the occupant within the injury criteria in a frontal barrier collision. In a sub-compact car of the Pinto-Vega class, there is about 15” of interior stroke available for the 50th percentile male and about 12” for the 95th percentile male. Front passenger energy-absorbing air bags currently exhibit deployment times of 35-45 ms, which are acceptable at 30 MPH with MVSS 208 test procedures using the 50th percentile dummy. The graph shows that
deployment time will have to be reduced to below 23 ms for the system to be feasible at 50 MPH. The question arises, then: can the deployment time be reduced to these levels using large volume bags without introducing the inherent problems of noise and out-of-position performance normally associated with large and fast air bag systems?

The effects of varying the occupant deceleration onset rate are shown in Figure 14. It is assumed that onset rates of the order of 1500-2000 g/sec are tolerable. The onset rate is determined by, among other things, the size of the bag and the inflation technique used. In particular, handling the out-of-position passenger within the onset rate limits restricts the choice of inflator and bag. Large volume restraints must use something like aspiration and/or two-level inflation if the bag is to fill fast enough to meet the deployment time requirements, yet limit the onset rate for an out-of-position occupant.

The effect of maximum deceleration levels on interior stroke is shown in Figure 15. Large volume bags must supply enough gas soon enough to handle the deployment time but slow enough to produce the appropriate onset rate. The resulting design must be a bag hard enough to provide forces decelerating the occupant at maximum tolerable g's.

The degree to which each of these objectives is accomplished, relative to the points on the curves labeled “nominal,” determines the efficiency of the system. When applying these criteria to a design trade-off of alternate restraints, there appear to be substantial advantages in using relatively small, non-energy absorbing bags mounted on mechanical energy absorbers. This is not to say that improvements in energy absorbing bags will not achieve the necessary performance. On the contrary, improvements to “conventional” passenger air bag systems are anticipated that will result in their being adequate to handle full size car occupants at or near 50 MPH. However, because of the promise involved in a mechanical stroking system, it seemed natural to try it as a driver restraint where the energy absorber would be the steering column. Thus, an opportunity was presented to evaluate this approach and determine its performance for a full size car. This was seen as a first step toward achieving the efficiency required in a sub-compact car, where doubts exist about the capabilities of an energy absorbing bag approach.

To summarize: if casualties are to be reduced, a restraint must work in conjunction with the deceleration distance for the accident impact mode of the car. Obviously, the smaller the car, the more nearly ideal the restraint performance must be, i.e., the system must have faster deployment time,
greater efficiency, and nearly ideal load distribution. The restraint problem is less difficult than might be expected because 1) statistics seem to indicate that most impacts are oblique where the deceleration distance is longer, and 2) most cars are full size.

There are, then, currently two basic types of deployable restraint systems being pursued. The first is the energy-absorbing air cushion restraint system which has been extensively tested by the auto industry and various suppliers as well as government contractors. The other, shown in Figure 16, can be categorized as using a non-energy absorbing or elastic bag system intended to reduce casualties to 50 MPH and is the focus of the remainder of this paper.

A driver system based on the "elastic bag" approach has been developed and is undergoing tests at 50 MPH at Minicars, Inc., and an occupant system based on this approach is being investigated at Calspan. Energy absorption of these systems is supplied by the structure supporting the bag. In the case of the driver's installation, this function is designed into the steering column, which then exhibits the necessary force/deflection characteristics. In the passenger positions, either an extended dash panel in the front, or a suitably designed credenza in the rear, supplies the desired energy absorption. The essential functions of the bag in this system are 1) to close the gap ("free-flight distance") between the occupant and the energy absorption device, and 2) to provide adequate load distribution.

In contrast to energy-absorbing bags as shown in Figure 17, it is of smaller volume (1.5 to 3 cu. ft.) and operates at higher internal pressures, typically 10 to 25 psig when fully "pumped up."

There are certain advantages and disadvantages to this system. Some of the advantages are 1) the smaller volume makes possible shorter deployment times, 2) the gas volume and the associated compartment overpressures upon deployment are lower, and 3) problems associated with inadvertent deployment (such as visibility) are lessened. Rebound, generally inherent in elastic systems, is not as severe as with the larger bags. This is due in large measure to the fact that penetration of the occupant into the bag is intended to be minimal (because of high working pressures) and to the complex interaction between the (elastic) bag and the (plastic) energy absorbing support structure. Some of the disadvantages are 1) in the passenger position, free space must be encroached upon to bring the
dash surfaces closer to the occupant, and 2) driver restraint systems based on this approach will be somewhat more "direction sensitive" than large bag systems.

In the elastic bag type of system, the bag acts also as the load distributor over the body of the occupant. When properly constructed, these smaller bags use the fabric orientation and the basic geometry of the design to allow for distension ("puckering") to achieve contact area on the thorax and to restrain the face and head with a minimum of flexion, as shown in Figure 18 (taken from an actual test run).

Another problem encountered with this system arises because of the high internal working pressures, the fabric and seams of the bag being liable to fail. Although stronger materials can to a large degree prevent such failure, such materials are heavy and increase deployment momentum disadvantageously.

The mounting of the bag to the backup structure must be carefully controlled so that high stress concentrations due to folds or kinks do not occur. Seamless weaving of the bag using high strength-to-weight materials can, in conjunction with appropriate sealers, resolve this problem; but on an experimental testing basis, as at present, the costs are prohibitive.

The lower torso can be restrained at tolerable acceleration levels in both types of systems by forces transmitted from the patella through the femur to the pelvis. This fact has led to the development of two basic types of knee restraints—fixed and stroking.

The fixed system has been discussed in a number of technical papers. The stroking system which we use in conjunction with the elastic bag type system is illustrated in Figure 19. It does basically the same job as the fixed system, but it allows the total acceleration and motion of the pelvis to compare with that of the chest. Kinematically, this prevents the rotation of the upper chest relative to the pelvis and, in turn, reduces the whipping of the head. Further, if the knee restraint is differentially coupled to the upper torso restraint, deceleration of the whole body in an upright posture is assured and stroking distance is minimized.

The driver system, shown in Figure 20, can use any of three basic types of inflators—stored gas, solid propellant, or a combination of both with multilevel augmentation. The latter is preferred for occupant systems because, in combination with bumper and inertial sensing, the hazards of deployment are reduced. Since it is hard to visualize a completely out-of-position driver, such an inflator has not been employed in our experimental driver restraint work to date. Instead, we use stored gas, released by mechanically rupturing a diaphragm.
There are various methods of inducing the gas into the inflatable. The simplest, and the one we use experimentally on the driver system, is to introduce the gas through a diffuser directly into the bag and fill it through a peripheral orifice (see Figure 20). In order to reduce inflation time, two 2" valved aspirating ports are used to augment the initial gas flow. This system deploys against the out-of-position driver with a maximum torso acceleration of 25 g and an onset rate of 2000 g/sec. In the non-deployment mode at 15 MPH, the maximum chest deceleration is approximately 20 g’s with a 1000 g/sec onset rate.

For an occupant system, an aspirating manifold might be desirable as a substitute for or in conjunction with a two-level gas generator and sensor system in order to handle the out-of-position problem.

Figures 18, 21, and 22 illustrate the deceleration distances achieved with the experimental driver restraint and various size drivers in the full size car. These and all other tests to date indicate that the system is operating at about 80% efficiency and is experimentally adequate for the full size car.

It is noted that the bag volume (the spacing between reaction plate and occupant chest) has been substantially reduced from its initial volume at the end of the stroke. Since the acceleration levels associated with these tests are only 30 to 40 g’s and all other injury criteria are well within the occupant’s tolerance range, greater decelerating forces with less column and internal bag stroke are required in order to meet the higher efficiency requirements of the sub-compact car. The factors which must be modified are the size of the bag, its ability to sustain the pressure, and the filling rate used. Unfortunately, the energy and momentum associated with these factors tend to be injury-producing.
to the out-of-position driver in low speed accidents.

The solution to this problem should enable the reduction of casualties to drivers in cars which have had reasonable structural modifications.

At present, as indicated in Figure 23, frontal 50 MPH BEV performance with an advanced deployable restraint for drivers of 4000 lb. cars has been achieved with about 80% restraint efficiency and within an increased cost over conventional deployable restraints estimated at about $20 per car. It is estimated that the same system could be effective in a sub-compact car to about 40 MPH in a frontal barrier crash and to 50 MPH in an oblique barrier crash. Using known techniques, it is predicted that acceptable 50 MPH frontal and oblique barrier performance will be realized for all cars. 100 MPH sub-compact to full size car oblique impacts without injury are also predicted.
Questions & Answers

E. H. LEE, STANFORD UNIVERSITY:
You mentioned the advantage which was gained from the fact that one has oblique impact. Isn't this bringing complications because of the asymmetry of the deceleration? Isn't it harder to design restraint systems when there's going to be a lateral component of acceleration also?

Yes, of course, and that's the real world problem. And that's the problem we ought to address.

Does one really have as big a gain because of the obliqueness?

Yes, the gain is a result of the difference in the structural deformation properties of the vehicle in frontal and oblique impacts. We get much longer stroke from the car as a result of oblique impacts and, if this data holds, then the requirements on the restraint are reduced because the deceleration distance of the car is increased.
ABSTRACT

A substantial number of research projects have involved testing of inflatable restraints, lap/shoulder belt restraints, and unrestrained occupants. The purpose of this presentation is to summarize these test projects and to compare the occupant injury potential data generated from the various tests.

Individual projects covered in this presentation include:

- Experimental Safety Vehicle interior and restraint systems tests, including those conducted by AMF, Fairchild Industries, Dynamic Science, and CALSPAN.
- Sled and full-scale vehicle crash tests involving subcompact passenger cars conducted by Southwest Research Institute.
- Sled and crash tests conducted by Wayne State University.
- Live occupant full-scale crash tests conducted by Eaton Corporation.
- Full-scale crash tests conducted by Agbabian Associates involving belted, IORS-restrained and unrestrained occupants.

Data generated from the Agbabian Associates’ subcompact project is presented in the form of a repeatability investigation. Where essentially identical tests have been conducted, the spread of measured data and of computed indices is shown.

Data comparisons include graphic reproduction of filtered time histories, and comparison charts showing the Head Injury Criteria and Head Severity Index values for various restraint system configurations.

INTRODUCTION

The National Highway Traffic Safety Administration, through its independent research contractors, is currently active in testing and evaluation of vehicle interiors and occupant restraint systems relative to the effectiveness of candidate systems in reducing occupant injury during vehicle collisions. The primary purpose of this paper is the presentation of results of some of this research, discussion of indicated trends and system performance potential, and evaluation of current state-of-the-art in testing and development of such systems.

Material presented herein is not totally comprehensive in illustrating NHTSA’s recent and on-going research in vehicle interiors and restraint systems. As with any dynamic program, new information is continually being generated. It would be impossible to stop at any point in time and declare that a review
would, at that point, reflect latest developments. However, the data presented is considered to be representative of the scope of the research being conducted in this field.

Projects Covered in This Presentation

Four major NHTSA-sponsored research efforts are discussed in considerable detail. These include:

2. Wayne State University, *Airbag Restraints for Automobile Drivers*, FH-11-7607.

In addition to these in-depth project reviews, other projects are mentioned including the rear seat air bag system development project at CALSPAN and live volunteer air bag crash tests conducted by Eaton Manufacturing Company’s Safety Systems Division.

The bulk of the testing done under these projects has been impact testing, either on a laboratory sled or in full-scale vehicle collisions, in the general speed range of 30 MPH. The Experimental Safety Vehicle Test Project gives some insight into the potential of air bag restraint systems and modified vehicle interiors for occupant injury reduction in higher velocity collisions. Finally, the Eaton tests, using live driver and passenger, provide information on the actual effect of air bag systems on humans, as opposed to system performance information derived from tests using anthropometric dummies.

Data Presented and Discussed

Data and films presented in this paper and the accompanying verbal presentation include samples of the following occupant/restraint configuration tests:

1. Unrestrained driver dummy
2. Driver dummy restrained by lap belt only
3. Driver dummy restrained by lap and shoulder belts
4. Driver dummy restrained by IORS*
5. Front seat passenger dummy restrained by IORS
6. Front seat passenger dummy restrained by lap/shoulder belts
7. Live human driver and passenger restrained by IORS and lap belts.

Vehicles covered in projects presented herein include standard full-size sedan, subcompact sedan, and experimental safety vehicles of the full-size family sedan category. Thus, a significant variance in structural response is explored in the range of projects along with the restraint system and interior configuration range and analysis of various occupant sizes.

**SUMMARY OF SYSTEM PERFORMANCE TRENDS**

Taking an overview of the results of these various projects to date, certain major trends become evident. From these, some preliminary conclusions may be drawn with the understanding that the conclusions are based on a relatively small data sample, and that conclusions given here may be subject to refinement or alteration as more information becomes available through further research.

Among major trends observed in data presented herein, those which seem most consistent and most relevant to current NHTSA objectives are as follows:

1. Prototype front seat IORS evaluated under NHTSA contracts appear capable of meeting requirements of the currently defined FMVSS 208 for both subcompact and full-size sedans, at impact velocities of 30 MPH, and for a

*Inflatable Occupant Restraint Systems (IORS).*
range of occupant sizes from 5th percentile female through 95th percentile male, especially considering the improvement in system performance which would be derived from an extensive production development program prior to implementation of such systems into production automobiles.

2. Current production lap/shoulder belt systems appear capable of providing occupant survival in barrier impacts at 30 MPH for adult occupants, considering the currently proposed relief for tests of such systems where head injury criteria are not considered in evaluating system performance unless contact occurs between the occupant’s head and some portion of the vehicle interior other than the restraint system.

3. Consistent attainment of 50 MPH barrier impact survival by vehicle occupants will be very difficult, even with vehicles of highly advanced structural configuration using the most advanced of currently available IORS, and may be impossible with vehicle structures of the type in current production due to loss of passenger compartment volume during impact crush.

These trends and conclusions reflect data presented herein. Other data, gathered from projects not included here, are generally supportive of these conclusions. However, it should be recognized that there remains in this field of safety research a considerable amount of variation in data gathered by different testing agencies, under slightly different test conditions, and for varied types of vehicles and occupant restraint systems. Some of this data variance is a natural result of studying different types of system configurations and thereby producing slightly different conclusions. Additional variation results from testing techniques and methodology, and from variances in test equipment, including both instrumentation and anthropometric dummies used by testing agencies and contractors.

TESTING PROCEDURES

While establishment of system performance potential and resulting potential for reduction of occupant injury in the real-world highway environment is the primary useful output of NHTSA’s research effort, there are significant secondary outputs. In the case of interior and restraint system research, a major secondary output of contracted research is information regarding the technical difficulties of conducting such tests and the attendant variations in data resulting from the technical complication of necessary testing procedures. Recent litigation and research community discussion has centered around the repeatability, or lack thereof, of currently available instrumentation systems, particularly the anthropometric dummies which are used as system transducers in restraint system evaluation.

A portion of the data presented herein (Figures 1 through 4, Appendix A) reflects the results of two sets of three repeated tests, under essentially identical conditions, presented in a manner which permits easy analysis of data variance over the three-test sample. These data are not displayed as a final answer to the question of testing methodology, potential compliance verification, test variance, or other aspects of such testing operations. Rather, they are shown as an indication of the level of repeatability achieved by one testing organization, using state-of-the-art instrumentation and procedures developed through a very large number of vehicle crash tests and attempting to control as closely as possible the test variables known to affect occupant injury potential. It is considered that a rather high level of repeatability is demonstrated by the data. It may be that careful application of existing state-of-the-art measurement systems (including dummies) would provide the accuracy and repeatability required to support compliance verification of restraint systems.

Clearly, much more work must be done in studying test parameter effects on restraint system performance evaluation data. At the
present time, it is possible for different testing organizations to achieve measurably different data while conducting what are apparently identical tests. Seemingly minor differences in anthropometric dummy construction, dummy position within the vehicle prior to impact, placement and mounting of vehicle structure acceleration transducers, types of signal conditioning equipment employed between transducers and recorders, and types of final data processing operations applied to test results can all materially affect the final display of a set of data from restraint system impact tests. Added to these test system variances are known variations in structural response of two apparently identical production automobiles under identical collision environments. For sled tests one must consider variance in the deceleration profile of the sled system from test to test, not to mention the basic deceleration profile of the sled compared to the actual vehicle being modeled.

Overlaying the problems of establishing identical test conditions within a given laboratory and between pairs of laboratories are problems of simply acquiring all desired test data from a given test. A full-scale vehicle collision is a very violent test environment. Failures of instrumentation system components have, in the past, been frequent. As testing experience is gained, more laboratories are developing the degree of expertise necessary to reliably acquire the desired data under the difficult and peculiar conditions of collision testing. And, as data acquisition system reliability and test methodology refinement reach higher levels, much more information can be obtained relative to absolute system performance. Further, data acquired at testing agencies throughout the world can be directly compared, greatly expanding the overall knowledge base for restraint systems and vehicle interiors.

SAMPLE PROJECT RESULTS

Sample data have been selected from four representative NHTSA contract projects. These data are displayed and discussed in this section. Where appropriate, comparisons are made between data gathered during the respective projects. Since FMVSS 208 compliance feasibility is a topic of critical importance at this time, data will be related to the specific injury criteria of this standard where appropriate.

Southwest Research Institute Project

Table 1 displays data taken from five tests conducted by Southwest Research Institute related to evaluation of driver IORS in a subcompact vehicle. Rocket Research Corporation and Olin Corporation systems were tested, and results for both types of systems are shown.

Four sled tests and one barrier crash test (Test No. AB-2) produced the data shown in Table 1. Of these, three tests involved Rocket Research systems and two were tests of Olin systems. The Severity Index (SI) and Head Injury Criteria (HIC) values shown on the chart may be slightly in error due to computational difficulties experienced during the project. However, these values are representative of the general system performance potential.

A major point of interest in the SWRI data presented are the conformance, in the majority of the tests, with FMVSS 208 criteria. In particular, the barrier impact Test No. AB-2 shows peak acceleration level, SI and HIC, all satisfying the specific injury criteria values of the currently proposed standard.

A rather broad variance in impact velocity makes analysis of test data repeatability for

<table>
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<tr>
<td>SED    SED    SED    SED    SED</td>
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<td><strong>RESTRANIT SYSTEM</strong></td>
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<td><strong>IMPACT TYPE</strong></td>
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<tr>
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<td>58*    76*    66*    55    58</td>
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<tr>
<td><strong>CHEST ACCELERATION PEAK</strong></td>
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<td>--    --    803    694    1092</td>
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<td><strong>HEAD INJURY CRITERIA</strong></td>
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<td>--    --    617    386    605</td>
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* MANUALLY REDUCED DATA

Table 1.
these tests difficult. As shown on the table, there is a large variance in peak acceleration values for driver chest data taken under similar conditions with similar IORS. Specific reasons for this variation in data are not known, but several steps have been taken at SWRI to improve instrumentation system reliability and data processing system accuracy.

In addition to tests using 50th percentile male occupants, SWRI performed tests using both 5th percentile female, and 95th percentile male anthropometric dummies. Data from these tests are summarized in Table 2. As with the data displayed in Table 1, there is some question regarding the accuracy of some of the values shown. However, based on the estimated values shown and considering the peak chest acceleration levels obtained during the tests, it appears that the systems developed and tested by SWRI under this project could meet the requirements of FMVSS 208, particularly after additional development and refinement for a particular vehicle.

Conclusions reached by SWRI regarding the final project results include high probability of survival and satisfaction of FMVSS 208 for 50th percentile male drivers experiencing 30 MPH perpendicular barrier collision. For 95th percentile drivers subjected to impacts into a rigid barrier at 30 MPH with the vehicle impacting the barrier at an angle 30 deg from perpendicular attitude, production steering columns probably will require redesign to achieve the required collapse performance under nonaxial loading.

System performance evaluation by SWRI indicates that injury prevention can be achieved with sensor closing, or system triggering, in the range of 5 msec to 25 msec after impact. Occupant loading also was insensitive to steering column angle, from the horizontal, through the range of 10 to 22.5 deg.

SWRI’s test project did indicate an area for extreme caution in relating accelerator sled testing to actual vehicle collision tests. In performing the full-scale barrier crash test, SWRI found that the vehicle pitched, in a tail-up attitude, during front end crush. This caused occupants to submerge or slide under the knee impact surfaces and ride underneath the inflated air bag. Pitching of the interior compartment had not been simulated during SWRI’s sled test development program. Thus, the knee impact surfaces refined during sled testing proved relatively ineffective in an actual vehicle collision with a rigid barrier.

Recognizing that their project covered a large number of occupant and restraint system variations, SWRI recommended that additional repeated tests be conducted for each system configuration. This was considered necessary in order to prove repeatability of system performance and in order to increase credibility for test results and conclusions.

Wayne State University Project

In the full-size vehicle driver IORS development project conducted at Wayne State University, data indicate consistent conformance with FMVSS 208 injury criteria. As shown in Table 3, Severity Index and Head Injury Criteria values are very low. Peak chest acceleration also consistently falls well below the permissible 60 g peak level, actually staying below 50 g for all tests presented here. One test produced head acceleration which was above the desired 80 g peak level. However, in considering average levels of performance of the IORS systems in this project, it appears very likely that full-size sedans can be fitted with driver IORS which

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<td>Head Injury Criteria</td>
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<td>259</td>
<td>808</td>
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Vehicle: 1971 Pinto
* Manually reduced data

Table 2.
Table 3.

will satisfy FMVSS 208 consistently and with a rather large tolerance margin.

In addition to IORS data Table 3 includes results of sled tests with dummies restrained by lap belt only, lap and shoulder belts, and also one dummy in an unrestrained attitude. It can be seen that, in general, head severity index values and head injury criteria are higher for these configurations than for the better IORS.

Special consideration must be given to the unrestrained driver data, since the impact velocity is significantly lower for this test than for others shown on the table. Many tests conducted over the past several years have proven that impact velocity is a major factor affecting occupant loading. Thus, the unrestrained occupant data shown here probably would be much higher were this a 30-MPH collision like the others shown on the table rather than being an impact at 25 MPH. Energy is a function of velocity squared. Therefore, the energy differential between 30 MPH and 25 MPH, other factors being equivalent, would be approximately 40 percent, a very significant margin.

In addition, some consideration must be given to the small contact area through which deceleration loads are applied to an unrestrained occupant. The highly concentrated loads on face, head, and chest very likely would cause serious injury or death for such an occupant in a 30-MPH barrier collision, even in cases where the overall occupant acceleration rate could be marginally survivable.

By comparison with unrestrained or belted occupants, drivers and passengers restrained by IORS enjoy the benefits of more uniformly distributed loads. It should be possible for occupants to receive quite high maximum acceleration loading through IORS without incurring skeletal fracture or body penetration. This may provide an even greater margin of survival for occupants restrained by IORS, although such a conclusion cannot be reached with confidence until further research in the field of biomechanics has been accomplished relating distributed loads to internal injuries for humans.

Aglabian Associates Subcompact IORS Project

A series of 12 Ford Pinto subcompact sedans were impacted against a rigid barrier at 30 and 35 MPH by Aglabian Associates. The first two of these vehicles were impacted at speeds of 30 and 35 MPH, respectively, with driver and front passenger dummies restrained by production lap and shoulder
belt restraint systems. The remaining 10 vehicles were fitted with IORS. Nine of these were crashed at 30 MPH, and one was subjected to a 35-MPH impact. Five of the latter group of 10 vehicles were fitted with Rocket Research Corporation IORS, the remaining five fitted with Olin Corporation systems.

The systems tested in the AA project were quite different in basic concept and configuration. Rocket research systems used a separate, solid propellant gas generator system for the driver steering wheel bag. Passenger protection was provided by a large bag inflated by the still-new aspirator inflator techniques. In the aspirator system, a large proportion of the bag inflation gas is made up of air taken from within the passenger compartment. The system has potential for the reduction of pressure increase and noise level during and following bag inflation.

The Olin system tested by AA features a single gas generator which feeds both steering wheel and passenger bags. Inflation gas for the driver steering wheel bag is ducted from the passenger side-mounted gas generator and would, in a production installation, be conducted up through a specially designed and sealed steering column jacket into the hub area of the steering wheel. Advantages of such a system include probable reduction in production cost due to savings in gas generator fabrication, reduction in required circuitry, and potential increase in overall system reliability due to reduction in number of critical components.

Tables 4 and 5 show driver and passenger data acquired under the AA project. While the bulk of the Southwest Research Institute and Wayne State University data was acquired from sled testing, all of the illustrated Agbadian Associates data were generated in full-scale barrier collision tests.

The AA acceleration data indicate consistent satisfaction of FMVSS 208 injury criteria with the possible exception of marginal peak chest accelerations. With further development of the Rocket Research and Olin IORS examined in this project, it is likely that this marginal chest loading could be brought well within the desired limits for FMVSS 208 conformance.

The peak femur loads show reasonably good consistency where data were acquired. Femur loads for drivers are generally higher than for the passengers, and approximately

<table>
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<td>1200</td>
<td>1150</td>
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VEHICLE: 1972 PINTO
*Vertical and Longitudinal Only

Table 5.

half the driver measurements exceed the FMVSS 208 standard while all passenger measurements are below the level in the standard. It appears to be quite feasible to reduce femur loads to satisfy the present standard by further study of the knee restraint materials, configuration and location. The lap and shoulder belt measurements are presented for reference but are not directly comparable to the other test data since no special knee restraint material was installed in the vehicle for this test.

It should be noted that the AA subcompact test project explored a limited number of occupant/restraint system configurations, and that all impacts were perpendicular collisions with a flat, rigid barrier at a speed of 30 MPH. Occupant size was 50th percentile male. In general, all test conditions were in the nominal center of the basic design range of the systems.

For a restraint system to be considered acceptable for production installation, it must satisfy reasonable injury criteria for a much greater range of variables than included in the AA project. For example, occupant size must be varied on either side of the 50th percentile male values. Also, occupant precrash position is important. If, for example, a driver is seated such that he is leaning against the left door inner panel, rather than sitting directly behind the center of the steering wheel, he may tend to slide off the side of a steering wheel air bag instead of riding down against the bag during the vehicle crush period. Or, if the passenger is leaning forward or to one side prior to impact, his ultimate injury potential could be significantly affected in terms of bag collapse pattern and contact with other portions of the vehicle interior.

Possible variations encountered in the real-world highway environment must be considered, and tests of these situations must be run before a final production system can be released. Some of these possible configuration differences have been examined in a preliminary sense in NHTSA projects. Others will be investigated in depth in later projects. Yet, the data gathered in projects included in this paper, though limited, present a very promising picture for IORS as an effective passive restraint system for occupant injury prevention in 30-MPH barrier collisions or highway collisions of similar severity.
Dynamic Science ESV Test Project

Data presented in Tables 6 through 8 were recorded during flat barrier impact testing of Experimental Safety Vehicles at Dynamic Science. Because of the extreme impact velocities, data from these tests should not be considered as reflecting upon the feasibility of conformance with FMVSS 208. Rather, these data indicate IORS potential for occupant protection in extraordinarily severe crashes.

Data shown for the Fairchild Industries ESV reflect results obtained with unrestrained occupants seated within a highly advanced interior compartment. The extensive use of energy absorbing padding and smoothly contoured interior components, while beneficial in low-speed collisions, clearly was not adequate for occupant survival in a 50-MPH rigid barrier collision, nor was it intended to be.

The AMF test vehicle did function as designed in that all IORS deployed properly during the 50-MPH collision. Data shown here indicate that the environment to which the occupants were subjected did not meet the generally accepted survival criteria. However, it is significant that the AMF vehicle driver dummy environment was not far from satisfying FMVSS 208 injury criteria despite a crash energy nearly three times greater than that related to the 30-MPH impact velocity currently specified for this standard.

REPEATABILITY OF IORS COLLISION TESTING

Much has been written and discussed regarding the repeatability, or lack thereof, of testing to the general procedures of currently proposed FMVSS 208. Within the overall NHTSA research effort in interior and restraint testing, considerable attention is given to establishment of probable tolerances and bounds for test repeatability and data consistency.

As an example, the full-scale barrier crash test project at Agiban Associates has included repeated tests under essentially identical conditions, with similar restraint systems. Figures 1 through 8 show sample data gathered from three tests with Olin IORS and three with Rocket Research IORS. These tests all were conducted using the same pair of 50th percentile Sierra Engineering adult
male anthropometric dummies. All tests were flat barrier impacts at 30-MPH nominal impact velocity.

In Figure 1, it may be seen that Tests 3 and 5 (03 and 05) using essentially identical Olin IORS in Ford Pinto subcompact sedans produced remarkably consistent head acceleration resultant profiles. Head injury criteria values also are very similar. Chest acceleration resultant data, Figure 2, show somewhat greater variance, but the calculated Severity Index values for chest data still show consistency for both Olin and Rocket Research IORS.

Representative femur load time histories are shown in Figures 5 through 8. As these figures indicate, there are instances where the data contain anomalies which could definitely influence the determination of the peak value. However, in most instances it is felt that the peaks shown do represent the load levels on the femurs during the test environment. Generally speaking, the character of the femur time history is a single compressive pulse. However, as can be seen, some channels contain a second peak of significant value. In some cases (e.g., trace 10PFLR of Figure 7) the double peak appearing in the data is not considered to be true data. On the other hand, the data shown in Channel 01PFLR of Figure 7 is considered to be accurate and as is shown there, the maximum peak is the second peak. It is to be noted that this data channel resulted from a lap and shoulder belt test rather than from a test with knee restraint materials installed in the vehicle.

It was the experience of AA during the test project that the acquisition of the femur load data presented considerably more problems than did, for instance, the acquisition of acceleration data. It is believed that these difficulties can be overcome by modification of the manner in which the femur loads are sensed and transduced, and that improvements in signal conditioning of these data, though a secondary source of problems, should also be investigated.

From limited data gathered during the Agbabian Associates project, it is premature to state positively what variance might be expected for FMVSS 208 compliance testing. However, the problem of test repeatability under these conditions does not appear to be overwhelming or insoluble. Studies should be undertaken to identify and separate the causes of such variance in test data acquired by testing contractors and agencies. Of particular importance is definition of the amount of variance due to (1) vehicular differences, (2) minor errors in initial placement of the anthropometric dummies within the passenger compartment, (3) errors in the measurement systems, and (4) the response of the IORS and the dummies themselves.

At the present time, the interior and restraint system research community is reaching agreement on best types of transducers, signal conditioning equipment and recording systems to use for collision testing. Along with this establishment of recommendations for electronic equipment, great emphasis is being aimed toward improvement of the anthropometric dummy both as a human analog and as a repeatable test transducer. Based on results obtained in the Agbabian Associates project and similar current research efforts, it is anticipated that test repeatability will be defined within narrow bounds in the near future.

OVERALL NHTSA PROJECTS REVIEW

As noted at the beginning of this paper, projects discussed in detail herein are not illustrative of the total NHTSA effort in interior and restraint system research. A recent project at CALSPAN resulted in development of a prototype rear seat IORS which is highly effective in protecting three rear seat occupants during a 50-MPH barrier collision. This, coupled with the already discussed development project aimed at producing front seat IORS which consistently meet the injury criteria of FMVSS 208, could well indicate that the day is not far off when a total complement of five or six passengers can be protected by fully passive restraints in collisions of 40-MPH barrier impact severity.
Live volunteer testing, conducted by Eaton Corporation’s Safety Systems Division, verifies the results of anthropometric dummy testing. In two barrier collisions at approximately 26 MPH, a male driver and female right front seat passenger not only survived without injury but were so comfortable when restrained by IORS that they indicated complete willingness to undergo this severe collision any number of times. Such testimony strongly reinforces data gathered during dummy tests and promises that IORS at today’s level of development are potentially the most significant single improvement in vehicle safety and occupant injury reduction yet achieved by researchers in this field of technology.

Data generated from projects such as those discussed in this paper provide NHTSA with a broad overview of the potential for injury reduction achievable through implementation of IORS into passenger cars. The promise of IORS, or other forms of passive restraints, is clear. However, further research is required to fill in the data base formed by these test projects and others of the recent past to support implementation of IORS in production vehicles.

CONCLUSIONS

The data acquired to this time, in the NHTSA IORS Research Project, support the following conclusions:

1. It is feasible using state-of-the-art IORS systems in production vehicles to provide occupant protection in frontal collisions in conformance with FMVSS 208. It is also feasible to develop IORS systems that in conjunction with vehicle interiors and structures will protect occupants in frontal collisions at velocities approaching 50 MPH.

2. Selection and utilization of measurement systems (including anthropometric dummies) need to be more standardized to facilitate direct comparison of data acquired in projects conducted by various testing organizations.

3. Data that have been acquired in sets of comparable tests indicate that the careful use of state-of-the-art measurement systems during IORS testing will yield data with sufficient accuracy and repeatability characteristics for use in determining conformance with FMVSS 208.

4. The positive results obtained in the testing of IORS systems in frontal collisions indicate that further evaluation and development of systems should be pursued to determine the system effectiveness in other accident conditions.

Future Research Requirements

As a result of the above conclusions and through review of the NHTSA contracted efforts, it is possible to identify specific areas for future research. Among the most prominently visible of these research requirements are:

1. Intensive study of test repeatability using latest developed instrumentation systems, anthropometric devices, and current testing methodology

2. Development of standardized data acquisition and data processing systems and methodology to improve consistency and comparability of data gathered by various independent and industry testing organizations

3. Continued research and development in refining anthropometric test devices to improve human simulation and to reduce variance in repeated testing

4. Close surveillance of, and continued liaison between, contractors engaged in NHTSA contract efforts involving testing of interiors and restraint systems to ensure that knowledge gained by one organization is efficiently passed on to others so that a broad base of qualified, effective testing agencies will be established across the United States
5. Continued testing and development of latest developments in IORS and other forms of passive restraints, both on component and total system levels, to maintain currency in knowledge of potential of such systems for reducing occupant injury under severe crash conditions

6. Establishment of definitive measures for comparing results of mathematical modeling, sled testing and full-scale collision testing to permit comparison and quantitative evaluation of developments wrought through all three general phases of interior and passive restraint research

7. Diversification of testing goals from basic design evaluation to study of possible occupant/restraint system configuration variables including occupant size effects, results obtained for various occupant out-of-position attitudes, performance implications of impacts at off-design speed and collision trajectory, and effectiveness of passive restraint systems in nonfrontal impacts.

It is difficult, at this point in time, to establish priorities for this list of research requirements. All of the categories indicated here demand attention before the ultimate potential of IORS, or any other interior or restraint improvement, can be implemented into production automobiles. While NHTSA is not in the business of developing production systems, it seems essential that those developing the standards be aware of the promise and limitations of current technology in this vital area. Before meaningful standards and legislation can be formulated regarding performance criteria of passive restraints, it is necessary to recognize the feasibility of such criteria considering obvious production vehicle limitations on cost, complexity, service, maintenance, and reliability.

The projects represented herein clearly indicate the very significant strides which have been made in the past two years in developing effective passive restraints. They also indicate voids in technical information which must be filled in the very near future. Data produced in these projects, together with that produced by other organizations in related research efforts, are being assembled by NHTSA into a cohesive, definitive picture of IORS effectiveness. Onto this base of knowledge will be built an increasingly illustrative and credible structure of accurate data on which to base future decisions governing American automobiles and their occupants.
Appendix A

TEST DATA—AGBABIAN ASSOCIATES

This appendix presents representative time histories of head and chest acceleration and femur loads measured during the IORS project conducted at AA. Identification of each time history is contained in a coded identifier for each channel presented. The information required to interpret the code is presented below:

**IDENTIFIER COLUMN**— 1 2 3 4 5 6

**Typical Number** — 0 3 D H A R

- **Columns 1 and 2** Test Number, e.g., 03 is Test Number 3
- **Column 3** Occupant identification, e.g., P—Passenger, D—Driver
- **Column 4** Measurement location on occupant, e.g., H—Head, C—Chest, F—Femur
- **Column 5** Parameter designation, e.g., A—Acceleration, L—Load
- **Column 6** Parameter descriptor to be used in conjunction with Column 5, e.g., AR—Acceleration Resultant, LL—Load Left, LR—Load Right

Typical number 03DHAR—Test Number 3, Driver, Head, Acceleration, Resultant
Figure 1. Driver head accelerations

Figure 2. Driver chest accelerations
Figure 3. Passenger head accelerations

Figure 4. Passenger chest accelerations
Figure 5. Driver femur loads right

Figure 6. Driver femur loads left
Figure 7. Passenger femur loads right

Figure 8. Passenger femur loads left
Testing and Evaluation
with Human Volunteers

Thomas H. Glenn
U.S. Department of Transportation
National Highway Traffic Safety Administration

ABSTRACT

The history of impact testing with human volunteers is largely limited to early work on the Daisy Decelerator at Holloman Air Force Base, the Horizontal Accelerator at NADC Philadelphia, ejection seat work at various DoD laboratories, and shipboard personnel protection studies at the David Taylor Model Basin. Until now NHTSA has been limited to human tests with air bags at Holloman and passive belt systems at NADC Philadelphia. Three new test facilities have announced that they are conducting or can conduct sled tests with human volunteer subjects—the HyGe sled at Wright Patterson Air Force Base, the HyGe sled at the Naval Aerospace Medical Research Laboratory and the Vehicle Crash Simulator at Southwest Research Institute.

The paper presents a history of dynamic testing with military and civilian volunteer subjects and the problems encountered in some of the previous programs. It covers use of the civilian volunteer subjects, design of experiments and test procedures to reduce the injury potential for volunteer human subjects, the recruiting and screening of volunteer subjects, subject motivation, required information and anthropometry.

Future programs with newly available human test facilities and an increase in the use of civilian volunteers are suggested.

INTRODUCTION

Impact testing with human volunteer subjects has been going on for years. However, there is very little technical or scientific data available in the biomechanics area to aid the designers of automotive restraint systems, although there is some information on human tolerances to impact (Refs. 1, 2, and 3).

The Research Institute's Biomechanics Division, which is a part of the Office of Vehicle Structures Research, has been engaged in two programs designed to evaluate the effectiveness of new restraint systems by using human volunteer subjects in simulated crash conditions. These programs have been in existence for three years as part of NHTSA's overall efforts to promote rulemaking or to assist in the development of systems or techniques which will reduce the horrible numbers of deaths and injuries occurring on the highways.

One of these projects is at Holloman Air Force Base in New Mexico where prototype and production model air bag systems provided by General Motors are under study. To date we have completed 63 dynamic sled tests with human volunteers impacting air bag restraint systems at speeds from 15 to 31 MPH with impacts as high as 22 G without a single injury. Under an Interagency Agreement with the Navy, NHTSA is also conducting an evaluation of advanced and passive belt restraint systems at NADC Philadelphia. The Phase I dummy test series has been completed, and we are now beginning the Phase II dynamic sled test runs with human volunteers on four belt restraint systems. As of this date, however, none of the human test runs have been completed.

The purpose of this paper is to provide a brief history of impact testing with human volunteers, to review some of the problems which have been encountered and to point out a possible avenue of future testing with civilian volunteers. The use of civilian volunteers may enable the biomechanics community to provide restraint system and
automotive designers with more meaningful data on man's kinematics and tolerance to injuries in the automotive crash environment.

THE HISTORY OF IMPACT TESTING WITH MILITARY VOLUNTEERS

Most of the participants at this Vehicle Safety Research Integration Symposium are familiar with test sleds, testing techniques and instrumentation, and with the anthropometric test dummies that have been in use for some years. Most of you are probably familiar with much of the information that has been published on the early sled test work with human volunteer subjects by Dr. John Paul Stapp in the late 1940's and early 1950's.

Thousands of human impact tests have been conducted with military volunteer subjects under various programs conducted by the Department of Defense. Human experiments with ejection seats, crew seats, pilot and aircrew restraint systems, parachute research, aircraft carrier landing shocks, and the protection of shipboard personnel to blast damage are but a few of the projects involved. Unfortunately, little of the information which has been generated in the considerable number of experiments that have been conducted is of much use to the field of automotive impact research because the overwhelming majority of the tests conducted at high G levels were in the vertical direction and were conducted for purely military purposes.

One of the major "hang-ups" in the past has been the lack of availability of sled test facilities that are truly "man-rated." Until very recently, when some human testing was done on the "Wham" sleds at Wayne State University with civilian volunteers (to be discussed later), there have been only two man-rated sled test facilities—both military—the "Daisy" Decelerator and "Big Bopper" sleds at Holloman Air Force Base in Alamogordo, New Mexico, and the Horizontal Accelerator at the Naval Air Engineering Center in Philadelphia, Pa.

A look at some "box scores" to date is rather interesting. Keep in mind that the Holloman sleds have been in operation for 19 years, and the NADC sled for 22 years.

When the early human runs in 1947-1954 by Dr. Stapp are added, we get a total of over 5,000 sled test runs with military human volunteer subjects spanning a period of 25 years. When thousands of runs in the vertical direction (conducted in the same time frame) are added, there is a truly impressive number of over 10,000 human tests. The important thing to remember is that no significant injuries have been recorded with hundreds of military human volunteer subjects undergoing tests under controlled conditions.

CIVILIAN VOLUNTEER SUBJECTS

The use of civilian volunteers for impact research or development programs has already been mentioned. Wayne State University has conducted a total of 221 sled runs with 19 human volunteer subjects. 152 of these runs and 17 of the subjects were involved in the head-neck study conducted by Dr. Chan Ewing. The remaining 70 runs, spanning 5 projects, have involved 2 subjects. One of the subjects has been Professor Larry Patrick; the other subject will have to be referred to as "et al." Results have been published (Refs. 4, 5, and 6), or will be published soon in the Final Report by Wayne State University under Army Quartermaster Contract DAAAG 17-67-C-0202.

Another example of civilian subjects undergoing controlled impact testing involves the barrier crash tests of air bag equipped Mercurys discussed by Jon McKibben in the preceding paper.

Table 1. Previous Military Human Test Runs

<table>
<thead>
<tr>
<th>Sled Test Facility</th>
<th>Human Runs</th>
<th>Total Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holloman—Daisy</td>
<td>2,200</td>
<td>6,670</td>
</tr>
<tr>
<td>Holloman—Bopper</td>
<td>2,438</td>
<td>5,060</td>
</tr>
<tr>
<td>WPAFB—HyGe (New)</td>
<td>35</td>
<td>100</td>
</tr>
<tr>
<td>NADC—H. A.</td>
<td>252</td>
<td>2,540</td>
</tr>
<tr>
<td>Totals</td>
<td>4,925</td>
<td>14,370</td>
</tr>
</tbody>
</table>
Other "tests" involving human participants have been conducted for a number of years during public demonstrations of various seat belts or lap-shoulder belts. The American Safety Equipment Corporation of Encino, California has used a portable "Little Bopper" sled since 1962. They estimate that they have conducted well over 100 human runs during that period, with the majority done at their exhibit during Transpo '72. The Commonwealth of Virginia has a portable demonstration unit to increase public usage of lap and shoulder belts, and other states may employ portable demonstration units to increase public awareness of the lifesaving benefits of belt restraint systems as the various states take steps to introduce mandatory restraint laws in their various legislative bodies. These "tests" are of little use to the automotive research world, except for their "P. R." value, because no attempts have been made to instrument the sled or the "volunteer" participants, and the runs were conducted at very low G levels.

Civilian volunteers have been used in DoD projects involving vertical accelerations. One major factor of interest to this symposium is the participation of civilian volunteers provided by two contractors for two Navy research projects concerned with the protection of shipboard personnel against blast effects from underwater or below-deck explosions. In one project, the contractor provided 23 volunteers to the David Taylor Model Basin (now the Naval Ship Research and Development Center), where a vertical HyGe facility is located. Twenty of these volunteers were part-time employees recruited from college campuses in the Washington, D.C. area, and three were full-time contractor employees assigned to work at NSRDC under an open-end, task-order type of services contract (Ref. 7). Three additional volunteers on this project were Navy Civil Service employees.

In the other project, the Navy issued an Interagency Agreement (Ref. 8) to the Protection and Survival Branch, Civil Aeromedical Research Institute of the Civil Aviation Agency (now the FAA) who conducted the experiments with students who were also recruited locally.

Let's take a look at the civilian subject box scores. Again, the important thing to remember is that there have been no recorded injuries in almost two thousand tests.

**PROBLEMS IN PREVIOUS PROGRAMS**

Given the large number of impact tests with human volunteers, why don't we have more usable data on man's kinematics, the mechanics of injury, and man's tolerances to injury in the crash environment? Problems exist which have reduced the amount of

<table>
<thead>
<tr>
<th>Group</th>
<th>Direction</th>
<th>Seated</th>
<th>Standing</th>
<th>Total Runs</th>
<th>No. of Subjects</th>
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<td>Allstate</td>
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<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Eaton</td>
<td>Horizontal</td>
<td>2</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Wayne State</td>
<td>Horizontal</td>
<td>252</td>
<td></td>
<td>252</td>
<td>19</td>
</tr>
<tr>
<td>American Safety Equip. Co.</td>
<td>Horizontal</td>
<td>100</td>
<td></td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>NSRDC</td>
<td>Vertical</td>
<td>381</td>
<td>670</td>
<td>1051</td>
<td>26</td>
</tr>
<tr>
<td>CAA</td>
<td>Vertical</td>
<td></td>
<td></td>
<td>500</td>
<td>13</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>1906</td>
<td>91</td>
</tr>
</tbody>
</table>
useful information generated in many of the previous programs:

1. The majority of the programs have been almost completely oriented toward the evaluation of hardware for military applications which are of little use to the automotive world.

2. In many of the previous programs, few or no attempts were made to provide the necessary instrumentation on the human subject to expand the literature available on man's kinematics or to determine the mechanics of injury or tolerance to injury. The human was merely placed in the loop on more or less of a "Go, No-go" basis. In some cases, since little or no instrumentation was available for use with human volunteers, each research group had to "reinvent the wheel" by adapting instrumentation developed for other purposes.

3. The volunteer subjects, both civilian and military personnel, were all male, relatively young, healthy, relatively "fit," and not truly representative of the wider ranges in the automotive driving public.

4. The problems of mounting instrumentation in or on living humans are extremely difficult. With dummies, you can just bolt something in a desired location. With primates or cadavers, instrumentation can be surgically implanted and fixed in position with sutures or wires, or screwed to bony elements. You can imagine the reactions of human volunteers. "You want to mount that transducer . . . where? . . . how?"

POSSIBILITIES OF INCREASED HUMAN TESTING

Today, I can see no unsurmountable obstacles in broadening the number of man-rated sled test facilities with civilian volunteer subjects and breaking the previous dependency on the military installations. Civilian

volunteer subjects are readily available. Students, for example, make excellent subjects because they can be highly motivated and because they are anxious to make additional money. Colleges and universities already carry extensive comprehensive and liability coverage for their students and for many athletic teams that are exposed to hazards beyond those involved in carefully controlled impact testing.

There is an increasing number of physicians and physiologists, both military and civilian, who have engaged in human testing and who can provide a vast amount of insight and guidance to the medical requirements. Medical guidelines are also available in Refs. 9, 10, and 11 as well as in the Test Protocols discussed in the following section.

Possible questions on legal or liability obligations can be successfully answered. There is a tremendous backlog of previous test experience and "know how" which can be marshalled as convincing arguments to overcome legal objections or liability considerations. Contractual precedents have been established by the Navy (Refs. 7 and 8) which contain indemnification by the Government to non-DoD contractors for the use of civilian volunteers for impact experiments conducted and/or sponsored by a Government agency. Indemnification and the lack of injuries in previous test programs make it a great deal easier for insurance companies to undertake underwriting the required insurance.

Much can be learned from past experience in human testing. The fact that no significant injuries have been sustained by hundreds of volunteers in thousands of tests at high G levels can be attributed to the following critical elements:

1. Careful planning and design of experiments
2. Careful conduct of the test procedures
3. Careful screening of all subjects
4. Careful medical supervision before, during, and after the tests.

All these elements add up to one basic credo: Every precaution must be taken to protect the subject's welfare.
In the sections which follow, detailed information on each of the important elements will be presented.

**DESIGN OF EXPERIMENTS INVOLVING HUMAN SUBJECTS**

Extreme care must be taken with the design of the experiments. Every precaution must be taken to protect the subject’s welfare. A comprehensive Test Protocol should be prepared in which every detail of each experiment is carefully spelled out. These protocols should then undergo a series of critical reviews by separate and unrelated panels to determine the adequacy of the experimental design and instrumentation from an engineering standpoint and to evaluate and approve the safety precautions and equipment involved. Another review panel should be composed of physicians and physiologists to review the screening and examination processes to be used in the selection of the volunteer subjects, the pre-test and post-test physicals and the lab tests to be performed, the emergency first-aid and evacuation techniques, and the adequacy of all safety measures designed to protect the welfare of the subjects.

There is a wealth of planning material available. Reference 9, “The Institutional Guide to Department of Health, Education and Welfare Policy on the Protection of Human Subjects” (which also contains interpretation of those policies), provides excellent guidelines. The Test Protocols prepared by the Air Force for human test programs at Holloman AFB and Wright-Patterson AFB, and by the Navy for programs at NADC Philadelphia are extensive and detailed and can supply invaluable information.

**TEST PROCEDURES**

In impact testing with human volunteers, experiments have to be designed to start at low G levels and to progress slowly using a “stepped-severity” concept such as that put forth by Brinkley et. al. for the air bag tests at Holloman AFB. The results of tests at each “step” should be carefully evaluated before continuing to a higher exposure. This entails a review of the high-speed motion picture films, analysis of the “quick-look” data traces from the oscillographs, and, in consultation with the medical personnel in attendance, an evaluation of the post-test physical examination data as well as a review of the subjects’ comments obtained during post-test debriefing.

After a review of results has determined that another level of testing can be undertaken safely, the Test Protocol and subject availability or utilization roster must be reviewed. An example of the subject utilization chart used at Holloman is shown in Figure 1. The Test Protocols in use at Holloman and at NADC both include a requirement that a volunteer cannot be used more than once in any one calendar week. This requirement is important to insure that any minor post-test trauma will have had ample time to dissipate and will not be aggravated by additional exposure, and to insure that any subtle trauma with delayed reaction will have had ample time to appear.

Once subject selection has been made for the next run, new sled input parameters and controls and/or brake settings must be established and carefully checked out against predetermined calibration levels. Minor adjustments to sled controls and equipment must be made. Pre-test physicals have to be administered. New seats and new restraint system components have to be installed. Instrumentation calibrations have to be carried out. “Back-up” restraint systems and safety circuits have to be checked out. Finally, a “proof” run using a dummy should be conducted as a final check that all elements of the test facility are ready and safe for the human volunteer. Only upon completion of the proof run, and with medical personnel, emergency treatment, and evacuation facilities manned and ready, should the next human test be conducted.
<table>
<thead>
<tr>
<th>Subject</th>
<th>Test Speed in MPH</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>A</td>
<td>8/9</td>
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<tr>
<td>B</td>
<td>8/9</td>
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<tr>
<td>C</td>
<td>8/10</td>
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<tr>
<td>D</td>
<td>8/10</td>
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<td>E</td>
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</tbody>
</table>

Figure 1. Repetitive utilization of subjects

RECRUITING AND SCREENING
OF VOLUNTEERS

Recruiting of civilian volunteers is much easier with insurance in effect. The subjects are more willing to sign a Consent Statement (that they understand element of risk involved and that their participation is voluntary) since they are assured that any and all medical expenses incurred in the event of injury will be paid. Subjects must also be assured that complete pre-test and post-test physicals and lab tests will be given by competent physicians, that a physician will be in attendance during all tests, and that adequate emergency measures are manned and ready during all tests, including an ambulance standing by for rapid transfer to the nearest hospital with available emergency treatment facilities. An example of a typical Consent Statement is shown in Figure 2, which is a copy of the form in use at NADC Philadelphia.

Careful physical screening of volunteer subjects is essential. Any skeletal, joint, or systemic abnormality must be found and evaluated. Full body X-rays are almost a requirement. In general, any abnormality, no matter how trivial, should be grounds for rejection of a volunteer because of the dangers involved in aggravating an existing pre-test condition. Comprehensive lab tests on blood and urine should be conducted before and after each test.

In addition to screening out physical abnormalities, many subjects should be
CONSENT TO PARTICIPATE VOLUNTARILY IN A RESEARCH, DEVELOPMENT,
TEST, OR EVALUATION (RDT&E) PROCEDURE.

DATE________________________

1. I hereby volunteer to participate as a subject in an RDT&E procedure being conducted
under Interagency Agreement DOT-HS-063-1-081 I.A. (amended) between the National
Highway Traffic Safety Administration, Department of Transportation and the Naval Air
Development Center. I understand that the adequacy of safety measures has been certified
by the Chief, Bureau of Medicine and Surgery, and that authority to use human volunteers
has been granted by the Secretary of the Navy.

2. The nature and purpose of the procedures have been explained to me, as indicated in the
attached “Summary of Test Procedure,” which is an integral part of this document.

3. In making my decision to volunteer, I am not relying upon any information or
representation not set forth in this document, including the “Summary of Test Procedure,”
and the attached NADC/NHTSA Automotive Passive Restraint Program Test Protocol. My
consent is given as an exercise of free will, without any force or duress of any kind. I
understand that I may withdraw my consent to participate in the experiments at any time,
without prejudice to myself. I further understand that my consent to participate does not
constitute a release from any possible future liability by the United States, and/or by other
participating parties, which is attributable to the experiments.

SIGNED________________________________

(typed name, rank, rate, or grade)

(date of birth)

WITNESSED
(not directly involved in test)

________________________________

APPROVED________________________________

Director
Crew Systems Department

Copy to:
Service Record or Personnel File

Figure 2. Consent statement used at NADC Philadelphia
rejected because of psychological factors. The overly meek and hesitant “nervous Nellies” should be eliminated because they will invariably withdraw from the test program after one or two exposures. This might require repeat experiments in the low-level or baseline tests. The overly eager, “rough-tough” volunteers should also be rejected because they are more likely to try to go beyond their own safe tolerance levels. Also, these latter types do not produce objective debriefing comments after exposure, since a negative comment or complaint of any kind could be interpreted as a personal failure in some degree. Subjects with “nervous mothers” should be looked at askance. Questions about family attitudes and relationships during the screening process should be designed to find this kind of volunteer—an only child with one deceased parent would be one example. The proverbial “sea lawyer” could prove to be a problem in a difficult situation, i.e., a volunteer coming from a family of lawyers, ready to sue at an instant’s notice.

SUBJECT MOTIVATION

Tests with volunteer human subjects must be conducted at sub-injury levels. Volunteers, regardless of their degree of motivation, cannot be expected to undergo further impact testing when a fellow volunteer has sustained a fracture, serious bruises, or even a bloody nose in a previous test. In real-world crashes with involuntary participants, minor injuries can be tolerated. Any type of injury must be considered as a very serious problem in the world of sled testing.

Attempts should be made to prevent “cross-talk” between the subjects after the experiments begin. One way to do this is to keep all information about peak values attained away from the subjects. Although this may smack of intentional subterfuge, it can be done gracefully by making the data unavailable or by placing it in a “classified” category. This suggestion is made to avoid the problem of the “eager beavers” who may be motivated largely by the spirit of competition in that they can “go higher than the next guy.” This tendency must be watched carefully and eliminated if possible. The danger of reaching beyond the safe individual tolerance level and producing an injury with life-long complications is never worth the data to be derived.

Few subjects are very highly motivated because of the “nature of the work” or the “good” that will be derived. The only common thread of motivation in most of the human volunteer subjects that I can think of is money! The extra duty pay or hazardous duty pay for military subjects and the “moonlighting” income for students is their prime motivation.

SUBJECT INFORMATION AND ANTHROPOMETRY

The importance of getting all anthropometric data, results of lab tests, X-rays, etc. for each subject into a single file cannot be overemphasized. The data should be gathered and filed as early as possible before the experiments begin. All too often, volunteers disappear, for one reason or another, during the experiments. In some cases with military personnel, some recourse is available since missing data can be requested from their next duty station. In other cases, however, some experiments in the past have been compromised because of the disappearance of a volunteer after a few runs before the anthropometric and medical information had been obtained.

Summary records, showing the comparative data on all of the subjects should also be started early and kept up to date during the experiments. Examples of typical kinds of data sheets are shown in Figures 3, 4, and 5.

EXISTING FACILITIES FOR FUTURE PROGRAMS

At the present time, there are twenty-six sled test facilities in the United States as shown in Table 3.

In the past, only three of the facilities shown above have been used for human testing. Recently, within the last few months,
ANTHROPOMETRIC DATA FOR TEST SUBJECTS

Individual Data Sheet

<table>
<thead>
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<th>ITEM</th>
<th>DEFINITION</th>
<th>VALUE</th>
<th>NAME</th>
<th>RANK OR RATE</th>
<th>UNIT</th>
<th>NEXT OF KIN</th>
<th>HOME PHONE</th>
<th>OFFICE PHONE</th>
<th>CODE LETTER</th>
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REMARKS
ANTHROPOMETRIC DATA FOR TEST SUBJECTS
Summary Data Sheet

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*Figure 4. Anthropometric data for test subjects—summary data sheet*
SUBJECT EVALUATION SHEET

TEST NUMBER ___________  SEVERITY ___________
DATE _________________  SUBJECT ___________
              HEIGHT ___________
              WEIGHT ___________

PRE IMPACT OBSERVATIONS
1. ________________________________________________
2. ________________________________________________
3. ________________________________________________
4. ________________________________________________

POST IMPACT OBSERVATIONS
1. ________________________________________________
2. ________________________________________________
3. ________________________________________________
4. ________________________________________________

SUBJECT DEBRIEFING
1. ________________________________________________
2. ________________________________________________
3. ________________________________________________
4. ________________________________________________
5. ________________________________________________
6. ________________________________________________
7. ________________________________________________
8. ________________________________________________

FILM OBSERVATIONS
1. ________________________________________________
2. ________________________________________________
3. ________________________________________________
4. ________________________________________________
5. ________________________________________________
6. ________________________________________________
7. ________________________________________________
8. ________________________________________________

Figure 5. Subject evaluation sheet
Table 3. Existing Sled Test Facilities

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<th>Industry</th>
<th>Universities</th>
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<td>8</td>
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<td>Other Sleds</td>
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<td>3</td>
<td>6</td>
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<td><strong>Totals</strong></td>
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Three new sled test facilities have come “on-line” with human volunteer test capabilities. The Naval Aerospace Medical Research Laboratory, Michoud Station, New Orleans, La., under the direction of Dr. Channing L. Ewing, has completed the installation of their new 12 inch HyGe sled. Elaborate biomedical instrumentation, precise control of sled input parameters, and on-line, real-time data acquisition and analysis systems will facilitate advanced research in biomechanics. Their charter includes provision for testing with live subjects as part of NAMRL’s mission to conduct biomedical research in a joint Army-Navy program. Preliminary arrangements to use Army volunteers had to be abandoned recently because of changes in the complex DoD inter-service personnel management practices, but new arrangements to utilize Navy personnel are being completed and human testing is expected to begin shortly.

Another new sled test facility with human test capability is the Vehicle Crash Simulator at the Southwest Research Institute, San Antonio, Texas. The latest design MTS Model 858.05 simulator is bungee-powered with both acceleration and programmable deceleration profiles available. Although no human testing has been conducted to date, SWRI has made arrangements for a panel of volunteers to be used in impact research.

The third new sled test facility with human test capability is located at the 6570th Aerospace Medical Research Laboratory, Wright-Patterson AFB, Dayton, Ohio, under the direction of Dr. Henning Von Gierke and James W. Brinkley. Prior to the end of April 1973, personnel of the Impact Branch had completed 210 sled tests. Twenty-five of these runs involved human volunteer subjects seated in a side-facing position and protected by an air bag restraint system undergoing test and development by the Air Force.

**CONCLUSION**

The field of impact experiments with living human subjects has been severely limited by the shortage of “man-rated” sled test facilities. This has been primarily due to the general unwillingness of organizations, other than the military installations, who do have sleds to deal with human volunteer subjects because of the possible injury liabilities, the lack of required medical facilities and personnel, and the problems involved in the recruiting and motivating of volunteers. It is hoped that the information contained herein will help some organizations in overcoming their reticence.

Impact sled test work with dummies, human cadavers, and primates is important because these surrogates for the living human must be used for the tests that are obviously beyond the human tolerance range. In each case, however, scaling problems are involved and many approximations or extrapolations are required. A great deal of additional research with living human volunteer subjects is required if we are going to be able to answer the many questions which still exist on man’s kinematics, his tolerance to injury, and the mechanics of the injury process in the real-world automotive crash environments.

Work with human subjects, cadavers, and primates will continue. New projects with joint industry-Government cost sharing are
being proposed. New instrumentation, new recording techniques, and new on-line computer analysis of data all present exciting possibilities to fill in the gaps in our knowledge of man's frailties in the crash environment.

APPENDIX

The following material concerning Indemnification has been taken verbatim, in its entirety, from the General Provisions of the SCHEDULE of Navy Contract Number N00024-69-A-5111 (x) issued by the Naval Ship Systems Command, Department of the Navy, Washington, D.C. 20360. The contract was issued on 1 July 1968, under Purchase Request Number 00167-8-000192, for work at the Naval Ship Research and Development Center, Washington, D.C. 20007. The contractor, Glenn Engineering Services, Inc., 5706 Frederick Avenue, Rockville, Md. 20852, was merged into IMCOR, Inc. in November, 1969. IMCOR, Inc. is now a defunct corporation.

INDEMNIFICATION UNDER 10 U.S.C. 2354 (MAY 1964)

(a) Pursuant to the authority of 10 U.S.C. 2354, notwithstanding any other provision of this contract, but to the following paragraphs of this clause, the Government shall hold harmless and indemnify the Contractor against—

(i) claims (including reasonable expenses of litigation or settlement) by third persons (including employees of the Contractor) for death, bodily injury (including sickness or disease), or loss of, damage to, or loss of use of property;

(ii) loss of or damage to property of the Contractor, and loss of use of such property, but excluding loss of profit; and

(iii) loss of, damage to, or loss of use of property of the Government; to the extent that such a claim, loss, or damage (A) arises out of the direct performance of this contract; (B) is not compensated by insurance or otherwise; and (C) results from risk defined in this contract to be unusually hazardous.

(b) The Government shall not be liable for any such claim, loss or damage that results from willful misconduct or lack of good faith on the part of any of the Contractor's directors or officers, or on the part of any of his managers, superintendents, or other equivalent representatives, who has supervision or direction of (i) all or substantially all of the Contractor's business, or (ii) all or substantially all of the Contractor's operations at any one plant or separate location in which this contract is being performed, or (iii) a separate and complete major industrial operation in connection with the performance of this contract. The Contractor shall not be indemnified under this clause for liability assumed under any contract or agreement (except for subcontracts which are covered by paragraph (d) below) unless such assumptions of liability has been specifically approved by the Department.

(c) No payment shall be made by the Government under this clause unless the amount thereof shall first have been certified to be just and reasonable by the Secretary or his representative designated for such purpose. Such payments shall be made from funds as stated in 10 U.S.C. 2354. The rights and obligations of the parties under this clause shall survive the termination, expiration, or completion of this contract.

(d) With the prior written approval of the Contracting Officer, the Contractor may include in any subcontract under this contract the same provisions as those in this clause,
whereby the Contractor shall indemnify the subcontractor against any risk defined in this contract to be unusually hazardous. Such a subcontract shall provide the same rights and duties, and the same provisions for notice, furnishing of papers, and the like, between the Contractor and the subcontractor as are established by this clause. The Contracting Officer may also approve similar indemnification of lower tier subcontractors upon the same terms and conditions. Subcontracts providing for indemnification within the purview of this clause shall entitle the Contractor or the Government, or both, to direct, participate in, and supervise the settlement or defense of relevant actions and claims. The Government shall indemnify the Contractor with respect to his obligations to subcontractors under subcontract provisions thus approved, by the Contracting Officer. The Government may discharge its obligations under this paragraph by making payments directly to subcontractors or to persons to whom the subcontractors may be liable.

(e) If insurance coverage maintained by the Contractor on the date of the execution of this contract is reduced, the liability of the Government under this clause shall not, by reason of such reduction, be increased to cover the risks theretofore insured, unless the Contracting Officer consents thereto in consideration of an equitable adjustment to the Government, if appropriate, of the price in a fixed-price contract, or the fee in a cost-reimbursement type contract, in such amount as the parties may agree.

(f) The Contractor shall (i) promptly notify the Contracting Officer of any occurrence, action or claim he learns of that reasonably may be expected to involve indemnification under this clause, (ii) furnish evidence or proof of any claim, loss or damage in the manner and form required by the Government, and (iii) immediately furnish to the Government copies of all pertinent papers received by the Contractor. The Government may direct, participate in, and supervise the settlement or defense of any such claim or action. The Contractor shall comply with the Government's directions, and execute any authorizations required, in regard to such settlement or defense.

(g) The Contractor shall procure and maintain to the extent available, such insurance against unusually hazardous risks as the Department may from time to time require or approve. All such insurance shall be in such form, in the amounts, for the periods of time, at such rates, and with such insurers, as the Department may from time to time require or approve. The obligations of the Government under this clause shall not apply to claims, loss or damage to the extent that that insurance is available and is either required or approved pursuant to this paragraph. The Contractor shall be reimbursed the cost of any such insurance in excess of that maintained by the Contractor as of the date of this contract, to the extent the cost thereof is properly allocable to this contract and is not included in the contract price. (MAY 1964).

(h) The indemnity provided pursuant to the "Indemnification Under 10 U.S.C. 2354" Clause for this contract shall be limited to costs arising as a result of unusually hazardous risks which for the purposes of this contract shall be the risks induced by intentionally subjecting human beings to mechanical shock, vibration and/or water impact (by high velocity waterjets, sheets, sprays, and/or droplets), produced by specially designed machines and devices, in the conducts of tests by the Navy to determine the effects of such shock, or vibration and/or water impact on the human body.

ADDITIONAL ALTERATIONS IN GENERAL PROVISIONS

(1) Clause 1 entitled "DEFINITIONS" is modified by addition of the following paragraph:

"(d) For purposes of the clause of this contract entitled "Indemnification Under Public Law 85-804," a claim, loss or damage shall be considered to have arisen out
of the direct performance of this contract if the cause of such claim, loss or damage occurred during the period of performance of this contract or as a result of the performance of this contract. (MAY 1964)."

(3) The following clause is added as Clause 59:
ORDER OF PRECEDENCE (AUG. 1965) (ASPR 7-104.56)
In the event of an inconsistency in this contract, unless otherwise provided herein, the inconsistency shall be resolved by giving precedence in the following order: (a) the Schedule; (b) General Provision; (c) the other provisions of the contract whether incorporated by reference or otherwise; and (d) the Specifications.

References


Questions & Answers

LARRY PATRICK, WAYNE STATE UNIVERSITY:
You mentioned the problem of instrumentation and I think if we're going to start with more civilian volunteers, we should have some standardization of the instrumentation. SAE had a committee started a while back to try to recommend instrumentation for human volunteers. We fell flat on our face on that, but I think that it would be a great idea to have some standard either through the government or by general consensus through one of the technical societies so that the future data are all official rather than a waste of time.

I can't agree with you more, Larry. Unfortunately, human instrumentation, as you well know, has been coming along pretty late. There are some new avenues available to us and Endevco is working at the problem pretty hard. We've been working on it at TSC in Cambridge and at NADC, Philadelphia. To standardize it, I don't know, Larry. It's a great idea but the "state of the art" is moving pretty fast at the moment. It's late in coming but it's moving, finally.

JACK E. MARTENS, ALLSTATE INSURANCE:
Tom, I'd like to add to what Larry said because you pointed out that Allstate tests were done on a PR basis, but we did come to the Department of Transportation—Colonel Stapp for one—for help on instrumentation for the human. There wasn't any available. We instrumented the vehicles but we couldn't instrument the human because we didn't know how to do it—nor was there assistance available to us.

Jack, I don't think you looked deep enough. You know, you had a large number of channels as it was but there were things available to you. Next time, check more thoroughly with more people.
Open and Closed Loop Testing and How They Are Integrated in Vehicle Handling and Dynamics Research

Robert D. Ervin
Leonard Segel
Highway Safety Research Institute
University of Michigan

Abstract

Requirements for a motor vehicle performance test technology differ depending upon whether the objective is to certify that a product is ready for the marketplace or to measure performance qualities which meet a defined societal need. Examination of these objectives shows that industry's needs are primarily satisfied by a closed-loop testing procedure, whereas a government agency charged with advancing highway safety requires test procedures that are open-loop.

This paper reviews the evolution of this art with attention given particularly to the new thrusts resulting from a desire to upgrade safety levels. Some recent applications of open- and closed-loop testing are cited, and the prognosis for making further advances in this test technology is examined. Particular consideration is given to the requirement for relating open- and closed-loop measures of performance, a requirement stemming from the level of objectivity that is necessarily associated with the standards development process.

Introduction

Feedback system terminology has been adopted by the motor vehicle community for purposes of making a clear distinction between two major modes of vehicle test. In this paper, we wish to show how "open-loop" and "closed-loop" testing differ in principle and in practice, and how they each fulfill a different set of needs, depending on whether the testing agency is a product developer, a regulatory body, or a research group. Of major concern are the testing requirements that derive from the rather special needs of the National Highway Traffic Safety Administration.

We shall not discuss testing in general. Instead, we shall specifically direct our attention to testing designed to measure or evaluate qualities related to the directional response to steering, although we shall consider the more general case of vehicle response to steering and braking/acceleration.

Prior to reviewing the state-of-the-art in open- and closed-loop testing and subsequently outlining the applications of same, we take some pains to differentiate between the vehicle testing and research that is required to produce a viable transport system and that which is required to achieve, or demonstrate, qualities which will impact, presumably, on the accident record. Following a review of applications, primarily in a safety context, we attempt a prognosis of future trends, wherein due recognition is given to the importance of the Federal Government's entry into regulatory activities that govern the ubiquitous motor vehicle.

The Relationship Between Vehicle Handling and Vehicle Dynamics and Safety

By definition, an evaluation of vehicle handling requires that closed-loop testing be employed. Open-loop testing, by definition, measures the static and dynamic response...
properties of the motor vehicle alone. Safety, on the other hand, is a quality that is exceedingly more difficult to define.

If we start with the consensus that safety may be divided into a “pre-crash,” “crash,” and “post-crash” phase, it is clear that vehicle handling and vehicle dynamics impinge exclusively on pre-crash safety. Given that this distinction can be made, it does not prove to be very helpful—namely, we still require a working definition whereby it becomes possible to evaluate pre-crash safety in an objective manner.

To this end, some contend that the only meaningful measure of pre-crash safety is the accident record. This position implies that the pre-crash safety quality of a motor vehicle is synonymous with its accident avoidance qualities and the presumption is that a vehicle population with better accident avoidance qualities will result in a lesser number of accidents than would be produced by a vehicle population with poorer accident avoidance qualities. Even if the presumption is correct,* accident statistics are not very useful as a measure of pre-crash safety unless we are able to find that certain vehicle handling qualities and/or vehicle dynamic properties are highly correlated with accident involvements. Determination of this correlation requires suitable measures of vehicle handling and/or vehicle dynamics and a reliable means of identifying the over involvements of specific models. A little reflection indicates that such a correlation is not likely to be realizable either in the near or far term, and perhaps never, since vehicle-in-use factors can conceivably mask whatever differences in handling qualities may have been extant in the as-new vehicle population. We conclude that, to develop an operational definition of pre-crash safety quality, it is necessary to resort to procedures other than an analysis of the accident record.

To develop this operational definition, it follows that we should determine the require-

*Note that there is not proof that it is correct and several deficiencies in the hypothesis are apparent.
This is not to say that testing is not performed within the industry. There is obviously considerable testing being done to provide each manufacturer with the assurance that he has a viable, competitive product line of high quality. In evaluating the handling qualities of the product line, the industry has found, however, that it is cost-effective to do the bulk of this testing in a subjective manner.* It seems clear that vehicle handling requirements, as they derive from the pressures of the marketplace, can be met (and are being met) by the test technology that evolved to fulfill that need. It would be most unusual, indeed, if such an evolution had produced open- and closed-loop test procedures that would be adequate to define and measure the pre-crash safety qualities of the motor vehicle.

THE STATE OF THE ART IN OPEN- AND CLOSED-LOOP TESTING

Having indicated the basis for the evolution of the test art within the automobile industry—namely, the requirements and constraints that go with operating a successful business—let us review the state-of-the-art as it currently exists. Note that the true state-of-the-art cannot be known with exactitude since, more often than not, the individual manufacturers conclude that it is in their interest (competitively speaking) not to disclose the procedures that they use or have under development. Simultaneously, there are influences at work that promote the development of a test standard or a recommended test practice.

Mention has already been made of subjective evaluations of vehicle handling performance which are conducted either on the ride and handling roads located at the manufacturer’s proving ground or on the open highway. In this review, however, we shall be concerned only with objective measurement practices.

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*See, for example, the paper by Versace and Forbes entitled Research Requirements for Determining Car Handling Characteristics, Highway Research Record No. 247.

Advances Deriving from Projects Independent of the Activities Pursued by the Office of Operating Systems Research

It is instructive to observe that whereas the relationship between design variables and steady turning characteristics was being explored in the U.S. in the thirties* (resulting in a circular turning test for measure of understeer), the Society of Automotive Engineers in the U.S. is currently in the process of formalizing, for the first time, a set of recommended test practices** for measuring the understeer and roll gradient of a motor vehicle. However, the conduct of steady turning tests on the “skid pad” is fairly widespread, both in the U.S. and abroad. Articles describing the equipment and procedures required to obtain an objective measure of under/oversteer have been generated by numerous British authors (Refs. 1, 2, 3). In addition, the British have developed schemes for measuring the influence of braking and drive thrust on equilibrium turning properties (Ref. 4). Note that it has not been common practice for vehicle manufacturers to publish, or otherwise disclose, the understeer characteristics of their product. However, the recent promulgations by NHTSA of a steady-state turning specification for the ESV have resulted in a wave of such disclosures (Refs. 5, 6, 7, 8) thereby providing evidence that steady-state turning measurements are either routine, or readily implemented, provided the motivation for so doing exists.

Measurement of the transient response to steering has similarly progressed from the research realm to a more or less routine activity. Nevertheless, the processing and subsequent interpretation of these dynamic measurements is far from routine, and it appears that current dynamic measurement and analysis practice is highly variable from test agency to test agency. To a large extent,
this variability stems from the absence of a consensus on the open-loop response characteristics that relate to driver-vehicle performance. Differences exist, for example, in the definition of response time and one observes that frequency-response techniques tend to be employed more widely abroad (Refs. 9, 10, 11, 12) than has been the case in the U.S. (Ref. 13).

Measurement of the open-loop dynamics at lateral accelerations beyond the range in which the motor vehicle behaves essentially as a linear system constitutes a task that has been approached in a large variety of ways. Although traditionally handled by driver observations, safety concerns have recently pushed the industry towards developing objective measurement schemes. In many instances, these procedures have involved measurements of the driver-vehicle system rather than measurements of the open-loop vehicle. Below we shall see that NHTSA-sponsored research has enabled some breakthroughs to be made in this regard.

As examples of open-loop dynamic testing in the nonlinear regime, it is possible to cite the endeavors of various car companies that have been occupied with meeting or examining the ESV accident avoidance performance specifications (Refs. 7, 14). It appears, however, that the ESV program in its international scope, has resulted in more ingenuity being directed towards devising objective measures of closed-loop performance (Refs. 6, 8). It shall suffice to observe that current test practice is better described as being in a state of flux rather than constituting a highly developed art.

Objective methods of measuring closed-loop performance have not been formalized within the current state-of-the-art, whether by industry, research groups, or the government. Although no accepted practices have been universally applied, extensive use has been made, within the industry, of various methods which seek a simple measure of the influence of certain vehicle design parameters on the naive driver’s control performance. Such maneuvers as the precision serpentine, lane curvature transitions, and the abrupt lane change have been effectively utilized to elicit measures of trajectory excursion (pylon strikings) which directly evaluate handling performance.

The principal drawbacks associated with these experiments all derive from the marginal objectivity and standardization that is achieved using naive (non-expert) subjects. The human factor problems which exist render special constraints on these tests limiting their utility and placing significant cost and time burdens whenever statistically significant findings are to be drawn.

Very likely the most ambitious program initiated to explore the relationship between vehicle performance and driver-vehicle performance was the GM-CAL Variable Stability Automobile (Ref. 15) followed by GM’s Variable Response Vehicle Program. In retrospect, it appears that the design, development, and utilization of elaborate test devices do not insure that research progress will be made at a rate in keeping with a given capital investment unless certain other requirements are satisfied.

We should not, however, leave the subject of closed-loop testing without mentioning the efforts of the research community, both within and without the industry, during the pre-Nader era. The research projects had a rather benign character and, in general, were marginally funded. The primary question being addressed was “What are the static and dynamic properties of motor vehicles that lead to good or optimum driver-vehicle performance?” Investigators, for lack of a better precedent, frequently posed the problem in a format that had been employed by the aircraft engineer. Structuring the question in this manner, while helpful, also led the uninitiated to make some serious errors. A common mistake was the failure to appreciate that an accident avoidance type of maneuver quickly pushes tire-vehicle systems into a nonlinear realm of behavior, such that linear descriptors of open-loop behavior quickly lose their applicability.
Advances Deriving from Projects Supported by NHTSA

NHTSA has not supported a program to date which has been specifically directed towards expanding the state of the art in closed-loop testing methods. Applications projects have been conducted, however, within the context of vehicle-in-use research in which the contracting organizations have found it necessary to define new closed-loop experimental techniques for use in their related testing programs. Whereas these vehicle-in-use studies have been concerned primarily with the identification of performance degradations relative to the baseline performance, the testing methods have not been intended to provide generic, normalized characterizations of performance which would be meaningful in universal practice. Notwithstanding this distinction of form, certain technological advances have been reported relative to the provision of roadway disturbances and data acquisition techniques which are pertinent to the art of objective testing in general.

The open-loop testing of passenger vehicles in the limit maneuvering regime represents that portion of the test state-of-the-art which has been most conspicuously advanced under NHTSA support. A set of tests has been defined to provide characterizations of limit maneuvering performance which are hypothesized to be safety relevant (Ref. 16). The tests involve steering and braking inputs of such a form that the driver is effectively eliminated as a system element. A high level of open-loop “purity” has been demonstrated through the use of programmable automatic vehicle controllers by which complex emergency-type control inputs are achieved repeatably and accurately.

A comprehensive methodology for measurement of open-loop limit maneuver properties has been developed, defining vehicle preparation practices, test procedures, test hardware, data-acquisition, -processing, -presentation, and -interpretation. To the extent that these methods will be instrumental in a scientific effort which intends to relate vehicle properties to safety, as discussed later in this paper, the NHTSA-supported contribution in this area may prove to have been most significant.

APPLICATIONS OF CLOSED- AND OPEN-LOOP TEST PROCEDURES AS THEY RELATE TO EVALUATING SAFETY PERFORMANCE

The area in which NHTSA has supported the broadest application of objective testing methods has been the investigation of vehicle-in-use safety. Three contractors have performed studies utilizing various open- and closed-loop test methodologies in examining the influence of steering and suspension degradation on vehicle controllability.

The Clayton Manufacturing Company performed tests which comprised both open- and closed-loop methods (Ref. 17). “Locked steering” procedures were used in straight-line braking and in the straight line encounter with fixed disturbances in road profile. The same experiments were also conducted with the test driver steering to minimize path error. Additionally, lane change and serpentine pylon tests were conducted under driver control.

The derived indices of performance encompassed error measures (path deviation, pylon scoring, etc.) as well as driver effort measures (steering displacement and torque) for maneuvering conditions that involved relatively low levels of lateral acceleration.

The Cornell Aeronautical Laboratory elected to employ closed-loop “task performance” measures in their study because of a pragmatic conviction that the link between safety and task performance, while not yet established, presented a reasonable prospect over the near term for its resolution (Ref. 18). This study involved nine task performance tests, intended to address the full range of steering and braking performance. The tests were predominantly of the limit performance variety, using the asymptotic capability of an expert driver as the indicator of limit system capability. Certain specialized tests were
devised to permit discriminatory examination of the influence of component degradations which were expected to impose minimal variations in task performance. The battery of test maneuvers included lateral obstacle avoidance tests, straight running and turning over pavement irregularities, negotiating a curb at a slight incidence angle, and braking, both straight-line and in-a-turn. Performance was characterized by a number of measures, including performance level descriptors (maximum speed through a course, minimum stopping distance), measures of driver control burden (steering wheel reversals and steering displacement), and binary indicators of the success or failure of course passage.

The Highway Safety Research Institute has applied strictly open-loop measures to the examination of the influence of component degradation on vehicle controllability (Ref. 19). The methods utilized were developed in an earlier “Vehicle Handling Test Procedures” (Ref. 16) study which intended to provide procedures for evaluating the limit performance capability of the O.E. vehicle. These test procedures prescribed steering and braking inputs, the response to which was characterized by various computed numerics, operating on the dynamic variables of longitudinal and directional motion.

Six tests were performed, three executed by a driver using passive steering and brake limiters and three by a programmable automatic controller. The automatic controller consisted of three servomechanisms which provided actuation of the steer, brake, and accelerator controls. Shown installed in Figure 1, these servos responded to command signals which originated from either a radio control link, or from an on-board programmable function generator. The system’s ability to provide precise programmed control inputs, of the emergency maneuver variety, permitted the conduct of certain test procedures which could not be performed acceptably well by a test driver.

The procedures encompassed braking in a straight line, braking-in-a-turn, turning on a rough surface, limit turning in response to step-like steering and in response to sinusoidal steering, and rollover immunity assessment, as challenged through combined steering and braking.

The derived measures assessed the trajectory achievement properties of the vehicle, as they constrain the dimensions of the performance envelope, as well as those anomalies of response which are hypothesized to impose increased burden on the driver.

In the application of the three foregoing test methodologies to the vehicle-in-use problem, it is interesting to observe that the findings which resulted have not been in uniform agreement. The Clayton study stands out as indicating a profound sensitivity of many of its measures to degradation of steering and suspension components, while the Cornell and HSRI programs produced findings of predominantly negligible sensitivities. It appears that this difference is not related to the closed- or open-loop character of the tests (since the Cornell and HSRI experiments represented the two alternate approaches) but rather to the severity of the maneuvers in terms of the proximity of tire shear forces to their saturation levels.

Another area in which application has been made of objective testing methods has
been the Experimental Safety Vehicle Program. Under an initial project conducted by the Digitel Corporation, a set of tests was defined for use in specifying the dynamic performance of the 4,000 lb. class ESV (Ref. 20). These procedures included both open- and closed-loop experiments examining dynamic performance properties in both the linear and limit maneuvering regime. The performance measures were not intended to assure optimization of the pre-crash safety quality of the ESV (Ref. 21), but rather to prescribe handling properties which were comparable to contemporary passenger vehicles. In that respect, these measures, and the associated test methodology, were not developed to play a role in pre-crash safety research.

The strict open-loop test methods which were developed by HSRI in the study entitled "Vehicle Handling Test Procedures," were applied to the gathering of a data base of the limit maneuvering characteristics of modern vehicles. In this study (Ref. 22), a twelve vehicle sample was tested, providing a magnetic tape library of response data, in addition to a set of numerics which are hypothesized as representing indicators of safety quality. A serious methodological problem was discovered in that program. This finding relates to the stability of the peak lateral force capability of the pneumatic tire during repetitive severe turning tests in which substantial wear of the tire shoulder results. Since it was found that certain tires indicate a profound sensitivity to this rather artificial type of wear, it is clear that the original equipment limit turning performance of vehicles equipped with these types of tires is not a measurable entity in a practical sense.

Notwithstanding the tire shoulder wear phenomenon, the study indicated the feasibility of a number of methodological advances such as the computerized derivation, from raw data recordings, of trajectory and sideslip (spin) responses, in addition to improvements in test precision and in the utility of the associated open-loop hardware.

THE PROGNOSIS FOR FURTHER ADVANCE IN THE TEST STATE OF THE ART

In attempting to forecast further advances that can be expected over the near term, we find it convenient to dichotomize vehicle test technology into four categories:

1. Open-loop measures—linear regime
2. Open-loop measures—limit regime
3. Closed-loop measures—linear regime

It is useful to define, firstly, the role that each of these measurement categories must play in the eventual attainment of the goal of developing an objective test technology capable of assessing the pre-crash safety quality of the motor vehicle. It is certainly clear that open-loop methods cannot stand alone in this quest because of their lack of inherent interpretability. One can only hypothesize that certain open-loop measures of linear and nonlinear behavior are safety relevant. For demonstration of the validity of any such hypothesis, one must either identify a causal relationship within the accident record, or implement the scientific method—i.e., demonstrate a causal relationship in driver-vehicle experiments which are sufficiently representative of actual driving conditions as to provide a high degree of confidence in the findings. Since the evidence and testimony provided by the accident record is ineffectively structured for identifying the relationship between accidents and vehicle performance properties, it appears that we must resort to the scientific method if open-loop measures are to be of demonstrated utility.

Closed-loop measures, on the other hand, are inherently easier to interpret in the highway safety context. Closed-loop test methods will be required to provide the crucial link to safety which must be established for open-loop measures to be declared meaningful. In terms of constituting a fully objective test technology, however, which is legally compatible with NHTSA's application to rule making, closed-loop measures cannot
be the final product of the envisioned research quest.

On examining the needed developments in each category of test technology, the open-loop linear regime measures are seen as providing the most nearly complete methodology within the current state-of-the-art. The steady-state and dynamic response testing of the linear vehicle, as has been practiced routinely within the auto industry, provides an adequate objective and comprehensive description of the understeer property as well as the transient steering response. Work is needed, however, to provide a generic characterization, covering the velocity range, for both the static and dynamic linear properties of response to steering such that meaningful research may be structured to demonstrate the safety relevance of linear performance. Observations of the real world suggest that the linear response properties of the motor vehicle will be of detectable significance to controllability only under in-service conditions in which tire inflation, loading, and after-market replacement dramatically alter the directional characteristics of the O.E. vehicle.

Research intended to demonstrate the extent of an "acceptable" range of linear properties must first develop and utilize a closed-loop methodology which is capable of evaluating the performance of the representative driver in accomplishing a full complement of realistic linear driving tasks. Such a methodology is not currently available, but presumably would be developed and applied within the course of an imminent NHTSA study entitled "Driver-Vehicle Response Research."

Although the open-loop linear testing methods are quite adequately developed and are firmly based on a solid understanding of the linear theory of vehicle mechanics, the development of nonlinear vehicle testing methods is currently constrained by limitations in the analysis of the mechanics of limit response. These analytical limitations give rise to experimental limitations in the context of limit maneuvering mechanics, as in many complex technologies in which:

1. Fundamental functional relationships remain to be identified.
2. Experimental condition variables are reasonably controllable only within certain bounds whose significance to the integrity of the experiment are not known.
3. The experimentally measured phenomena are of such a complex and varied character as to demand a comprehensive analytical tool by which test data can be challenged to assure its validity.

To minimize the extant analytical limitations in limit response prediction, efforts must be pursued to improve the mathematical models of tire-vehicle systems. It is apparent that a number of aspects of existing mathematical simulations are inadequate for the proper treatment of limit maneuvering conditions. To the extent that the existing models represent the total of all those functional relationships which are felt to be applicable and significant, their failure to predict certain limit response indicts the currently limited understanding of these processes. Further substantive progress in the prediction and evaluation of open-loop limit regime response will be limited until this situation is rectified.

Closed-loop measures of limit performance deserve extensive development if the basic goal is to be realized. Emphasis must be given to the development of experimental techniques which can provide authentic measurements of the operational character of the driver-vehicle system at the limit. It can be argued that such authenticity will only derive when truly representative (non-expert) subjects are given their first exposure to demanding simulations of traffic conflicts.

Substantive progress in this area should be forthcoming as a result of an imminent NHTSA study entitled Determination of Motor Vehicle Characteristics Affecting Driver Handling Performance. In this study, data will be obtained, demonstrating the extent to which certain open-loop limit performance characterizations correlate with the
performance of the representative driver-vehicle system. It appears unlikely, however, that we can conclude causal relationships from statistically correlative relationships without first attaining significant advances in modeling the human controller under emergency situations.

CONCLUDING REMARKS

It must be recognized that the prognosis for further advancement which has been presented here reflects a very specific view of the future of vehicle pre-crash safety research. We have outlined a structured research approach, placing closed- and open-loop methodologies in that mutual relationship which is geared toward NHTSA's application. This particular relationship (casting closed-loop methods as the scientific tool by which open-loop methods are proven valid) does not, indeed, address the host of non-government uses of these subject methodologies.

Closed-loop testing is still seen by many as offering an efficient means by which vehicle development can be prosecuted. Additionally, the typical future industry application of closed-loop methods will involve the use of expert drivers since the representative, or "naive," subject is an impractical constituent for any routine proving-ground operation.

Organizations which endeavor to recommend standardized practices, such as ASTM, SAE, etc., will most assuredly encourage the development of testing methods whose level of objectivity is balanced against the utility of the method to user groups.

It is only the legalistic posture of federal standards which demands the development of strictly objective measures and which suggests, in our view, a specialized role for open- and closed-loop methodologies in future research.

In retrospect, it would be a narrow view, indeed, to contend that NHTSA's research into vehicle pre-crash safety performance has not markedly expanded the base of knowledge on the subject. The value of such progress, however, in contributing to the ultimate goal of accident reduction rests in the strength of the causal influence that vehicle performance properties have on operational safety. If future efforts eventually demonstrate that certain properties exercise a strong causal influence, countermeasures may be implemented which prove these public research dollars to have been well spent. It is evident that the Safety Administration perceives that such positive influences do exist, thereby rendering justification for the pursuit of the outlined research.

References


Questions & Answers

VANN WILBER, AMERICAN MOTORS:
I have a question that might be a little philosophical: How important can any test method be when you have the variables of driver performance and the degradation of the vehicle in use to contend with and when we take an OEM vehicle out on a test track and it does so much, how meaningful is that to what it will do a year from now in the consumer’s hands?

I'd say that's a very good question. It's apparent that both linear properties of the vehicle and the nonlinear properties of the vehicle, limit maneuvering properties, can change markedly as a result of service degradation. Principally, nonlinear properties will change as a result of tire performance changes and shock absorber degradation. To the extent that this is so, a truly viable standard on pre-crash handling performance or vehicle dynamic performance must somehow address the changing vehicle as it exists in the hands of the consumer. Currently, I think NHTSA's position and their trust is to evaluate the influence of such tire properties and other degradations to determine an objective, in an objective way with objective test procedures, how large these changes are and how really meaningful they are. And I could also have mentioned the study that's about to begin under NHTSA sponsorship that examines the sensitivity of the vehicle system in limit maneuvering and linear operation to tire property changes as they occur in service. So you have a very valid point and it may be that such in-service changes are so profound that to know what the OE vehicle does is rather an academic piece of information. That may well be so but I think it's fairly apparent that NHTSA recognizes this as they are procuring, at the moment, research to investigate and objectify our knowledge on such a matter.
Particular Handling Safety Problems of Trucks and Articulated Vehicles

Ronald L. Eshleman
IIT Research Institute

ABSTRACT

A comprehensive survey of the literature yields this integrated overview of truck and articulated vehicle handling safety technology. Research utilizing modeling, mathematical analysis, and experimental techniques has been evaluated to determine its role in providing safe operation of trucks and articulated vehicles on the highway. In this paper the application of this technology to the solution of safety related problems and to the establishment of operational limits is discussed. Conclusions on the present state of truck and articulated vehicle technology are provided along with recommendations for future work in this area.

INTRODUCTION

Increasing demands on highway usage involving higher speeds and larger volume of traffic have created a need for the development of vehicle handling safety technology. Trucks and articulated vehicles constitute a large family of complex, massive vehicles that are required to maneuver within the constraints of heavy traffic over existing highways. For this reason, models for the prediction of the dynamic behavior of trucks and articulated vehicles during commonly encountered road and speed maneuvers on varied road surfaces and configuration subject to environmental influences are required. Vehicle handling criteria based on an experimentally verified mathematical model will provide the facility for review of existing and new vehicles for safety prior to testing and will aid in the generation of effective and enforceable standards that ensure vehicle safety on the highway.

An integrated overview of truck and articulated vehicle handling safety technology is presented in this paper. Research utilizing modeling, mathematical analysis and experimental techniques has been evaluated to determine its role in providing safe operation of the aforementioned vehicles. The application of this technology to the solution of safety related problems and to the establishment of operational limits is discussed. Conclusions on the present state-of-truck and articulated vehicle technology are provided along with recommendations for future work required to fill technological voids and to develop procedures for handling safety evaluation.

Within this paper the present state-of-technology in vehicle handling as applied to trucks and articulated vehicles is discussed in a technical subject oriented format. The necessary background for this discussion is contained in a short synopsis of the literature and a concise description of the concepts of vehicle handling and stability.

Truck and articulated vehicle technology has evolved from the early experimental studies of Huber and Dietz (Ref. 1) in 1937 at
the Automotive Research Institute at Stuttgart, Germany, to the present studies concerned with the development of valid computer simulation models. However, the major fundamental research on road vehicles has been performed in the last 10 years. Despite steady activity in this field, much work remains to be done.

In the context of a total dynamic analysis of vehicle systems, the following general analyses must be conducted:

1. Mathematical Analyses
   - Stability
   - Response
   - Synthesis

2. Experimental Analyses
   - Verification
   - Characterization.

Table 1 shows an evaluation of the major work in articulated vehicles in synoptic form. The modern works are discussed herein according to when a fundamental understanding of the phenomena that governs the dynamic behavior of trucks and articulated vehicles was developed.

The common response modes of trucks which constitute vehicle instability, illustrated in Figure 1, are rollover, spinout, and driftout. Roll stability is a function of ratio of half track width to center of gravity height. Spinout is characterized by excessive vehicle yaw which results from unequal tire side force availability. Driftout occurs when the total vehicle tire side force cannot control vehicle lateral accelerations.

Figures 2 and 3 show the two modes of instability common to articulated vehicles. Jackknifing occurs when the tractor swings around the kingpin owing to a loss of side force at the rear wheels. Trailer swing, the second mode of instability, is characterized by a large yaw angle; it occurs as a result of a partial loss of side force at the trailer wheels.

In any case, the sudden loss of or lack of sufficient tire side force is the cause of articulated vehicle instability. This condition may occur during partial skidding when braking is applied or because of a total slip of the wheel due to tire/road interaction. No universally accepted figure of merit on allowable yaw angles for articulated vehicles has been established to date; however, large "controlled" responses, such as trailer swing or catastrophic jackknifing, are deemed undesirable on the highway.

A nonallowable tire slip constitutes a meaningful conservative criterion for truck and articulated vehicle stability. If vehicle
<table>
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<tr>
<th>Date</th>
<th>Contributor</th>
<th>Contribution</th>
<th>Ref. No.</th>
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| 1963  | F. D. Hales  
Motor Industry Research Assoc. | Simple simulation model for articulated vehicle lateral stability; four degree of freedom linear model; lateral, forward, and yaw motion of tractor, and articulation angle between tractor trailer; lateral tire force linear function of slip angles. | 2        |
| 1963  | F. Jindra    
General Motors Corp. | Simple directional stability of three degree of freedom longitudinal, lateral, and relative yaw linear model; constant speeds, steady flat turn.                                                                 | 3        |
| 1963, 1964 | J. R. Ellis  
Advanced School of Automotive Engr. Cranfield, England | Analysis of tractor-semi trailer with four degrees of freedom lateral-forward motion tractor and trailer yaw angles; first use of nonlinear tire model including braking and side force; digital computer solutions for instability based on response. | 4,5      |
| 1965  | F. D. Hales  
Motor Industry Research Assoc. | Effect of locked wheels on the stability of tractor-semi trailer vehicles; linear model; experimental work.                                                                                                           | 6        |
| 1965  | F. Jindra    
General Motors Corp. | Extension of earlier work on lateral handling; constant speed, flat turn; influence of design parameters on lateral stability; linear tire model, four degree of freedom linear system model.                                  | 7        |
| 1965  | F. Jindra    
General Motors Corp. | Analog computer study of tractor semi trailer and full-trailer combination handling at constant velocity on a flat road; five degrees of freedom linear vehicle model; linear tire model.                                             | 8        |
| 1966  | F. D. Hales, et al.  
Motor Industry Research Assoc. | Extensive field testing on the lateral behavior of articulated vehicles during braking; anti-jackknife device evaluation; trailer swing instability; jackknifing instability.                               | 9        |
| 1967  | I. Schmid    
Battelle Institute | A study on the directional stability of tractor single and double semitrailer and truck-trailer systems. Routh criteria are used to study stability of a linear model. Special attention is given to braking.             | 10       |
| 1968  | R. E. Nelson and  
J. W. Fitch  
American Brakeblok; Western Highway Inst. | Braking and stability tests of single, double, and triple trailer articulated vehicles; test results; brake system evaluation and modifications.                                                                          | 11       |
| 1968  | R. P. Joyce and  
T. M. Scopelite  
IIT Research Inst. | Full scale experimental evaluation of an anti-jackknife device on a tractor-semi trailer vehicle.                                                                                                                 | 12       |
| 1968  | T. A. Byrdsong  
NASA-Langley Research Center | Effect of braking on tire cornering force; experimental data for wet and dry road surfaces.                                                                                                                      | 13       |
| 1968  | H. Dugoff  
Stevens Inst. Tech. | Theoretical analysis of lateral dynamic stability of articulated vehicles; scale model aerodynamic tests; influence of aerodynamic effects on stability.                                                                 | 14       |
| 1968  | E. C. Mikulcik  
Univ. Calgary | First complete nonlinear model of a tractor-semi trailer with three translational and three rotational degrees of freedom; steering-braking input; comparison of linear and nonlinear models; parameter variation studies. | 15       |
<table>
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<tr>
<th>Date</th>
<th>Contributor</th>
<th>Contribution</th>
<th>Ref. No.</th>
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<tbody>
<tr>
<td>1969</td>
<td>K. E. Holmes and R. D. Stone Road Research Lab. Ministry of Transport Crawthorne, England</td>
<td>Tire braking and cornering forces on dry and wet surfaces; experimental data; theoretical models.</td>
<td>16</td>
</tr>
<tr>
<td>1969</td>
<td>E. E. Hahn and T. M. Scopelte IIT Research Inst.</td>
<td>Articulated vehicle dynamic simulation; linear simulation model; operator response evaluation.</td>
<td>17</td>
</tr>
<tr>
<td>1970</td>
<td>T. M. Scopelte IIT Research Inst.</td>
<td>Articulated vehicle dynamic simulation (AVDS I); nonlinear digital simulation model for tractor-semi trailer handling with variable trajectory; fifth wheel damping; nonlinear tire model.</td>
<td>18</td>
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<tr>
<td>1970</td>
<td>P. M. Leucht Univ. of Michigan</td>
<td>Examined the effect of brake-torque distribution on tractor semitrailer directional dynamics.</td>
<td>19</td>
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<tr>
<td>1971</td>
<td>R. Limpert Highway Safety Research Inst. Univ. of Michigan</td>
<td>Tractor-semi trailer braking predictions in terms of available tire/roadway friction; effects of load transfer; tandem axles; braking distribution studies.</td>
<td>20</td>
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<tr>
<td>1971</td>
<td>A. K. Krauter and D. L. Bartel Cornell Univ.</td>
<td>Design and analysis of a tractor-semi trailer using a digital simulation model; optimization technique used for design; wheel rotation degrees of freedom; braking and steering input.</td>
<td>21</td>
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<tr>
<td>1971</td>
<td>R. W. Murphy, R. Limpert, and L. Segel Univ. of Michigan HSRI</td>
<td>The range of braking performance currently exhibited by buses, trucks, and tractor-trailers and to establish the maximum braking performance capabilities of these vehicles based upon full utilization of the technology related to brake system design was investigated.</td>
<td>22</td>
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<tr>
<td>1972</td>
<td>R. L. Eshleman and S. Desai IIT Research Inst.</td>
<td>Articulated vehicle dynamic simulation (AVDS II); nonlinear digital simulation model for single and double bottom tractor-trailers; trajectory analysis including hills, bends, and curves; multiple degrees of freedom per body; variable braking input; tire model (modified Ellis model); steady and transient aerodynamic loads; full scale verification tests.</td>
<td>23</td>
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<tr>
<td>1972</td>
<td>V. T. Nicolas and T. R. Comstock Univ. of Cincinnati</td>
<td>A computer simulation model for determining the dynamic behavior of tractor semitrailer vehicles when anti-skid braking systems were employed. Mathematical models representing the brake system, anti-skid controller, tire mechanics, and three-dimensional vehicle dynamics were developed. Results of simulating the braking performance of a vehicle employing a simple on-off wheel controller during straight line and fixed steering angle stops are presented.</td>
<td>24</td>
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<tr>
<td>1972</td>
<td>E. A. Susemihl Cornell Univ.</td>
<td>This Ph.D. work was concerned with the problem of indirect sensing (identification of the initiation of instability before it can be directly observed) of tractor jackknifing. Forms of corrective action are also considered.</td>
<td>25</td>
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parameters, speed, braking, environmental influences, and/or maneuvering combine to create uncontrollable vehicle side slip or unusually large response, then the vehicle is unstable. This can be described in terms of vehicle maneuverability. For double-semi-trailer vehicle handling ability there are many more modes of "controlled" response or instability due to the length and complexity of this vehicle.

The essence of truck and articulated vehicle handling lies in the efficient energy dissipation at the tires, with the interaction of side force generation and braking force being a major crucial unknown.

**HANDLING SAFETY FACTORS**

The handling safety factors that influence truck and articulated vehicle behavior are listed in Table 2. Major areas listed are road surface, road geometry, environments, vehicle geometry, and vehicle control.

The effects of road surface—dry, wet, ice covered—including its roughness are reflected in tire cornering and braking ability. Road geometry affects the direction of gravity forces through banks and grades. The road curves and other maneuvers require control factors of braking and steering; and, effectively are system constraints.

Environments include steady and transient wind loadings of the vehicle induced by adjacent vehicles, weather and adjacent walls, barriers, bridges, etc. Aerodynamic forces are a function of aerodynamic coefficients, the relative velocity between the environment and the vehicle and the effective area of the vehicle. The importance of these disturbances depends to a large extent on the weight of the vehicle.

For articulated vehicles, the vehicle geometry introduces constraint conditions by the location of articulation points. The mass distribution of the vehicle is characterized by its weight, center of gravity, and moments of inertia. The suspension systems are composed of springs and dampers; the shock absorbers dissipate some energy; both influence the pitch and roll angles. The normal loading on the tires which ultimately governs the tire cornering force is affected by the vehicle pitch and roll.

The final set of factors on vehicle control are probably of most importance in maintain-
ing vehicle stability. Steering constitutes first-hand directional control of the vehicle through front wheel development of cornering force. It is affected by human response and mechanical adjustments. Brakes influence the forward motion control of the vehicle and are affected by pressure equalization, response time, temperature, etc. Fifth wheel devices are added to vehicles in an attempt to control stability; however, in most instances they are ineffective because of increased steering requirements.

Vehicle Factors Rank

The factors that affect vehicle handling performance have been ranked on the basis of the information generated by Eshleman and Desai (Ref. 23). Information from published literature, simulations conducted during a parameter variation study and experimental verification tests were used to generate these results. For directional maneuverability, the factors were ranked in the following order of importance:

1. Primary Factors
   - road surface condition
   - tire tread condition
   - brake torque distribution
   - brake tractive power
   - aerodynamic environments
   - truck center of gravity location

2. Secondary Factors
   - tractor trailer center of gravity location
   - tractor fifth wheel location
   - suspension systems
   - road geometry
   - fifth wheel dampers.

The road surface condition and tire tread determine the tire/road interface friction which when varied results in large changes in vehicle maneuverability, and in cases of ice, loss of control for some typical maneuvers. Brake torque distribution also is important because side-to-side unbalance causes either a loss of lateral control or increased demand on steering. The distribution of brake tractive power is important to lateral stability due to the fact that a locked wheel or a wheel with longitudinal slip above 0.25 diminishes the tire side force capability. In addition, tractive power controls the vehicle’s forward motion. Aerodynamic environments can substantially affect maneuverability limits, particularly in unloaded vehicles where side winds increase demand on steering and tire side forces. Similar to braking, aerodynamic forces alter the forward motions of the vehicle. Truck center of gravity location controls potential rollover instability.

The remaining factors are of secondary nature and involve the design of highways and the vehicle. Variation in the parameters that govern these factors does not radically alter articulated vehicle handling. The factors listed previously and ranked herein are described in detail in the succeeding sections.

Road Surface and Geometry

The handling of trucks and articulated vehicles is affected by the road surface condition through the tires. The road/tire interaction is an important consideration because it determines the fundamental mechanism for control. Identification of the road surface condition is a major factor associated with the driver. Improper assessment of the road skid resistance often results in an accident. It is suggested by Ludema (Ref. 26) that maximum allowable speed signs be posted for road conditions to aid the driver in his road condition assessment. In addition Ludema notes that the tractive coefficient between the road and tire depends on temperature where temperatures above freezing result in less traction than those just below freezing due to the fact that a water film on the ice acts as a lubricant. Figure 4 shows a typical tire tractive coefficient dependence on road surface condition.

In their Utica test series Nelson and Fitch (Ref. 11) identify typical road/tire friction coefficients. Murphy et al., (Ref. 22) and Wilkins (Ref. 27) characterized road surfaces during vehicle testing. These values of road/tire friction coefficients are shown in Table 3.
Easton (Ref. 28) notes that, "qualitatively speaking, the various pavement conditions can be put in order of increasing stopping distances:

- dry concrete
- wet concrete
- packed snow
- rough granular ice
- glare ice (slipperiness increased with increased air temperature)."

Figure 5 shows how tire/road friction is reduced by road surface contamination such as dust or water. In addition it shows skid and slip number* values for critical slip and skid during normal tire operations such as braking and cornering.

Road geometry such as banks, curves, and hills is a function of road design. The literature does not deal with data on road geometry; however, average and maximum grades and radii for hills, banks, and curves could be established.

Environments

The environmental factors present in truck articulated vehicle handling include those induced by the driver such as steering and braking, those caused by the forces of nature, and finally those present due to the

*Skid number is the ratio of skid resistance to tire load times 100.

Table 3. Road Surface Data

<table>
<thead>
<tr>
<th>Type Surface</th>
<th>Conditions</th>
<th>Friction Coefficient</th>
<th>Comments</th>
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presence of man. The latter may include other vehicles as well as road obstructions.

Induced environments in the form of braking and maneuvers are related to the driver. This area presently is not quantitatively described; however, commonly encountered driving maneuvers include lane changes, double-lane changes, and cornering. These maneuvers combined with variations of braking and acceleration provide an infinite number of induced environmental possibilities. It has been noted in this paper that bounds on maneuvering could be established. It appears that an index based on time duration may be the key to characterizing maneuvers. For instance, results of this paper show that, independent of speed, it takes about 3 sec to perform a safe lane change maneuver.

The aerodynamic environment has interested articulated vehicle investigators from the point of view of wind resistance. The aerodynamic drag properties of the articulated vehicle are important because they influence braking and acceleration demand on the tires. Flynn and Kyropoulos (Ref. 29) note that at 60 MPH, rolling resistance and aerodynamic drag are equal and the reductions in drag (this was pursued from a point of view of power consumption) are as high as 37 percent where possible. They characterized the drag in terms of a drag coefficient (a function of Reynold's number), the aerodynamic dynamic pressure (function of air density and relative velocity), and the effective cross sectional area of the vehicle. Flynn and Kyropoulos provide extensive data for a Chevrolet tractor-semitrailer in terms of vehicle angle of attack.

Dugoff (Ref. 14) claims, "Experimental data indicate that the influence of Reynold's number on these coefficients (aerodynamic) is small provided the Reynold's number is high enough to ensure the development of a fully turbulent boundary layer."

Dugoff found that aerodynamic forces and moments affect the directional stability (stabilizing and destabilizing) of articulated vehicles through an analytical/experimental program with the vehicle traveling on a straight level road in still air. Scale model experimental data is given for aerodynamic forces and moments as a function of wind velocity direction.

Vehicle Geometry

The factors involving vehicle geometry and design that affect handling include:

- suspension system
- axle location
- fifth wheel location
- weight
- center of gravity location
- moment of inertia.

Figure 6 shows the commercial vehicle types based on axle arrangement as described by Petring (Ref. 30). This illustration shows single unit trucks, tractor single and double semitrailers, and truck-trailers with single and tandem axles.

Vehicle Control

The factors involved in articulated vehicle control are steering, brakes, fifth wheel damping devices, and tires. Steering factors manifest themselves in the phenomenon of
understeer-oversteer. For a vehicle subject to lateral acceleration or forces at the center of gravity, its yaw rate response to neutral steering determines whether it understeers or oversteers. Increasing yaw rate denotes oversteering, while decreasing yaw rate denotes understeering. Bergman (Ref. 31) notes that “The basic source of under-oversteer is a yawing moment produced by tire forces about the vertical axis through the vehicle center of gravity, which can be broken down into three components:

- yawing moment produced by tire aligning torques,
- yawing moment produced by tire aligning torques,
- yawing moment produced by fore and aft forces.”

The three sources are listed in their order of importance with the third source having little or no significance.

The location of the resultant lateral tire force with respect to the horizontal location of the center of gravity of the vehicle is the most important factor determining understeering or oversteering properties.

Lateral tire forces are produced by the slip angle and dynamic camber angle, and are modified by lateral and longitudinal weight transfer forces resulting from traction and braking application. The distribution of lateral tire forces can be changed by changing the distribution of slip angles and cornering force between front and rear tires, and also by changing wheel camber. The slip angle distribution is controlled by toe-change, rear axle steer, and compliance steer. Inflation pressure, dynamic wheel load, and power and braking applications are major factors controlling tire cornering forces.

Front and rear tire cornering force is not applied at the centerline of the wheel, the force is actually applied behind the centerline of the wheel. The moment produced by the tire cornering force about the vertical axis through the center of the wheel is defined as aligning torque. It is not difficult to see that the aligning torque at each tire tends to turn the vehicle in a direction away from the disturbing force, thus producing an understeering response.

Understeer produced by aligning torques is additive to the understeer produced by the yawing moment generated by a couple composed of the resultant lateral tire force and the disturbing lateral force.

The yawing moment generated by longitudinal forces such as tire rolling resistance, aerodynamic drag, traction, braking, and longitudinal inertia force produced during acceleration and braking is determined by the distance between the resultant force acting forward and the resultant force acting rearward, and is affected by vehicle roll and lateral weight transfer. The direction of this yawing moment can be different in various vehicles and also can change with a change of operating conditions.

Bergman (Ref. 31) notes that understeer-oversteer effects are produced by individual design factors including:

- rear axle roll-steer
- toe change
- camber change
- weight distribution
- lateral weight transfer
- power application
- tire tread change.

Bergman gives detailed descriptions of the mechanism for characterizing each of these factors.

Vehicle control through braking, like steering, is intimately involved with the tires. Since the function of braking is to control forward motion, many studies have been conducted on vehicle stopping distances. Recent work has been concerned with the effect of braking on vehicle directional stability where the tractive force must be controlled in order to avoid loss of tire side force. Therefore, many devices have been developed or are under development for the control of braking force.

The factors involved with braking in articulated vehicle handling include:
- brake pressure
- brake temperature
- brake response time
- brake equalization
- axle bounce.

A recent study on vehicle braking system performance by Murphy et al., (Ref. 22) notes that, “For tractor trailers tested, the average maximum deceleration, wheels unlocked, is 15.0 ft/sec² empty and 16.5 ft/sec² loaded, with performance empty increasing to 19.4 ft/sec² when wheels are locked.” From the same study Murphy et al., (Ref. 22) also note that, “The average maximum deceleration achieved (without wheel lock occurring) with the tested trucks is 15.5 ft/sec² in the empty condition and 17.0 ft/sec² in the loaded condition.” Nelson and Fitch (Ref. 11) noted in the Utica tests that 25 ft/sec² was the maximum practical deceleration attainable under ideal road and braking conditions. They also note that improved stopping distance was achieved by providing braking systems with smooth inner wall tubing with streamline fittings with relay and quick release valves to improve air transmission and decrease lag time. Double and triple combinations demonstrated stopping distances comparable to singles, the conclusion being that average axle weight is important.

On brake response time Murphy et al., (Ref. 22) note that the average response time for the rear tractor axle was 0.24 sec when testing in combination with a trailer and the average response time for the trailer axle was 0.28 sec at a pressure of 60 psi at each axle. Release times noted were 0.55 sec on the tractor and 0.79 sec on the semitrailer axle. Application and release times were considerably longer on the doubles combination. Many data are given in this report on articulated vehicle braking capability with advanced braking systems. A maximum deceleration of 19.8 ft/sec² was achieved with a lockup of three wheels on the trailer and 14.0 ft/sec² with no locked wheels. This condition is important to lateral directional dynamics of articulated vehicles.

Brake temperatures continuously change under operating conditions with a varying lining-to-drum coefficient of friction.

Brake equalization affects the lateral handling capabilities of an articulated vehicle. In an analytical study, Krauter and Bartel (Ref. 21) show through a nonlinear mathematical programming procedure that braking torques are nearly optimum if they are proportional to the instantaneous vertical loads on the tires.

Fifth wheel damping devices have been noted to be somewhat ineffective as factors in articulated vehicle handling due to (1) the lack of available torque, and (2) the fact that the side force demand is passed on to the steering. Basically the devices noted to date utilize the phenomena of coulomb and viscous damping. Actual damping values have not been published in the open literature.

The final and perhaps most important factor involved in articulated vehicle handling is the tires. Tires develop the necessary longitudinal and cornering forces to control the motion of the vehicle. The important factors in tire performance include:
- tire cornering force
- tire tractive force
- tire tractive-cornering force interaction.

Thus, in fact, the tires, brakes, steering, vehicle geometry, load, and suspension, and road surface all interact. Tires for articulated vehicles have not been well characterized and therefore little data exists on cornering and tractive force.

MODELING

Modeling is one of the central tasks in the study of dynamic systems. For road vehicles, it involves distribution of vehicle physical characteristics, road conditions, environmental influences, and related maneuver factors such as braking and steering. Decisions pertinent to the modeling tasks may enhance or constrain the results of the mathematical analyses and experimentation. Full scale models must be used for experimental verification of the mathematical analyses.

The mathematical model must be detailed enough to simulate the behavior of the system, and scrutinizingly exclude prediction of insignificant behavior; and, it must be only as mathematically complicated as needed. Models fall into two general classifications: those that determine local behavior such as stresses, strains, and deformations of the system; and those that determine global behavior such as forces, and accelerations at the centers of gravity of the system components. The latter type is important for vehicle handling studies.

Vehicles

Perhaps the most important consideration in beginning the mathematical development of the model is the selection of the coordinate system. The coordinate system used for articulated vehicle studies must allow description of the kinematical (vehicle motion) and kinetic (tire forces) nonlinearities and yet afford solutions. In this application, the use of coordinates which facilitate the problem solution by elimination of excess variables is necessary. The choice of coordinates are Eulerian angles for rotation and either Cartesian or curvilinear coordinates to describe the tractor translational behavior. Cartesian coordinates are convenient in Newtonian mechanics because they allow methodical formulation of the problem in state vector form. Much modeling insight on the relative merits of the contribution of vehicle yaw, roll, and pitch is contained in the work of E. C. Mikulcik (Ref. 15) who was first to generate a complete six degree of freedom description of the vehicle rigid bodies ending with a tractor semitrailer described by eight independent nonlinear equations involving the translational and angular motions of the tractor and yaw and pitch of the trailer. The truck is a special case involving only six independent nonlinear equations.

In actuality, Mikulcik’s (Ref. 15) work is truly an investigation in modeling because it shows the effects of linearization having formulated both the nonlinear and the linear problem and conducted companion parameter studies. His statement, “For steering input angles of 0.06 rad (\( \sim 3.4 \text{ deg} \)) and greater, the nonlinear response departs entirely from that of the linear model,” tells the sad story that complicated nonlinear models are a requirement in vehicle handling studies. Figure 7 after Mikulcik illustrates his statement; and, in fact shows an observation first made by Ellis that jackknifing is not possible without braking using a linear model. For instance, it is shown that for a single-trailer vehicle, linearization negates the effect of jackknifing without braking.

Mikulcik has shown theoretically that the magnitudes of vehicle angular motion for a given problem rank as follows:
- yaw
- roll
- pitch.

Roll angles were about one-half yaw angles and pitch angles were an order of magnitude less than yaw angles. These results have been verified experimentally by Eshleman (Ref. 32). However, it must be remembered that this is for a specific articulated vehicle with
given suspension systems; and, the use of softer suspensions can introduce greater roll and pitch angles. Similarly trucks with varied suspension systems will have the same relative angular motions.

Pitch and roll variables greatly increase the complexity of the articulated vehicle model; and, semistatic load transfer can be used at a savings in mathematical complexity for directional studies by redistributing tire normal loads. Tire normal load transfer is determined as a quasi-static function of the forward and lateral accelerations of the center of gravity of the unit vehicle. It is possible to simulate the major contributions of pitch (forward acceleration) and roll (lateral acceleration) without having to treat these motions as degrees of freedom.

The most recent improvements in articulated vehicle modeling are due to Krauter and Bartel (Ref. 21) with the upgrading of the Mikulcik model to include wheel rotation for each of the six wheels. Thus the wheels have rotational inertia and the angular speed of the wheel is a function of the torque produced by the wheel brake and the tire/road interface force. Krauter and Bartel use this to model the effect of braking performance on the directional dynamics of articulated vehicles.

TIRES

After the basic vehicle model, tires are of next importance, if a hierarchy need be established, in the mathematical modeling of articulated vehicles. Tires control cornering, braking, and tractive forces and, as the vehicle kinematics, are nonlinear functions. Even though truck tires have not been extensively characterized through experimentation, some nonlinear mathematical models do exist. Figure 8 shows typical tire data after Freudenstein (Ref. 33). The tire side force (lateral force or cornering force) is a function of side slip angle. Of course this data is for tires subject to zero longitudinal slip.

The brake/tractive forces create longitudinal slip between the tire and the road. Since tires normally function simultaneously in the braking and cornering modes of operation, some allocation is made between the two. In fact, Dugoff (Ref. 34) summarizes the situation aptly by stating: “The modern analyses of vehicle directional dynamics (in the absence of significant longitudinal traction) have revealed that the essence of dynamic performance is the interdependence of the applied

Figure 7. Linear and nonlinear comparison of yaw angle difference (15)

Figure 8. Typical truck tire cornering force data (33)
forces and moments and the kinematic variables of motion. It therefore appears clear that the accurate prediction of vehicle motions involving combined steering and braking requires the representation of tire force and moment components as explicit functions of both side and longitudinal slip.”

The Ellis formulation of the tire side force phenomenon has been used intensively in analytical studies. This formula, namely,

\[ F_s = \frac{3z \mu \alpha}{2 \alpha_m(z)} \left(1 - \frac{\alpha^2}{3 \alpha_m^2}\right) \]

where

- \( z \) = normal tire load
- \( \alpha \) = slip angle
- \( \alpha_m \) = slip angle at which maximum cornering force occurs; this factor is a linear function of the load
- \( \mu \) = tire-road friction,

was modified by Eshleman and Desai (Ref. 23) to allow variation of the angle at which the maximum side force occurs with normal tire load. Later the side force slip angle relationship was further modified by Eshleman (Ref. 32) to include a second order term in the slip angle. This model was motivated by experimental data by Brown (Refs. 35, 36).

A theoretical model on the interdependence of tire tractive and side force developed by Dugoff (Ref. 34) was correlated with the results of Holmes and Stone (Ref. 16). In view of previous use of the “friction circle theory,” a priori allocation of tractor force led Dugoff to comment: “This concept appears to be valid in a qualitative sense; it states that the total shear force vector cannot exceed the normal force times a prevailing friction coefficient. However, recent experimental data (Byrdsong (Ref. 13), Holmes and Stone (Ref. 16)) indicate that tire force predictions based on friction circle theories may be in considerable error. Moreover, the previous analyses have involved the assumption that the longitudinal traction component is a quantity imposed, a priori, to be accounted for in so far as it may effect the lateral traction component, but invariant with respect to the generalized trajectory of motion.” It was shown by Eshleman and Desai (Ref. 23) that Dugoff’s reasoning is borne out when the friction circle concept is inadequate for experimental/analytical correlation during hard braking maneuvers.

Ludema (Ref. 26) has another way of looking at the tire force interaction problem and suggests that, “The manner in which a tractive force may be developed, which is greater than the classical coefficient of friction times the normal load, is not yet well understood. In this article (see Figure 9), we shall refer to the ratio of horizontal force to normal force as the tractive coefficient rather than the coefficient of friction.” This concept alludes to the idea of a “gearing action” between tire and road prior to longitudinal slip. The interdependence of combined side and longitudinal slip on cornering and braking forces is well illustrated for automobile tires by Ludema. The loss of cornering force with increased braking force is shown. However, if the longitudinal slip is controlled at about one or two percent, then optimum cornering force and braking force are obtained.

Mathematically the tire side force and the tractive or braking force must be apportioned in simulation models. The “friction ellipse” concept described by McHenry (Ref. 37) provides a solution to this problem; however, this tire model like all others has not been experimentally verified. The concept appor-

![Figure 9. The interdependence of combined side and longitudinal slip on lateral and braking tire force](image-url)
tions tractive and side force such that the vectorial total of the allowable tire/road adhesive force must lie within the ellipse. However, tractive force is still given priority in the utilization of total available force (this procedure is subject to criticism by many users as previously noted). The tractive friction coefficient \( \mu_s \) governs the minor axis. Thus, if the maximum side force is \( \mu_s N \) (normal load), then the maximum tractive force is \( \mu_s N \rho_s \) where \( \rho_s = \mu_T / \mu_s \). For increased braking and/or tractive force the side force decreases until vanishing side force is obtained at maximum traction. Thus the combination of a side force, slip angle curve, and friction ellipse concept determines the availability of side force for all steering and braking situations.

**Steering-Brakes**

The modeling of the steering function in vehicles in general is important, albeit easily described. The steering angle alters the side slip angle at the steered wheels and thus directly affects the tire cornering force. Consequently, steering provides the necessary forces (through tire phenomenon) to provide vehicle directional control.

The effects of braking on the directional control of articulated vehicles has been studied extensively by Mikulcik (Ref. 15), Leucht (Ref. 19), Krauter and Bartel (Ref. 21), and Eshleman and Desai (Ref. 23). Mikulcik introduces braking at various wheels as a linear function of time forces of vehicles. The work of Leucht is concerned with brake distribution and braking efficiency in using the friction capability of the tire/road interface. He notes, "The spatial distribution of brake torque is a design parameter of the vehicle and is dependent upon the physical characteristics of the brake system components."

In theory, researchers such as Morse (Ref. 38) have tended to utilize a brake balance proportional to the normal load on the wheels. Morse noted that load transfer changed the static brake distribution. He argued that since vehicle stability is more likely to be a problem on wet pavement than on dry, it would be more reasonable to use dynamic axle loads at 0.3 g rather than static balance. Of course this whole question arises because it is desirable to obtain maximum tractive force without slip. Therefore, in directional dynamics, the whole question of allocation of tire force comes into play.

By means of the calculated deceleration vs. brakeline pressure relationship, he demonstrated the difference in braking characteristics between a vehicle whose brakes were statically balanced and one whose brakes were balanced at a 0.3 g dynamic load. Generally, dynamic balancing increased the front axle braking effectiveness and reduced the braking effectiveness on the trailer rear axle, while maintaining the braking effectiveness of the tractor rear axle. Morse (Ref. 38) further demonstrated that the use of load sensitive proportioning valves would improve brake balance even more. He suggested that improvement of pneumatic balance through elimination of pressure and time differentials, and uniform pushout pressures for all brakes on a given vehicle, would aid braking response, especially on low coefficient surfaces.

Krauter and Bartel (Ref. 21) modeled brakes in an articulated vehicle using wheel rotational degrees of freedom. Vehicle brake force was allocated according to the instantaneous wheel normal loading and proved to be the optimum distribution.

**Disturbances: Maneuvers and Aerodynamics**

Modeling of articulated vehicle disturbances that alter directional dynamic response will be restricted to maneuvers and aerodynamic effects. Chiesa and Rinonapoli (Ref. 39) describe three maneuvers that are of interest to articulated vehicle operational ability. The U test called for a rapid change from a circular to a straight path at a given speed. This maneuver illustrated the phenomena associated with the lateral flexibility of the tires. The E test consisted of a change from a straight to a circular path at a high speed. This maneuver was used to evaluate the rapidity of response of the vehicle tire assembly. The S test was the classic lane change maneuver used...
by Eshleman and Desai (Ref. 23). This maneuver illustrated some of the features of the preceding two maneuvers. The double lane change maneuver provided similar information without favoring right or left hand tire-vehicle characterization.

At present, however, models based on standard aerodynamic nomenclature do exist. In response to the direct need to know vehicle power capabilities, drag data is available for a number of vehicles. The articulated vehicle in an airstream provides a complicated problem because of its ability to alter direction, the interference effects between vehicles, and the basic complicated nature of turbulent fluid flow. Flynn and Kyropoulos (Ref. 29) conducted an extensive study of truck aerodynamics, the determination of factors that reduce drag being the primary concern in their work. Of course drag data are needed in complete articulated vehicle studies because track tractive power and braking are involved. Their model, used in this work, characterized the total vehicle in terms of lift, drag, and side force coefficients, and pitching yaw and rolling moment coefficients. The values of the coefficients are a function of the dynamic pressure* on the vehicle, the effective cross-sectional area and the Reynolds number. Usually vehicles are operational at Reynolds numbers associated with turbulent flow.

Dugoff (Ref. 14) has investigated the influence of motion-variable-dependent aerodynamic forces and moments on the dynamic stability of a simply articulated vehicle traveling in still air. It was found that the forces and moments arising from aerodynamic side slip, aerodynamic damping, and aerodynamic resistance all may exert appreciable influence on both oscillatory and nonoscillatory stability. Furthermore, the aerodynamic effects can and have either a stabilizing or destabilizing influence, depending upon the design and operating characteristics of the vehicle. Dugoff recommended additional study of the influence of aerodynamic effects on articulated vehicle dynamics, particularly of time-varying effects at high angles of wind attack and under nonuniform flow conditions.

**MATHEMATICAL ANALYSIS**

The evaluation of articulated vehicle models utilizing modern mathematical techniques has come to fruition in the last ten years. The main reasons why this problem has not been studied more effectively in the past are because of the nonlinearity of the problem and the unavailability of methods to solve these formulations in closed form. Hence, early linearized models were used to solve stability problems in the classical sense. It is interesting to note that in the field of road vehicle dynamics, available mathematical computational techniques governed the modeling of the vehicle. There is some doubt as to the value of early work, particularly for studies of vehicle stability where highly nonlinear tire characteristics were linearized. To date, nonlinear mathematical analyses of vehicle handling problems have been conducted through the use of direct integration of the system equations of motion.

Mikulcik (Ref. 15) developed a comprehensive digital simulation of a three-axle simply articulated vehicle. The studies of Mikulcik show detailed work in varying many articulated vehicle parameters. His comparison of linear and nonlinear models is an undeniable contribution to the understanding of articulated vehicle dynamic modeling. Mikulcik showed the following nonlinear responses as functions of time:

- Tractor yaw angle rate
- Semitrailer yaw rate
- Yaw angle difference
- Tractor side velocity
- Tractor roll angle

for step-steering and braking inputs. The friction circle concept was used to allocate tire side forces. Jackknifing caused by maneuvering and braking was discussed in detail. Steering and gradual (linear) braking inputs were applied at the rear tractor axle, front tractor axle, and semitrailer axle. Maneuvera-
bility, jackknifing, and trailer swing were discussed for each of these braking modes and although space does not permit presentation of this material herein, it is highly recommended informative reading. Mikulcik's extensive analysis concludes with an analysis of fifth wheel damping including viscous, coulomb, and velocity squared damping devices.

In conclusion, the words of Mikulcik describe this articulated vehicle simulation model perfectly: "The results (his study) have demonstrated the occurrence of jackknifing with a nonlinear model of a tractor-semitrailer vehicle both with and without the application of brake forces. The linearized vehicle was stable, hence equations which have been linearized about the vehicle's equilibrium position are not applicable to jackknifing studies." (Ref. 15)

In an independent study, Leucht (Ref. 19), mechanized a hybrid simulation of the articulated vehicle model; however, this model is not as comprehensive as Mikulcik's. The simulation was exercised to examine the influence of brake system design variables on the directional response of a tractor semitrailer, while turning with a fixed steering wheel, to brake applications of various forms. Considerable potential for improvement in performance through the utilization of static load-proportioning schemes was demonstrated.

Leucht used the 0.3 g as a baseline brake-torque distribution to a fully loaded vehicle at a deceleration of 0.3 g from which he makes two conclusions, quoted, "Longitudinal and lateral brake-torque variations from a baseline distribution had the overall effect of decreasing the performance of the vehicle in a combined steering and braking maneuver without any wheel locking. The overall braking efficiency of a partially loaded or empty vehicle can be improved by load-sensitive brake torque control." (Ref. 19)

Krauter and Bartel (Ref. 21) used an improved Mikulcik model (wheel rotation added and friction ellipse concept) and optimization techniques to evaluate a proportional braking procedure for an articulated vehicle. The problem studied was to determine the effect of proportional braking on lateral stability; the lateral motion being caused by lateral brake unbalance. Proportional braking is governed by brake torque distribution among the axles in proportion to the instantaneous load transfer. The design objective was to minimize the lateral instability of the vehicle. The lateral kinetic energy was selected as the objective function for the optimization.

They found that ideal proportional braking is optimal and therefore is a desirable design goal; consequently, more or less total braking compared to the optimum calculated value decreases lateral stability.

This is a sophisticated analysis and this statement from Krauter and Bartel summarizes the situation: "The results (also) show that the computational details associated with these techniques are very important if the combination (simulation and optimization) is to be successful." (Ref. 21)

Susemihl (Ref. 25) has modified the normal integration process to find vehicle stability by using the Routh stability criteria to check locally linearized equations of motion of the system. The results of this method indicate that the impending state of jackknifing can be predicted. No experimental verification of this technique has been offered.

An inverse approach to the solution of vehicle handling problems, shown schematically in Figure 10, was developed by Scope-lite (Ref. 18). A prescribed maneuver such as lane changing or cornering that a driver of a vehicle is commonly called upon to perform on the highway serves as input data. The nonlinear mathematical model reflects physical characteristics of the vehicle, the road, and the environment. The mathematical model yields the driver control requirements, information on nonprescribed vehicle response and information on its stability for the prescribed maneuver. A modified version of the articulated vehicle dynamic simulation, AVDS II computer program developed by IITRI (Ref. 23) for NHTSA can be used to
determine physical stability (based on tire slip and angles and yaw-angles) or vehicle response of tractor-single and double semitrailers.

A semi-inverse computational method that determines driver steering and braking demands and vehicle responses for given tire characteristics and a prescribed vehicle trajectory is integral to AVDS II. Experimental validation (Ref. 23) was accomplished by direct comparison, on a time basis, of simulation results with measurements from full scale tractor semitrailer field tests. The actual trajectories performed by the test vehicle were used as input data for the simulation model yielding a firm basis for one to one data correlation.

The semi-inverse method of computation used in AVDS II provides a measure of vehicle performance and driver demand for commonly encountered road maneuvers such as cornering and lane changes. The following parameters involving the vehicle and its environment can be evaluated:

- road maneuvers including lane changes, corners, banks and grades
- braking/traction
- vehicle suspension geometry and loading
- tire/road interface
- aerodynamics, and
- fifth wheel damping devices.

Figure 11 shows results typical to the AVDS model compared to experimental results. A tractor semitrailer performed a lane change maneuver at 50 MPH with hard braking. Note that the motions of the tractor center of gravity are input data; and, the steering (control) obtained from the experimental results is compared to that predicted by analysis. In addition, experimentally and analytically obtained vehicle yaw angles are also compared.

**EXPERIMENTATION**

Because of the equipment, instrumentation, and time required, there has been little experimental work conducted on trucks and articulated vehicles. To date full scale tractor semitrailer handling tests have been conducted to verify and develop mathematical models, to develop and evaluate brake systems, to obtain safe handling limits and to develop test procedures.

**Techniques**

Vehicle maneuverability was assessed by Eshleman and Desai (Ref. 23) through the use of tests involving lane change maneuvers at constant speed and with braking. Vehicle trajectory tests were utilized because of their direct similarity to the natural environment of the vehicle. During the tests, the vehicle
trajectory, marked by a washable die, was recorded along with vehicle response including accelerations, velocities, yaw angles and steering angles. Brake application was monitored through the brake electrical circuits. The test response values, plotted as a function of time, were used to verify the AVDS simulation model results when the actual vehicle trajectory data was used as input data to the simulation model. Figure 12 shows the vehicle handling philosophy developed by IITRI for NHTSA. The results of the test program are used as direct inputs to the AVDS simulation model. Experimentally and analytically obtained controls and unprescribed responses are compared to provide a basis for simulation model refinement.

Techniques used to date by other investigators have been based on known control inputs rather than prescribed vehicle maneuvers. The prescribed control inputs are intended to simulate cornering, lane changing and other pertinent vehicle maneuvers.

**Significant Investigations**

An experimental study of the lateral dynamic stability of a multiarticulated vehicle was conducted by Dugoff and Parekh (Ref. 40). These investigators suggest a possible explanation for the scarcity of said experimental data by emphasizing the inherent risk of injury and/or property damage associated with such experiments. The principal purpose of their study was to evaluate the feasibility of a vehicle configuration comprised of four self-powered units. A cursory investigation was also made of the influence of various

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**Figure 11.** The response of an articulated vehicle performing a lane changing maneuver at 50 MPH

**Figure 12.** Analytical-experimental correlation of vehicle handling data
characterizing parameters on the stability of the vehicle, and it was recommended that additional theoretical work be performed to obtain analytical predictions for comparison with the experimental results.

As mentioned, the earliest documented experimental research on the directional dynamics of articulated highway vehicles was performed in 1937 by Huber and Dietz (Ref. 1). The study was specifically concerned with the dynamic stability of straight-running vehicle configurations having full (as opposed to semi) two-axle trailers with either wagon or Ackerman steering.

The investigation consisted primarily of scale model tests on an endless moving belt, supported by “satisfactory correlation,” with a limited full-scale test program. Trailer models were constrained laterally by springs attached at the forward end of the towbar. The motions of the model hitch, so constrained, showed small deviations from those of the full scale trailer hitch attached to a tractor; however, according to the authors, the fundamental consistency of the results was not affected by this discrepancy.

The principal conclusion reached was that trailer yaw oscillations could be most effectively suppressed by the introduction of kingpin damping. Other measures found to reduce oscillations included elimination of play in steering mechanisms and towbar joints, lengthening of towbar and/or wheelbase, and the application of moderate levels of braking effort at the trailer only.

The authors point out that the effectiveness of trailer brake application in reducing instability is limited to the “nonskid range” (more properly, that region of longitudinal tire slip wherein tire cornering forces are not significantly reduced from rolling values). More recent research—and practical experience—indicates that application of trailer brakes at levels that produce trailer wheel locking has a dramatically deleterious effect on the vehicle stability.

Bode and Görge (Ref. 41) tested articulated vehicles in 1961. Although they were concerned mainly with developing test procedures, results of their experimental work reinforced many of the conclusions of their theoretical analysis. Values were found for brake actuator pressure buildup time, response delay, and force buildup time. Factors contributing to these times and delays were discussed, along with their effect on forces at the coupling pin. Tests were conducted using both a single axle and a tandem axle trailer. One of the major considerations in these tests was to determine the influence of proportional braking on performance. This work probably represents the greatest single contribution to the study of tractor trailer braking.

Experimental work on synchronizing brake response and minimizing time lags has been reported. Both Underhill (Ref. 42) and Sido (Ref. 43) used brake system mockups closely resembling the vehicle brake system to obtain their results; whereas Guevara (Ref. 44) performed response tests on actual vehicles.

The objective of the well-known Utica tests reported by Nelson and Fitch (Ref. 11) was to demonstrate that longer truck combinations (double 40's and triple 27's), when employing properly maintained equipment in current use, could achieve braking, stability, and structural characteristics comparable with shorter combinations. The double and triple units were made up of two 4 x 2 and two 6 x 4 tractors equipped with diesel engines, seven 27 ft single-axle and two tandem-axle dollies.

The test program consisted of the following:

1. Brake actuation and release timing tests (both bench tests and vehicle tests)
2. Torque balancing according to SAE J880 procedure
3. Vehicle brake rating tests
4. Braking performance tests
5. Stopping distance tests
6. Directional stability tests
7. Structural integrity tests.

The vans were tested at no load, half-load and full-load using waste paper bales of approximately 1500 lbs. as ballast. The tests demon-
strated that obtaining the desired results necessitated some modifications of the braking system on the vehicles, as received, including the use of smooth inner wall tubing with streamline fittings, addition of relay and quick release valves, and, in certain cases, the use of load-sensitive proportioning valves. Placement of trailers in sequence to require heavier trailers ahead of lighter trailers improved directional stability.

In a series of tests conducted by Kibbee (Ref. 45) and the State of Virginia (Ref. 46), the braking performance of a five-axle tractor semitrailer was compared to a five-axle tractor double-trailer combination. In straight-ahead stops on wet and dry pavement, with the vehicles fully loaded, half-loaded, and empty, nearly equivalent performance was demonstrated over a range of speeds of 20 to 55 MPH, with the vehicles capable of achieving average decelerations as high as 17 ft/sec². This study demonstrated, as did the Utica tests, that reasonably good braking performance can be achieved by multiarticulated vehicles if appropriate attention is paid to maintenance of the brake system, adjustment of the brakes, and proper brake balance.

Experimental verification tests were conducted by IITRI (Ref. 23) for NHTSA on a dry jennite sealer covered skid pad at the Bendix Automotive Development Center with a Diamond Reo single-axle tractor and Fruehauf 40 ft sliding double-axle flat bed trailer as the test vehicle. Tests were made at speeds ranging from 20 to 50 MPH with and without braking at varied lengths and widths. In the beginning of the test series, two pylons were used to indicate the length of the maneuver to the driver. In later tests, the driver was instructed to make a lane change as fast as safety would permit. As shown in Figure 12, the trajectory actually marked on the skid pad was used as input data to the AVDS model.

It was interesting to note how the driver steers to make a lane change maneuver and to compare it against the mode of steering suggested by the computer simulations. It is apparent from test results that the driver follows the most efficient mode of steering with the steering angle approximating a sine wave. It can be noted, however, that near the end of the maneuver the driver gradually steers the vehicle to reduce tractor-trailer yaw whereas the computer reduces tractor-trailer yaw in a shorter time frame by oversteering (see Figure 13). In the results shown here, the driver performed the maneuver similar to the computer prediction.

APPLICATIONS

The application of vehicle handling safety technology to the design of vehicles, to the evaluation of safety related controls, and to the development of safe operational limits is in its infant stages. The recent and continuing development of confidence in simulation models will provide the necessary tools for routine evaluation of equipment, roads and drivers.

Safety Related Controls

The problems of handling and maneuverability of trucks and articulated vehicles in normal traffic have motivated the design of several braking and articulated motion control devices. The characteristics of these are reviewed with respect to the handling safety aspects of trucks and articulated vehicles. Jackknifing results with or without the presence of braking forces when side force is lost at the tractor rear wheels. Jackknifing without braking is caused by severe maneuver demands on tire side force which is determined by the road, tires, and normal loads. Mikulčík notes that, "The load should be placed in the semitrailer so that the rear

![Figure 13. Comparison of typical driver performance to computer simulations](image-url)
tractor tires carry a maximum amount of weight.” (Ref. 15) When jackknifing occurs with braking, the loss of tire side force is due to longitudinal slip while braking.

Available jackknifing prevention devices are of two types:

- those which introduce fifth wheel damping
- those which aim to prevent skid of the rear tractor and semitrailer wheels.

The following statement by Mikulcik reflects the view of this paper: “The results of the work indicate that devices which attempt to prevent skidding of the wheels are truly prevention devices, while those which employ fifth wheel damping do not prevent jack- knifing, but rather they attempt to control it if and when it occurs.” (Ref. 15) In this and other studies it has been found that the fifth wheel device does not help the fundamental cause of jackknifing or trailer swing, namely, the loss of tire side force. The fifth wheel antijackknifing device merely locks the articulated vehicle (if it does anything) and passes the side force demand on to other tires—usually the front tractor tires causing unattainable steering demands.

The available fifth wheel devices which work toward the goal of controlling jackknifing (as long as side force demands do not exceed availability) are numerous. Rather than go into specific commercial devices, the fifth wheel dampers will be discussed from a phenomenolized or conceptional view. Whether the device be associated with viscous, coulomb, or velocity squared damping, the useful amount of damping must be high during jackknifing and low during normal driving.

Viscous damping (rate dependent) approaches the mentioned requirements without need for instantaneous activation. Mikulcik claims that it would be difficult to build an effective compact viscous damper: “For example, the viscous damping constant between two circular plates having a radius of 1 ft and separated by a 1/16 in. film of SAE 70 oil at 75°F is only 11 lb-ft/rad/sec.” (Ref. 15) He shows that viscous damping coefficients of the order $10^6$ lb-ft/sec/rad are needed. In fact, one can take an example of a trailer at 0.2 g (a modest amount) side acceleration. Loss of side force at the trailer wheels would require 80,000 lb-ft/rad moment at the kingpin for a 20,000 lb. trailer with the center of gravity at 20 ft.

A multidisk brake providing a large amount of coulomb damping is compact and shows promise; however, activation is needed either independently or by braking. Braking makes little sense because of the many situations where loss of articulation is undesirable. Nonlinear damping devices such as velocity squared phenomena have advantages because self-activation increases as needed, or, high articulation rate automatically increases force as required. However, this fails to eliminate the fact that side force must be generated in some manner somewhere on the vehicle.

As Ludema notes: “It appears that the only way to optimize braking and lateral control is to devise braking control systems for vehicles. Such devices would operate from several complex inputs, some of which are not yet available. Current braking control devices operate only to prevent wheel locking and they are often called ‘antiskid’ devices. Current designs are fairly good at minimizing stopping distance on medium-friction surfaces, with good directional control. However, they often compromise braking performance while cornering, or stopping distance on ice, or stopping distance on dry surfaces, or combinations of these. Where the antiskid braking device is designed to seek out the maximum braking force, it is apparent from Figure 9 that for a side slip angle of 16 deg the device would settle upon $S = 0.15$. Anti-skid devices must not completely avoid wheel lockup because then complete stopping of a vehicle would not be possible.

“In the meantime, a popular substitute for the antiskid braking system is pumping the brakes. This has been successfully done by many drivers on ice. However, normal human reaction times are apparently not fast enough to significantly shorten stopping distance on
high traction surfaces by pumping brakes.” (Ref. 26)

Although development of antiwheel-locking systems for use on trucks and articulated vehicles has been in progress for several years, there is a dearth of published reports of tests using such systems installed. Wilkins (Ref. 27) reported on the Dunlop maxaret system and with the device fitted to the rear tractor wheels of an articulated vehicle, Wilkins found that jackknifing did not occur in straightline braking of an unladen vehicle from 30 and 40 MPH on four different road surfaces (including low coefficient surfaces). When the same maneuvers were repeated with the device inoperative, jackknifing did occur. Jackknifing occurred only on the slippery surface with the device inoperative with a loaded vehicle, but did not occur with the device in use. Generally, stopping distances were shortened by use of the device on slippery surfaces but were the same or slightly longer on dry surfaces.

Haviland (Ref. 47) reported on the development of the Jacobs mechanical system. The results of tests with this device were similar to those of Wilkins, except that Haviland reported that the use of the device drastically reduced the wheel hop problem during severe braking. Chinn and Wilkins (Ref. 48) conducted tests using an electronic antilock device fitted to the rear tractor axle of an articulated vehicle. Significant improvement in vehicle stability was noted for braking from several speeds on a variety of surfaces.

Latvala and Morse (Ref. 49) recently reported the development of an adaptive antilock braking system especially designed for airbraked vehicles. Whereas some of the other antilock systems control both wheels on an axle with a single controller, this system has a sensor and controller mounted on each wheel, including the tractor front wheels. Thus braking stability is improved on a wide variety of surfaces and steerability is also maintained.

The relative cost and performance trade-offs for a wheel-by-wheel system, as opposed to an axle-by-axle system, and other possible configurations were discussed by Yarber and Airheart (Ref. 50). Using a two axle vehicle (a bus) as an example, they concluded that the best overall stability and performance can be achieved with a wheel-by-wheel system, but at the greatest cost. A rear-axle-only system would prevent instability due to rear wheel lockup at minimum cost. A good compromise seems to be individual front wheel control, which would maintain steerability, and a single rear-axle control, which would maintain vehicle stability.

Operational Limits

Stability and handling limits for trucks and articulated vehicles have not been extensively developed to date. Figure 14 shows an example of a stability limit curve generated by IITRI (Ref. 32) for NHTSA. This stability boundary represents a theoretical upper limit for tractor semitrailer operation in a 75 ft radius corner on varied road surface conditions. The results of one cornering experiment are shown on this limit curve.

CONCLUSIONS AND RECOMMENDATIONS

This review of handling safety problems of trucks and articulated vehicles shows that significant advances have been made on the analysis of articulated vehicle response in combined braking and cornering through the use of nonlinear models and advanced computational techniques. However, while the theoretical base is rather complete except for tire models, there is a lack of depth in comple-

![Figure 14. Articulated vehicle limit velocity as a function of tire/road interface](image)
mentary experimental work on articulated vehicle response.

The experimental verification of the AVDS computer program developed by Eshleman and Desai (Ref. 23) shows that the dynamic response of articulated vehicles can be predicted on the digital computer. In addition, the trajectory method allows the determination of driver, braking, and tire demands to make a prescribed maneuver.

The tires, brakes, and aerodynamic forces are of primary importance in any ranking of the factors that affect articulated vehicle handling including jackknifing. The interaction of tire tractive/braking and cornering force combined with the road surface condition is the central phenomenon governing the potential for vehicle instability. From the results of this survey it can be concluded that antilock braking devices that control longitudinal tire slip and thus avoid loss of cornering force are more effective in preventing jackknifing than fifth wheel devices. Fifth wheel antijackknifing devices may control trailer swing and delay the loss of stability; however, they merely pass on the demand for cornering force to the tractor tires, thus moving the burden to another point in the vehicle rather than controlling it.

It can be concluded that experimentally determined tire data would provide better correlation between experimental and simulation models. Both the AVDS (Ref. 23) and the Mikulcik (Ref. 15) models indicated that tires in reality generate more cornering force than the Ellis model. This fact was later verified by Eshleman (Ref. 32) through the examination of experimental data on tire side forces. It was concluded by Eshleman and Desai (Ref. 23) that the “friction ellipse” concept yields better traction/braking and cornering force interaction simulation than the “friction circle” concept.

The parameter variation studies conducted by Eshleman and Desai (Ref. 23) led to the conclusion that double-articulated vehicles are not subject to catastrophic jackknifing during severe maneuvers but large trailer swing precludes the safe execution of such maneuvers. In fact, the studies show the double-articulated vehicle to be almost as stable as the single. However, the double-articulated vehicle requires longer maneuver space and time than that required for the single. Therefore, trailer swing must be considered the criterion for safety in double-articulated vehicles.

In the same study it was concluded that severe braking and traction during maneuvers imposes greater demands on the articulated vehicle operator by requiring rapid multisteering cycles during a maneuver. In addition braking and traction decrease available tire cornering force which leaves the vehicle subject to a loss of stability. Aerodynamic effects impose more demand on steering in some cases and less demand in others, depending on wind direction. Increased load and a higher center of gravity increase steering demand (greater side force generation is required) thereby imposing greater demands on the tires. Loaded double-articulated vehicles tend to be less than stable than unloaded vehicles and require greater maneuvering distance. Holding weight constant and the variation of trailer moment of inertia show little variation in vehicle response. Finally the variation of fifth wheel location from the tractor center of gravity showed that this design factor is important for the improvement of articulated vehicle maneuverability.

Realistic safety standards and specifications for articulated vehicles can be established; however, further work is needed to study, in depth, the factors that affect articulated vehicle handling.

Recommendations for further work on articulated vehicle handling resulting from the findings of this survey involve the operator, the vehicle, and the highway. It is recommended that in-depth, stability and response studies in articulated vehicle dynamics be continued to evaluate the stability and maneuverability of trucks and articulated vehicles in normal traffic flow. The parameters of road design including surfaces, curves, grades and banks should be evaluated in response studies. Stability analyses should be
conducted to determine articulated vehicle stability limits and to identify sources of catastrophic jackknifing. The results of these studies should enable the formulation of realistic safety specifications and standards for trucks and articulated vehicles.

Even though the models of trucks and articulated vehicles are sufficiently comprehensive for the prediction of gross vehicle response, effort should be expended to determine the sensitivity of the response to modeling assumptions. This would involve formulating the problem in terms of more degrees of freedom and determining the effect of governing parameters on the response. Areas most likely to show fruitful investigation are the suspension system, wheels, tandem axles, fifth wheel hitch points in doubles, and the tires. The vertical suspension system properties involve the forward or lateral load transfer from wheel to wheel caused by maneuvering, aerodynamic forces, and braking forces. The lateral suspension system properties include lateral, forward and yawing motions of the vehicle, particularly in softly supported vehicles such as moving vans. The ability to model tandem axles would provide better prediction of tire cornering force on the sprung mass of the vehicle.

The assumptions made in fifth wheel connection and hitch point connections, particularly as they affect the transmission of forces and moments to other parts of the vehicle, should be critically examined. Wheel rotation degrees of freedom are involved in direct study of the dynamic implementation of braking systems, particularly antilock systems. Phenomena such as brake fade and how it affects articulated vehicle handling should be studied. Without a doubt, tires show the most pressing need for effort on modeling. A longitudinal/lateral force model that predicts the tractive acceleration/cornering force interaction for tractor semitrailer tires should be developed. This will in all probability involve curve fitting of empirical data. The model would be characterized for tires of typical size and construction with varied road surface, temperature, and velocity effects included. Curve fitting or computer identification schemes may have to be utilized for individual tires under specified conditions.

In view of the control and maneuverability problems confronting the driver of trucks and articulated vehicles, studies should be undertaken on the demands on driver skill, measured in terms of potential loss of control and in the context of the vehicle operating over its full range of environments and design configurations.

Experimental work should be utilized to verify the overall dynamic response and stability of trucks and single-, double- and triple-articulated vehicles. The experimental results of this program should be used with actual tire data to verify the Mukulcik (Ref. 15) model for both trucks (as a special case of the tractor semitrailers) and tractor semitrailers. In addition, this response model should be extended to triples. In this manner, both direct response and semi-inverse (AVDS) models would be available for vehicle evaluation. The experimental generation of tire characteristics should be pursued whether it be accomplished indirectly with a special test fixture, directly from an articulated vehicle, or from analytical/experimental parameter identification studies. Actually, the test data obtained in the present program could be used with the AVDS II or Mikulcik model to determine tire characteristics for the particular tires and operating conditions of this program.

Further work is required on the characterization of aerodynamic effects, including the effects of steady wind and gusts on articulated vehicle response, and the interaction of these vehicles with other road vehicles. Aerodynamic constants associated with lateral and forward rectilinear motions and roll, pitch, and yaw angular motions require further study. In addition, the interaction effects of articulated vehicle units or the total characterization of the vehicle is required.

Roads should be characterized to facilitate study of the potential maneuverability conditions to be encountered by drivers of articulated vehicles. This characterization
should include tire/road interaction for specific road surfaces, road conditions (oil, ice, water, dust), and geometry (hills, banks and curves).

References


MODELING AND SIMULATION IN VEHICLE HANDLING RESEARCH

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ABSTRACT

Controlled experiments of mechanical and electronic systems are required in order to evaluate the behavior of the system and to substantiate the attainment of the original specifications and qualities designed into the system. As these systems become more complex, and thus more expensive, the engineer's ability to reliably and repeatably perform experiments becomes more difficult. Increasingly, the expense of experimentation is dictating the experimenter's schedule rather than the availability of the system requiring experimentation.

Passenger carrying vehicles, such as automobiles and buses, currently are included in the class of systems for which the cost of experimentation limits the number of experiments performed. An acceptable alternative to experimentation is the development of a vehicle simulation on which experiments can be performed.

This paper discusses the currently available vehicle simulations applicable to handling studies. Specifically discussed are 1) the type of handling experiments which can be performed, 2) availability of these simulations, and 3) what data is required in order to make a simulation represent a specific vehicle.

SUMMARY

This paper contains information and references describing the currently available capabilities for modeling and simulation in vehicle handling research. The following topics are discussed:

- Advantages of simulation for vehicle handling studies
- History of vehicle handling simulations
- Currently available vehicle handling simulation programs
- Required simulation data
- Need and method of model verification
- Extension of vehicle handling knowledge using a validated simulation.

The NHTSA hybrid computer simulation for vehicle handling studies, operational at the Applied Physics Laboratory of the Johns Hopkins University (APL/JHU), is highlighted. Sample transient responses from this simulation for computer runs with braking and steering inputs are presented. Also included is a bibliography of recently developed vehicle models and simulations.

INTRODUCTION

Controlled laboratory and field experiments of any mechanical and electronic system are required in order to evaluate the behavior of the system and to substantiate the attainment of the original specifications and qualities designed into the system. As these systems become more complex and more expensive, it is more difficult to reliably and repeatably perform these experiments. Increasingly, the expense of experimentation has become a dominating factor for determining the type and amount of experiments to be performed for a large class of systems.

Passenger carrying vehicles, such as automobiles and buses, currently are included in
such a class of systems. An acceptable alternative is the development of a vehicle simulation program through which experiments can be performed in a computer.

The general motivation for vehicle experimentation and subsequent modeling and simulation has been to determine safety-relevant performance qualities for passenger carrying vehicles. To this end, the National Highway Traffic Safety Administration (NHTSA) and its predecessors, the National Highway Safety Bureau (NHSB) and earlier, the Bureau of Public Roads, have funded vehicle handling studies. These studies have combined full-scale vehicle testing with model building and simulation. The research has progressed through the stages of general vehicle modeling, development of standard vehicle maneuvers for measuring safety related aspects of vehicle dynamic performance, and detailed investigations of the effects of variations in vehicle subsystems (suspension, steering, tires, etc.) on handling performance. Each stage of modeling and simulation has been validated by laboratory testing. For comparison of handling qualities in the subsystem investigations, the same standard vehicle maneuvers are used for most testing. This provides a common data base for comparison between various vehicles as well as subsystem configurations.

The ultimate goal, when all subsystems have been modeled, is the availability of a collection of simulations that may be used to evaluate the handling qualities of many vehicles, particularly in relation to vehicle safety investigations using only minimal full-scale testing. Also, parameter variations on system inputs could yield useful trends for setting vehicle standards and safety inspection criteria.

**MOTIVATION**

The reason for modeling* and simulation,* which immediately comes to mind is that computer experiments are less expensive, more convenient, not affected by the environment, and repeatable. These reasons are well discussed in the literature and are more or less self-evident. There are two other motivations of perhaps equal importance.

First, modeling and simulation activities force a thorough examination of a physical problem. The modeling activity yields a thought process unsurpassed for gaining insight into physical, economic, and other phenomena. Such insight aids the interpretation of real-world data. Once a system is modeled, the simulation activity prompts parameter and initial condition questions and provides feedback to modify the understanding of the phenomena. Assuming correct implementation, agreement between simulated system response and the projected system response provides positive reinforcement to system understanding. If the responses do not correspond, it would indicate a lack of system understanding or a deficiency in the model. In either case, the system and/or the model need to be re-examined. This feedback mechanism continues as sensitivity* studies are performed on system parameters and initial conditions until an adequate system understanding and model are achieved.

Thus, it is for the two reasons just described that modeling and simulation are necessary activities in an engineering investigation when the complete system performance and test data are to be understood, reasonably well validated, and adequately documented to enable an independent verification of results and conclusions by others. It can be said that without modeling and simulation, engineering activities are incomplete.**

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*By sensitivity it is meant the comparison of amounts of variation in output parameters relative to changes of model coefficients and possible other parameters. This provides an indication of how much care must be taken in certain areas of the model to provide correct, detailed, precise, and accurate analysis. In a validated model it provides an indication of what external and internal parameters are of most importance to system performance.

**Occasionally the reduced model is in a linear form that yields an analytic solution. In such cases, the simulation part of the activity may be unnecessary.
HISTORICAL REVIEW

The modeling activity is the older of the two activities of modeling and simulation, since computers—a later development—were required for most simulations to become practical. Models related to vehicle handling generated prior to the advent of computers generally concentrated on vehicle subsystems (steering, suspension, braking, etc.) and were simplified and linearized to yield analytic solutions. The first computers that appeared on the scene were analog computers. Although these machines were cumbersome to use, they did provide a means for solving medium-sized, non-linear models. The digital computer was the next available computational device. The size of models that could be solved was primarily limited by digital resources, usually core storage; however, solutions to fairly large non-linear simulations are within the capability of the state-of-the-art. Reference 1 provides an extensive list of earlier references in which analog and digital computers have been employed successfully in the study of ride, handling, and vehicle stability. These references have been augmented by more recent works (Refs. 2-11 for analog simulations with Refs. 12-27 for digital simulations).

In recent years there has come into use the hybrid computing system (Ref. 1), which combines the advantages of both analog and digital computers while eliminating some of the disadvantages when either working individually, see Table 1. The hybrid computer consists of an analog computer and a digital computer connected via data and control interfaces. The data interface allows information (data) communication between the computers so that both machines can simultaneously contribute to the simulation solution. The control interface allows the digital computer to control the analog computer which greatly reduces the awkwardness of analog computation. Examples of hybrid vehicle handling simulations are presented in Refs. 28-31.

Large hybrid computers require an extensive investment in manpower (maintenance, software, and applications) as well as computer hardware. For these reasons, hybrid system installations are distributed mainly among large corporations, engineering and research centers, and government facilities which can generate multiple-use requirements. Small engineering companies cannot generally afford hybrid systems (except via subcontract) and must rely on "stand-alone" analog computer simulation and/or digital computations. Used vacuum tube analog computers are inexpensive and time sharing service bureaus make digital computation available to engineering companies at a minimum of investment. Because it is more accessible, all digital simulation will probably remain important in vehicle handling research.

CURRENT STATUS OF SIMULATIONS

The recent trend in vehicle handling simulations has been towards the use of the hybrid computer; however, all digital simulations are still extensively used. This trend toward hybrid computation may be due to the availability of a detailed (17 degree-of-freedom) hybrid vehicle handling simulation which is moderately inexpensive to run ($.50/1.0 sec of real-time simulation). This simulation is documented in Refs. 28, 30, and 31 and its application to vehicle handling studies is documented in Refs. 27, 28, 30, and 33. Table 2 is a listing of current NHTSA contractors engaged in vehicle handling research, the type of simulation each uses, and an indication of their available computing facilities.

The simulations described in Refs. 24, 26, 27, 28, 29, 30, 31, and 33 are derived from a model defined by McHenry and DeLeys in a Cornell Aeronautical Laboratories Report (Ref. 19). Ref. 24 is their own adaptation of the model of Ref. 19 to vehicle handling. These references provide excellent background information on vehicle handling models. The purpose of all the vehicle handling models and simulations is the prediction of vehicle handling transient and steady state response to braking, drive torque, and steering inputs.
Table 1. Advantages and Disadvantages of Analog, Digital and Hybrid Computation

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<thead>
<tr>
<th>System</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Analog</td>
<td>Wide bandwidth</td>
<td>Amplitude scaling required</td>
</tr>
<tr>
<td></td>
<td>Convenient operator interfacing and control</td>
<td>Large amounts of hardware required for large simulations</td>
</tr>
<tr>
<td></td>
<td>Convenient interfacing with other equipment</td>
<td>Long manual set-up and check-out time</td>
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<tr>
<td></td>
<td>Continuous &quot;real time&quot; or &quot;faster than real time&quot; operation</td>
<td>Accuracy limited due to component tolerances</td>
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<tr>
<td></td>
<td>Low cost per solution</td>
<td>Difficulty in generating functions of two or more variables</td>
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<tr>
<td></td>
<td>Integration performed directly</td>
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</tr>
<tr>
<td>Digital</td>
<td>High Accuracy</td>
<td>Large cost per solution due to numerical integration routines</td>
</tr>
<tr>
<td></td>
<td>Programmable simulation control</td>
<td>Possible model instabilities due to numerical integration techniques when</td>
</tr>
<tr>
<td></td>
<td>Large simulation capability due to modern operating systems</td>
<td>simulations have wide frequency range</td>
</tr>
<tr>
<td></td>
<td>Amplitude scaling not required</td>
<td>Limited engineer interfacing and control</td>
</tr>
<tr>
<td></td>
<td>Non-linear functions of two or more variables easily programmed</td>
<td>Solutions occur in unfavorable data processing environment</td>
</tr>
<tr>
<td></td>
<td>Nearly unlimited data output</td>
<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td>Simulation can be properly divided between the analog and digital systems</td>
<td>Possible model instabilities due to sample data solution</td>
</tr>
<tr>
<td></td>
<td>to meet wide bandwidth and high accuracy requirements</td>
<td>Some amplitude scaling still required</td>
</tr>
<tr>
<td></td>
<td>Convenient engineer interfacing and control</td>
<td>Difficulty in scheduling long periods of computer time</td>
</tr>
<tr>
<td></td>
<td>Convenient interfacing with other equipment</td>
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<td></td>
<td>Real-time simulation</td>
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<td></td>
<td>Low cost per solution</td>
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<td></td>
<td>Stored program setup and checkout and control of analog computer</td>
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<tr>
<td></td>
<td>Non-linear functions easily simulated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minimal numerical integration required</td>
<td></td>
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The models of Refs. 30 and 31 are implemented on hybrid computers and are applicable to both solid and independent rear axle vehicles. Figure 1 is a representative simulation block diagram of the models which are characterized by having seventeen degrees of freedom and consisting of:

1. A basic ten-degree-of-freedom model of the vehicle body, front wheels, and rear axle
2. A three-degree-of-freedom steering system model
3. A four-degree-of-freedom wheel rotational dynamics model.

The basic ten-degree-of-freedom model regards the vehicle as an assembly of four rigid masses (the vehicle body, two front wheel masses, and the rear wheel axle combination). In the modified vehicle model, which includes independent rear suspension, each rear wheel is considered as an independent mass. The ten degrees of freedom consist of the six standard translational and rotational degrees of freedom for the body, two for the
<table>
<thead>
<tr>
<th>Contractor</th>
<th>Type of Simulation</th>
<th>Facilities</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bendix Research Laboratories Southfield, Michigan</td>
<td>Hybrid, digital</td>
<td>AD-4/XDS Sigma-5 (hybrid) Sigma-5 (digital) Remote Batch (digital)</td>
<td>27, 28, 30</td>
</tr>
<tr>
<td>Applied Physics Laboratory Johns Hopkins University Silver Spring, Maryland</td>
<td>Hybrid, digital</td>
<td>EAI 680/IBM 360/91 (hybrid) IBM 360/91 (digital) EAI 231-R (analog)</td>
<td>31</td>
</tr>
<tr>
<td>IIT Research Institute Chicago, Illinois</td>
<td>Digital</td>
<td>Univac 1108</td>
<td></td>
</tr>
<tr>
<td>AMF Corp. Santa Barbara, Calif.</td>
<td>Digital</td>
<td>University of Santa Barbara IBM 360/75</td>
<td>26</td>
</tr>
<tr>
<td>Calspan Corp. Buffalo, N.Y.</td>
<td>Digital</td>
<td>IBM 370/165</td>
<td>19, 24</td>
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</table>

vertical motion of each front wheel, and two for the rotation and vertical motion of the rear axle.

The steering system model with three degrees of freedom represents the compliance in each of the front wheels and in the steering linkage. The tire moments about each kingpin axis are functions of the circumferential and side tire forces, the inclination and caster of the kingpins, and the pneumatic trail effects of the tires. Steering wheel torque is the steering system input.

Four additional degrees of freedom (for a total of seventeen) are contained in the rotational equations of motion about the spin axis of each wheel. These equations, which include the differential effects of the rear wheels, yield the wheel rotation rates from which slip and, in turn, the variable friction coefficients are computed. The input to the equations can be either drive torque or brake torque.

The equations of motion of the vehicle body, wheels, and rear axle are perturbed by suspension, gravity, and tire forces and moments. The suspension equations include the effects of the springs, shock absorbers, and the auxiliary roll stiffness of the stabilizer bar.

The tire forces (radial, circumferential, and side) are computed for each wheel. The radial load is assumed to be proportional to the distance between the wheel center and the road. The circumferential forces are a function of the radial load and circumferential coefficient of friction which, in turn, is a function of wheel slip. The side tire forces are a function of wheel slip, camber and wheel slip angle, and radial load.
The model presented in Ref. 25 differs from those of Refs. 19, 24, 26, 27, 28, 29, 30, and 31 in two respects:

1. The vehicle body can roll about an axis inclined to the horizontal plane.
2. The inertial coupling between the mass of the independent suspension and body due to the geometry of the suspension is included.

However, the effects of these two restraints on dynamic response were never ascertained. Although this model is implemented for all-digital solution, it is unique in that it is programmed in the simulation language CSMP.* Other interesting capabilities of this simulation are the following:

1. Two solution modes—14 or basic 10 degrees of freedom (wheel spin as a degree of freedom is eliminated);

2. Provision is included for aerodynamic drag forces;
3. Nine suspension systems are simulated:
   - Solid axle front and rear
   - Independent front and solid rear axle
   - Torsion bar independent front and solid rear axle
   - Trailing arm independent front and solid rear axle
   - Independent front and rear
   - Torsion bar independent front and trailing arm independent rear
   - Independent front and trailing arm independent rear
   - Trailing arm independent front and rear
   - Trailing arm independent front and independent rear.

Unfortunately, the CSMP simulation never became completely operational but the model may still be useful.

*CSMP is a Fortran based language developed by IBM (International Business Machines) specifically to perform digital simulation. The letters CSMP are an acronym for Continuous System Modeling Program.
SIMULATION DATA

Once a model has been specified and implemented into a simulation, the next major task is acquisition of the parameter description of a specific vehicle and the functions representative of the specific vehicle’s springs, shock absorbers, tires, etc. Occasionally, model changes are required to accomplish correct simulation of vehicle functions. A representative list of vehicle descriptors for an American passenger car as required for the model of Refs. 30 and 31 is presented in Table 3. A list of vehicle functions is

<table>
<thead>
<tr>
<th>Table 3. List of Typically Required Vehicle Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a, b = ) distances along the vehicle fixed X axis from the sprung mass center of gravity to the spin axes of the front and rear wheels, respectively, inches.</td>
</tr>
<tr>
<td>( a_i = ) length of steering linkage arm, inches.</td>
</tr>
<tr>
<td>( a_o = ) length of steering arm, inches.</td>
</tr>
<tr>
<td>( \alpha = ) drive axle ratio.</td>
</tr>
<tr>
<td>( C_{CR} = ) Viscous damping coefficient of steering system connecting rod, lb-sec/in.</td>
</tr>
<tr>
<td>( C_{CFR} = ) coulomb damping coefficient of steering system connecting rod, pounds.</td>
</tr>
<tr>
<td>( C_F, C_R = ) viscous damping coefficient for a single wheel, effective at the wheel for the front and at the spring for the rear suspension, at the front and rear, respectively, lb-sec/in.</td>
</tr>
<tr>
<td>( C'_F, C'_R = ) coulomb damping for a single wheel, effective at the wheel for the front and at the spring for the rear suspension, at the front and rear, respectively, pounds.</td>
</tr>
<tr>
<td>( f(\delta_i, \psi_{FNT}) = ) change in front wheel toe-in angles relative to the vehicle fixed coordinate axes, radians.</td>
</tr>
<tr>
<td>( H_i = ) front wheel viscous damping coefficient, in-lb/rad/sec.</td>
</tr>
<tr>
<td>( i = ) wheel identification—1, 2, 3, 4 = RF, LF, RR, LR, respectively.</td>
</tr>
<tr>
<td>( I_D = ) drive line moment of inertia for rear wheel drive, lb-sec^2-in.</td>
</tr>
<tr>
<td>( I_{FW} = ) moment of inertia of one front wheel about the kingpin axis, lb-sec^2-in.</td>
</tr>
<tr>
<td>( I_R = ) rear unsprung mass moment of inertia about a line through its center of gravity and parallel to the X axis, lb-sec^2-in.</td>
</tr>
<tr>
<td>( I_{WJ} = ) rotational inertia of individual wheel at front and rear ((j = F, R)), respectively, lb-sec^2-in.</td>
</tr>
<tr>
<td>( I_x = ) roll moment of inertia of sprung mass, lb-sec^2-in.</td>
</tr>
<tr>
<td>( I_y = ) pitch moment of inertia of sprung mass, lb-sec^2-in.</td>
</tr>
<tr>
<td>( I_z = ) yaw moment of inertia of sprung mass, lb-sec^2-in.</td>
</tr>
<tr>
<td>( I_{xz} = ) product of inertia, lb-sec^2-in.</td>
</tr>
<tr>
<td>( K_F, K_R = ) suspension load-deflection rate for a single wheel in the quasi-linear range about the design position, effective at the wheel for the front and at the spring for the rear suspension, at the front and rear, respectively, lb/in.</td>
</tr>
<tr>
<td>( K_{RS} = ) roll steer gain of rear wheels relative to the vehicle coordinate systems, rad/rad.</td>
</tr>
<tr>
<td>( K_{SC} = ) Steering column-gear box flexibility, in-lbs/rad.</td>
</tr>
<tr>
<td>( K_T = ) radial tire rate in quasi-linear range for a single tire, lb/in.</td>
</tr>
<tr>
<td>( K_{TQ} = ) gain in drive torque equation for controlling vehicle velocity, in-lbs/in/sec.</td>
</tr>
<tr>
<td>( \Sigma M = ) total vehicle mass, lb-sec^2/ft.</td>
</tr>
<tr>
<td>( M_{CR} = ) mass of steering system connecting rod, lb-sec^2/in.</td>
</tr>
<tr>
<td>( M_s = ) sprung mass, lb-sec^2/in.</td>
</tr>
<tr>
<td>( M_{UF} = ) front unsprung mass (both sides), lb-sec^2/in.</td>
</tr>
<tr>
<td>( M_1 = M_2 = M_{UF}/2 = ) front unsprung mass at a single wheel, lb-sec^2/in.</td>
</tr>
<tr>
<td>( M_3 = M_{UR} = ) rear unsprung mass, lb-sec^2/in. (solid axle)</td>
</tr>
<tr>
<td>( M_4 = M_{UR}/2 = ) rear unsprung mass at a single wheel, lb-sec^2/in. (split axle)</td>
</tr>
<tr>
<td>( N_G = ) gear ratio of steering gear box.</td>
</tr>
<tr>
<td>( N_L = ) gear ratio of steering linkage.</td>
</tr>
<tr>
<td>( FT = ) caster offset of front tires, inches.</td>
</tr>
</tbody>
</table>
Table 3 (Continued)

| $R_F$, $R_R$ = auxiliary roll stiffness (suspension stiffness in roll), at the front and rear suspensions, respectively, in-lb/\text{rad}. |
| $R_w$ = undeflected radius of wheels, inches. |
| $R_{WR}$ = width of wheel rim, inches. |
| $T_F$, $T_R$ = track width at front and rear, respectively, inches. |
| $T_S$ = distance between spring connections for solid rear axle, inches. |
| $\delta_{SW}$ = steering wheel angle, radians. |
| $\epsilon_{KI}$ = static front wheel toe-in offset angles, radians. |
| $\epsilon_{PI}$ = dead space play in connecting rod excursion, radians. |
| $\epsilon_{SP}$ = dead space play in steering system, radians. |
| $\theta_{SI}$ = caster angle as a function of relative vertical deflection between wheel and body, radians. |
| $\lambda_F$, $\lambda_R$ = term by which $K_F$ and $K_R$ are multiplied to represent the suspension spring rate when the suspension deflection stops are encountered. |
| $\mu_{yi}$ = friction coefficient for side forces. |
| $\mu_i$ = circumferential coefficient of friction. |
| $\phi_{CGi}$ = camber angle of wheel $i$ relative to its tire-terrain contact plane, radians. |
| $\Omega_{FC}$, $\Omega_{RC}$ = maximum suspension deflections in compression from the positions of static equilibrium relative to the vehicle for quasi-linear load-deflection characteristics of the springs, inches. |
| $\Omega_{FT}$, $\Omega_{RT}$ = maximum suspension deflections in tension from the positions of static equilibrium relative to the vehicle for quasi-linear load-deflection characteristics of the springs, inches. |

Presented in Table 4. Appendix B of Ref. 28 contains detailed definitions of vehicle parameters and functions and possible sources (automobile manufacturers, general literature, experimental tests) to be explored for obtaining the data.

The most difficult functions to model are those which produce the tire forces. Currently, the “friction ellipse” concept is the most accepted tire force modeling method (Ref. 19, Section 5.1; Ref. 24, Appendix 3). The “friction ellipse” is an extension of the “friction circle” concept that permits a more realistic analytical treatment of interactions between the circumferential force (tractive or braking) and the side force of a tire.

**SIMULATION STEERING AND BRAKING COMMANDS**

After a vehicle has been modeled and all vehicle descriptors obtained, the simulation can be implemented. Given a complete model, implementation is straightforward regardless of whether a hybrid or digital mechanization is selected. During the implementation, thought should be directed toward the type of runs to be made. The result of this effort is sets of initial values for the system variables and the type and sequence of external commands.

The vehicle system may be defined with or without a driver. Since drivers are very adaptive and thus difficult to model, efforts have been directed towards the development of objective procedures for measuring safety-related aspects of the dynamic performance (stability) of passenger carrying vehicles with-
out a driver. Implicit in this effort is the assumption that there are certain specific performance characteristics of motor vehicles which, during either the normal driving process or during emergency situations, cause the potential for loss of control to rise above a threshold beyond which driver skill and experience are not useful. The result of this work has been a family of six safety-relevant handling test procedures, utilizing steering and braking inputs, based on a concept of “limit performance maneuvers,” i.e., extreme, yet realistic, maneuvers in which vehicle performance qualities deemed to have safety relevance play a significant and clearly defined role. These six vehicle handling test procedures (VHTP’s) are the typical external driving functions input to vehicle handling simulations. The same VHTP’s are attempted during full-scale tests which allow a comparison of simulated and test transient responses and other comparison variables. The VHTP’s, which were defined in Ref. 29 and refined in Ref. 32, are detailed for simulation application in Appendix A. The six types of VHTP’s are listed below:

1. Straight-Line braking
2. Braking in a turn
3. Turning on a rough road
4. Trapezoidal steer
5. Sinusoidal steer
6. Drastic steer and brake.

A representative simulation run from Ref. 30 with both braking and steering inputs is presented in Figure 2.

**MODEL VERIFICATION**

An important input to the modeling and simulation activities is the real-world information provided by full-scale testing. These tests, using a vehicle that has been or is to be simulated, provide the feedback to accomplish model verification. Refs. 27 through 31 and 33 detail comparisons between simulated

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**Figure 2.** Time histories—braking in a turn
and test runs for model verification. Once a simulation has been verified, it can be used to perform controlled computer vehicle parameter sensitivity experiments. To effectively accomplish model verification, identical simulated and full-scale experiments must be performed. The Vehicle Handling Test Procedures (VHTP's) provide a standard set of experiments that can be required in all full-scale and simulation experiments.

As previously mentioned, the VHTP's are intended to define the open-loop stability of the vehicle (no driver). However, several of the VHTP's (Appendix A) require steering and braking inputs which are extreme in magnitude and restrictive in timing. These are easily accomplished on a computer, but difficult to attain in full-scale tests. Although many test drivers have the ability to apply control inputs without regard for vehicle response, there is difficulty in producing a repeatable response from test to test.

In response to the need for more accurately controlled braking and steering inputs, the Automatic Vehicle Controller was developed by the Highway Safety Research Institute (HSRI) of the University of Michigan (Ref. 29, Section 3.2.3; Ref. 32, Appendix I). This controller was designed to provide control inputs to the steering wheel, brake pedal, and accelerator in three distinct operational modes:

1. A drone mode, whereby the control loop on vehicle direction and speed is closed manually by an operator in a following vehicle, using a pulse modulating radio transmitter.
2. A program execution mode, in which the steer, brake, and accelerator control inputs originate from an on-board programmed function generator with no loop closure on vehicle response.
3. An abort mode in which the brakes are applied (and the accelerator released) spontaneously upon the occurrence of critical failures, or can be commanded by the test operator, through the transmitter link.

Although designed to be installable in passenger cars having automatic transmission, the controller can operate in manual transmission vehicles for a single selected gear. A clutch activator is provided to apply or release the clutch pedal in response to a transmitted command. The braking and steering servo-mechanisms are electro-hydraulic position feedback systems. The accelerator motion is produced by a DC torque motor system.

The function generator is the key component of the automatic control system. It is an electromechanical instrument which stores the maneuver program and ultimately commands the servos to execute the programmed steering, brake, and accelerator control inputs.

Steer function inputs can assume either a sinusoidal or trapezoidal wave shape or any superposition of the two. Braking inputs can be generated with trapezoidal wave shapes. A brake application or release can be selected to occur at any time relative to a steering input.

Accelerator inputs can be programmed into a maneuver as step functions only. Both the on/off times and level are adjustable.

The controller has proven very useful in performing repeatable full-scale tests, the data from which is directly comparable to similar simulation experiments. The automatic controller is shown in Figure 3.

DATA PRESENTATION

Since passenger carrying vehicles vary in many physical properties (weight, wheelbase, center-of-gravity locations, etc.), it is essential to have a normalizing method of data presentation if the relative merits of vehicles are to be compared. Such a method is applicable to results from both simulation and full-scale testing experiments. A data presentation method has been suggested by HSRI which is particularly applicable to data collected from VHTP type tests, simulation runs and full scale (Ref. 29, Section 4; Ref. 32, Section 2.5 and Appendix V). The suggested comparison variables, calculation methods, and data presentation are summarized in Appendix B for the six VHTP tests. Vehicle handling
Figure 3. Automatic vehicle controller

Figure 3-a. Programmed function generator

Figure 3-b. Function generator control panel

Figure 3-c. Function generator circuit cards
simulations should be programmed to include this type of data reduction and presentation.

**KNOWLEDGE EXTENSION**

Once a simulation has been validated by comparison of simulation and full-scale test data including transient response as well as the normalized VHTP variables, a tool is available for performing extensive sensitivity analysis. Practically speaking, every vehicle descriptor is more conveniently altered in a simulation than on a test vehicle. Therefore, it is feasible to perform thousands of computer experiments to gain additional insight into the effects on vehicle handling of various vehicle parameters. Admittedly, this sensitivity procedure does provide the opportunity for incorrect judgment on system response, since the analysis is being performed without the backup of full-scale test validation. This danger can be minimized by thorough data evaluation by engineers specializing in vehicle handling and familiar with the simulation model and expected system response corresponding to specific parameter changes. Simulation response from a sensitivity analysis of a particular vehicle descriptor contrary to the "seat-of-the-pants" inclinations of the engineer may indicate the areas of vehicle handling which requires further investigation with modeling, simulation, and full-scale testing.

Sensitivity analysis and good engineering judgment make the operational simulation a valuable tool for extending the engineers knowledge of vehicle handling.

**SUMMING UP**

The information contained in this document should be sufficient to enable the reader to become quickly oriented in the aspects of passenger vehicle handling modeling and simulation. Although detailed equations for a particular model are not presented, adequate references are provided so that model definitions can be freely obtained. The majority of the recent work is available from NTIS (National Technical Information Service).

The names of organizations involved in vehicle handling and the types of computing equipment used by each is detailed. In addition, a set of standard vehicle maneuvers and recommended data presentation format is presented.

**Acknowledgement**

Information, including text and graphs, from reports performed under Government contracts has been freely used in this report. Material generated at HSRI (Highway Safety Research Institute, University of Michigan) and BRL (Bendix Research Laboratories, Southfield, Michigan) was especially useful.

**References**


Appendix A

VEHICLE HANDLING TEST PROCEDURES FOR SIMULATION USE

VHTP #1  Straight-Line Braking

Initial Conditions:
\( V_o = 40 \text{ MPH} \)
\( \delta_{sw} = 0^\circ \)

Purpose:
To determine maximum vehicle deceleration characteristics prior to wheel lockup.

Procedure:
Increase brake pressure from initial value of 200 psi to determine, within 25 psi, when two wheels indicate positive lockup above 10 MPH.
Brake application should be a ramp function requiring .1 sec from zero to desired brake pressure.
Normal termination is vehicle velocity = 10 MPH.

Signals of Interest:
\( A_x, V_5, W_1, W_2, W_3, W_4 \)

VHTP #2  Braking in a Turn

Initial Conditions:
\( V_o = 40 \text{ MPH} \)
\( \delta_{sw} = \text{magnitude required for initial lateral acceleration to be } 0.3 \text{ g.} \)

Purpose:
To determine maximum vehicle deceleration characteristics prior to wheel lockup while in a constant radius turn.

Procedure:
Determine steering angle required for constant .3 g turn at 40 MPH.
Increase brake pressure from value of 200 psi to determine, within 100 psi, when two wheels on a single axle indicate positive wheel lockup above 10 MPH.
Brake application should be a ramp function requiring .1 sec from zero to desired brake pressure.
Perform experiment for positive and negative steering polarities.
Normal run termination is vehicle velocity = 10 MPH.

Signals of Interest:
\( A_x, A_y, r, V_5, W_1, W_2, W_3, W_4 \)
VHTP #3  Turning on a Rough Road

Initial Conditions:
\[ V_o = 30 \text{ MPH} \]
\[ \delta_{sw} = \text{magnitude required for initial lateral acceleration of .}4 \text{ g.} \]

Roughness Requirement:
Road disturbance model having bump frequencies of 9, 11, and 14 Hz. At 30 MPH, these frequencies yield center spacings of 4.8, 4.0, and 3.14 feet, respectively.

Procedure:
Determine steering angle required for constant .4 g turn at 30 MPH.
Initiate test without road disturbance, introducing disturbance within 2 seconds of run initiation.
Disturbance should be present for 40 ft of vehicle travel.
Run termination can occur one second after removal of disturbance.

Signals of Interest:
\[ A_x, A_y, r, V_5 \]

VHTP #4  Trapezoidal Steer

Initial Conditions:
\[ V_o = 40 \text{ MPH} \]
\[ \delta_{sw} = N_g (L/10) \sigma' \]
\[ \text{for } \sigma' = 4, 6, 8, 12, 16, 20, 24 \]
where \( L \) = wheel base in feet
\[ N_g = \text{overall steering ratio} \]
\[ \sigma' = \text{normalized steer angle, degrees} \]

Steer Specifications:
Input steer 1.0 sec after run initiation.
Maximum steer angle should be achieved in 0.4 sec.
Maintain steer angle for 3.1 sec.
Remove input at the rate of \( \delta_{sw} \) °/sec.

Procedure:
For positive and negative polarities of \( \delta_{sw} \), perform experiments at each magnitude of \( \delta_{sw} \).
Normal run termination is 5.5 sec.

Signals of Interest:
\[ A_x, A_y, r, V_5 \]
VHTP #5  Sinusoidal Steer

Initial Conditions:
\[ V_o = 45, 60 \text{ MPH} \]
\[ \delta_{sw} = (66/V)(\ell/10)\sigma N_g \sin (\pi t_s) \]
for \( \sigma = 2, 4, 6, 8, 10, 12, 14, 16, 18 \)
where \( V \) = initial velocity in ft/sec
\( \ell \) = wheel base in ft
\( N_g \) = overall steering ratio
\( \sigma \) = normalized steering angle
\( t \) = simulation time
\( t_s = 0; (t - 1) \leq 0 \)
\( t_s = (t - 1); (t - 1) > 0 \)

Steer Specifications:
Input steer 1.0 sec after run initiation.

Procedure:
Perform complete experiments for both values of \( V_o \).
For positive and negative polarities of \( \delta_{sw} \), perform experiments at each magnitude of \( \delta_{sw} \).
Normal run termination is \( t = 5 \) sec.

Signals of Interest:
\( A_x, A_y, r, V_s \)

VHTP #6  Drastic Steer and Brake

Initial Conditions:
\[ V_o = 50, 60 \text{ MPH} \]
\[ \delta_{sw} = \gamma \delta_{sw} \]
for \( \gamma = .75, 1.0 \)
and \( \delta_{sw} = 360(N_g/22.5)(\ell/10) \sin (\pi t_s) \)
where \( N_g \) = overall steering ratio
\( \ell \) = wheel base in feet
\( t \) = simulation time
\( t_s = (t - 1); 1 \leq t \leq 2 \)
\( t_s = 0; \) all other \( t \)

Steer Specifications:
Input steer 1.0 sec after run initiation.

Brake Specifications:
Brake pressure should be adequate to lock all four wheels.
Brake application should be a ramp function transition from zero to maximum in .05 sec.
Input braking at time, \( t_B \), to coincide with timing of 95% peak yaw rate value.
Release brake at time = \( t_B + 2 \).
Procedure:
Perform complete experiments for both values of $V_o$.
Perform a simulation run with steering input only.
Examine yaw rate time history to determine time when 95% of its peak value was attained. This is time $t_B$ for brake application.
Perform a second run with brake input at $t = t_B$ and brake release at $t = t_B + 2$.
Examine roll rate time history and select times $t_p$ and $t_z$, coinciding with 2nd sympathetic polarity peak and 3rd zero crossing, respectively. The times $t_p$ and $t_z$ are new brake release times.
Perform simulation runs with brake input at $t = t_B$ and brake release at $t = t_p$ and $t_z$ for each value of $\gamma$.
Normal run termination is $t = 5.0$ sec or roll angle $\phi > .3$ radians.

Signals of Interest:
$A_x, A_y, r, \phi$

SYMBOL DEFINITIONS

$V_o$ Initial Vehicle Velocity
$\delta_{sw}$ Steering Wheel Angular Displacement
$A_x$ Vehicle Longitudinal Acceleration
$A_y$ Vehicle Lateral Acceleration
$W_1$ Angular Velocity Right Front Wheel
$W_2$ Angular Velocity Left Front Wheel
$W_3$ Angular Velocity Right Rear Wheel
$W_4$ Angular Velocity Left Rear Wheel
$V_5$ Fifth Wheel Velocity
$P_B$ Brake Pressure
$r$ Yaw Rate
$\dot{\phi}$ Roll Rate
$\phi$ Roll Angle
$\beta$ Vehicle Sideslip Angle
$\dot{\beta}$ Derivative of Vehicle Sideslip Angle
$1/R$ Path Curvature
Appendix B

COMPARISON VARIABLE CALCULATION AND PRESENTATION FOR SIX VEHICLE HANDLING TEST PROCEDURES

VHTP #1  Straight Line Braking

Comparison Variable:
Average Longitudinal Deceleration, \((A_x)_{AVE}\)

Calculation:

\[
(A_x)_{AVE} = \frac{1}{t_1 - t_0} \int_{t_0}^{t_1} A_x \, dt
\]

\[
\approx \frac{\Delta V \times 1.467}{32.2 \times (t_1 - t_0)}
\]

or \[
\approx \frac{1}{n} \sum_{i=1}^{n} A_{x_i}
\]

where
- \(A_x\) is the longitudinal deceleration, g's
- \(A_{x_i}\) is the discretized representation of longitudinal deceleration, g's
- \(t_0\) is the initial time at \((V_o - 5)\) MPH, sec
- \(t_1\) is the final time at \(V = 10\) MPH, sec
- \(i\) is the integer count of data points over the summation interval
- \(V_o\) is the initial velocity when brakes are applied, MPH (40 MPH is suggested)
- \(t\) is time, sec
- \(\Delta V\) is the velocity excursion = \((V_o - 5) - 10\), MPH
- \(n\) is the total number of data points

Data Presentation:
Average Longitudinal Deceleration Plotted Versus Brake Pressure (Figure A-1)

VHTP #2  Braking in a Steady Turn

Comparison Variables:
1) Average Longitudinal Deceleration, \((A_x)_{AVE}\)
2) Average Path Curvature Ratio, \(R_o (1/R)_{AVE}\)
3) Peak Body Sideslip Rate, \(\beta_p\)

Calculation:

\((A_x)_{AVE}\) (see VHTP #1)

Data Presentation:
Average Longitudinal Deceleration Plotted Versus Brake Pressure (Figure A-2)
Calculation:

\[ R_o \left( \frac{1}{R} \right) \text{AVE} = \frac{(1/R) \text{AVE}}{(1/R)_o} \]

where

\[ \left( \frac{1}{R} \right) \text{AVE} = \frac{1}{1} \int_{t_2}^{t_2+1} \left( \frac{1}{R} \right) \, dt \approx \frac{1}{s_f} \sum_{i=1}^{s_f} \left( \frac{1}{R} \right)_i \]

\[ \left( \frac{1}{R} \right)_o = \left. \frac{1}{R} \right|_{t_2} \approx \left( \frac{1}{R} \right)_i , \quad i = 0 \]

and,

- \((1/R)_i\) is the discretized representation of path curvature, 1/ft
- \((1/R)\) is path curvature, 1/ft
- \((1/R)_o\) is the path curvature at the time the brakes are applied, 1/ft
- \((1/R)\text{AVE}\) is the average path curvature for 1 second after the brakes are applied, 1/ft
- \(t_2\) is the time the brakes are applied, sec
- \(t_2 + 1\) is the one second following brake application, sec
- \(s_f\) is the digitizing rate, samples/second

Data Presentation:

Average Path Curvature Ratio Plotted Versus Average Longitudinal Deceleration (Figure A-3)

Calculation:

\[ \dot{\beta}_p = \text{maximum absolute value of rate of change of sideslip angle} = \max |\dot{\beta}(t)| \]

where

- \(t\) is defined over the interval \([t_2, t_2 + 1]\)
- \(t_2, t_2 + 1\) as previously defined

Data Presentation:

Peak Body Sideslip Rate Plotted Versus Average Longitudinal Deceleration (Figure A-4)

VHTP #3    Turning on a Rough Road

Comparison Variables:

1) Average Path Curvature Ratio, \(R_o (1/R)\text{AVE}\)
2) Peak Body Sideslip Rate, \(\dot{\beta}_p\)
Calculation:

\[
R_o \left( \frac{1}{R} \right)_{AVE} = \frac{(1/R)_{AVE}}{(1/R)_o}
\]

\[
\left( \frac{1}{R} \right)_{AVE} = \frac{1}{1} \int_{t_3}^{t_3+1} \left( \frac{1}{R} \right) dt \approx \frac{1}{s_f} \sum_{i=1}^{s_f} \left( \frac{1}{R} \right)_i
\]

\[
\left( \frac{1}{R} \right)_o = \left. \left( \frac{1}{R} \right) \right|_{t_3} \approx \left( \frac{1}{R} \right)_i, \quad i = 0
\]

and,

\( (1/R), (1/R)_i \) are defined the same as under VHTP #2

\( t_3 \) is the time the vehicle enters the grid, sec

\( t_3 + 1 \) is the time 1 second after the vehicle enters the grid, sec

\( (1/R)_{AVE} \) is the average of \( (1/R) \) over the above defined interval \([t_0, t_0 + 1]\), 1/ft

\( (1/R)_o \) is the value of \( (1/R) \) at the time the vehicle enters the grid, 1/ft

Data Presentation:

Average Path Curvature Ratio Plotted Versus Road Roughness Fundamental Frequency (Figure A-5)

Calculation:

\( \dot{\beta}_p = \text{maximum absolute value of rate of change of sideslip angle} = \max |\dot{\beta}(t)| \)

where

- \( t \) is defined over the interval \([t_3, t_3 + 1]\), sec
- \( t_3, t_3 + 1 \) as previously defined

Data Presentation:

Peak Body Sideslip Rate Plotted Versus Road Roughness Fundamental Frequency (Figure A-6)

VHTP #4 Trapezoidal Steer

Comparison Variables:

1) Normalized Path Curvature Ratio, \( R_o (1/R)_{AVE} \)
2) Peak Body Sideslip Angle, \( \beta_p \)
3) Peak Body Sideslip Rate, \( \dot{\beta}_p \)
4) Maximum Lateral Acceleration over the Entire Maneuver Time Interval, \( A_{Yp} \)
5) Maximum Yaw Rate over the Entire Maneuver Time Interval, \( \dot{r}_p \)
Calculation:

\[ R_s \left( \frac{1}{R} \right)_{AVE} = \frac{(1/R)_{AVE}}{(1/R)_s} \]

where

\[ \left( \frac{1}{R} \right)_{AVE} = \frac{1}{2} \int_{t_4}^{t_4 + 2} \left( \frac{1}{R} \right) dt \approx \frac{1}{2s_f} \sum_{i=1}^{2s_f} \left( \frac{1}{R} \right)_i \]

and

- \( t_4 \) is the time of the steering input, sec
- \( t_4 + 2 \) is the time 2 seconds after the steering input, sec
- \( (1/R)_{AVE} \) is the average path curvature over the above defined interval \([t_4, t_4 + 2]\), 1/ft
- \( (1/R)_s \) is the value of path curvature deriving from a steady 1 g turn at \( V_o \) MPH, 1/ft

Data Presentation:

Normalized Path Curvature Ratio Plotted Versus Normalized Steer Angle (Figure A-7)

Calculation:

\[ \beta_p = \text{maximum absolute value of sideslip angle} = \max |\beta(t)| \]

where

- \( \beta \) is defined over the interval \([t_4, t_4 + 2]\), sec
- \( t_4, t_4 + 2 \) as previously defined

Data Presentation:

Peak Body Sideslip Angle Plotted Versus Normalized Steer Angle (Figure A-8)

Calculation:

\[ \dot{\beta}_p = \text{maximum absolute value of rate of change of sideslip angle} = \max |\dot{\beta}(t)| \]

where

- \( \beta \) is defined over the interval \([t_4, t_4 + 2]\)
- \( t_4, t_4 + 2 \) as previously defined

Data Presentation:

Peak Body Sideslip Rate Plotted Versus Normalized Path Curvature Ratio (Figure A-9)

Calculations:

\[ A_{Yp} = \text{maximum lateral acceleration over the entire maneuver time interval} = \max A_Y(t) \]

\[ r_p = \text{maximum yaw rate over the entire maneuver time interval} = \max r(t) \]

Data Presentation:

None
VHTP #5  Sinusoidal Steer

Comparison Variables:
1) Lane Change Deviation, $\Delta$
2) Maximum Absolute Value of Sideslip Angle, $\beta_p$
3) Heading Angle at the End of Maneuver, $\Delta \psi$

Calculation:

$$\Delta = \frac{1}{T} \int_{t_5}^{t_5+T} |y - 12| \, dt \approx \frac{1}{T \cdot s_f} \sum_{i=1}^{T \cdot s_f} |y_i - 12|,$$ for right-left steer.

$$= \frac{1}{T} \int_{t_5}^{t_5+T} |y + 12| \, dt \approx \frac{1}{T \cdot s_f} \sum_{i=1}^{T \cdot s_f} |y_i + 12|,$$ for left-right steer.

where
- $t_5$ is the time of the steering input, sec
- $T$ is the length of time of the maneuver, usually 3.4 sec
- $y$ is the time history of the lateral displacement of the vehicle after $t_5$, ft
- $y_i$ is the discretized representation of $y$, ft
- $s_f$ is the digitizing rate

Data Presentation:
Lane Change Deviation Plotted Versus Normalized Steer Angle (Figure A-10)

Calculation:

$$\beta_p = \text{maximum absolute value of sideslip angle} = \max |\beta(t)|$$

where
- $t$ is defined over the interval $[t_5, t_5 + T]$
- $t_5, t_5 + T$ as previously defined

Data Presentation:
Peak Body Sideslip Angle Plotted Versus Normalized Steer Angle (Figure A-11)
Peak Body Sideslip Angle Plotted Versus Lane Change Deviation (Figure A-12)

Calculation:

$$\Delta \psi = \text{heading angle at the time} (t_5 + T)$$

where
- $t_5, T$ are as previously defined

Data Presentation:
None
VHTP #6  Drastic Steer and Brake

Comparison Variable:
Maximum absolute value of roll, $\phi_{\text{max}}$

Calculation:
$\phi_{\text{max}} = \text{maximum absolute value of roll angle over the entire maneuver time interval}$
$= \max | \phi(t) |$

Data Presentation:
Peak Roll Angle Plotted Versus Run Test Number (Figure A-13)
Figure A-1. Average longitudinal deceleration versus brake line pressure, VHTP #1

Figure A-2. Average longitudinal deceleration versus brake line pressure, VHTP #2

Figure A-3. Average path curvature ratio versus average longitudinal deceleration, VHTP #2
Figure A-4. Peak body sideslip rate versus average longitudinal deceleration, VHTP #2

Figure A-5. Average path curvature ratio versus road roughness fundamental frequency, VHTP #3

Figure A-6. Peak body sideslip rate versus road roughness fundamental frequency, VHTP #3

Figure A-7. Normalized path curvature ratio versus normalized steer angle, VHTP #4

Figure A-8. Peak body sideslip angle versus normalized steer angle, VHTP #4

Figure A-9. Peak body sideslip rate versus normalized path curvature ratio, VHTP #4
Figure A-10. Lane change deviation versus normalized steer angle, VHTP #5

Figure A-11. Peak body sideslip angle versus normalized steer angle, VHTP #5

Figure A-12. Peak body sideslip angle versus lane change deviation, VHTP #5

Figure A-13. Peak roll angle versus test run number, VHTP #6
Driver Factors and Driver Modeling as They Relate to Vehicle Handling Research

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ABSTRACT

Driver factors and models which relate to control of the vehicle along the roadway are considered. The point of view taken combines that of the psychologist and the engineer, with the models discussed emphasizing the latter in order to obtain operational descriptions and quantitative measures of driver/vehicle response and performance. Handling situations of interest include both the nominal and emergencies. These can involve discrete events and maneuvers as well as on-the-average behavior, and the corresponding control modes are a combination of open-loop and closed-loop operation. Important parameters can be classified according to vehicle properties, task variables, and driver-centered variables. The status and nature of pertinent driver models are reviewed, and their applicability is noted. Although the paper gives a broad brush treatment in general, specific applications of driver modeling to aerodynamic disturbance regulation and trailer towing are given. Example full scale data correlates are shown.

INTRODUCTION

Some form of driver steering control is required to maneuver a motor vehicle or to regulate its path performance. To understand driver control quantitatively it is appropriate to consider the actions of random and deterministic inputs on a dynamic system comprising a vehicle whose equations of motion are known and a driver whose response under various conditions can be measured and modeled.

This paper provides a general discussion of some driver factors and models as they relate to handling research and illustrates their application. Vehicle control and operation involving steering wheel, throttle, and brake are emphasized. The ultimate concern is with vehicle performance in a given situation involving either a discrete maneuver or on-the-average behavior. The modeling approach has an engineering orientation which has proved useful in quantifying driver/vehicle response and performance and solving design problems. A selection of driver modeling oriented literature in this area (including a historic overview) is given in Refs. 1-16.

ROLE OF DRIVER FACTORS IN VEHICLE HANDLING

The importance of driver factors in vehicle handling is generally taken as an article of faith because of the close dynamic interaction between driver and vehicle. Analyses and full scale experiments certainly confirm this, but corroborative accident statistics which might reveal the causal interactions are sparse.

Variables Which Affect the Driver

The driver's response properties when operating as a controller are affected by a large number of physical, psychological, and experimental effects. These are categorized in Fig. 1.

Task variables comprise all the system inputs and those control system elements
external to the driver which enter directly into the control task. Stability of the closed-loop system is always a necessary, though not sufficient, control strategy. Consequently, the driver's dynamics are profoundly affected by the visual field display and controlled element (vehicle dynamics), and his properties must be adapted accordingly. The characteristics of other task variables such as disturbance and command inputs also influence the driver's dynamics, although their effects are more in the nature of adjustment and emphasis than of change in fundamental dynamic form.

The state of the environment external to the driver is shown as the vector $\varepsilon$. Included as components of this vector are such factors as ambient illumination, vibration, and temperature. The variables denoted by the vector $\pi$ include such aspects of experimental procedure as instructions and order of presentation, as well as some of the less obvious effects induced by the statistical analysis procedures used.

The driver-centered variables ($\sigma$) include the characteristics the driver brings to the control task: training, motivation, "set to respond," physical condition, etc. Many of these factors are difficult to quantify in terms meaningful to a given experiment. They can, however, at least be qualitatively graded by pretest, interview, etc., or controlled or modified by procedures (therefore there may be some interaction between $\pi$ and $\sigma$).

**Open-Loop/Closed-Loop Dichotomy**

Driver control to accomplish a driving task comprises a combination of open-loop and closed-loop operation. Open-loop control actions are learned actuation patterns which typically result from a discrete stimulus, while closed-loop activity involves relatively continuous feedback of various visual and motion
cues. The open-loop/closed-loop dichotomy relates to both nominal emergency situations. Even limit of performance maneuvers have some closed-loop content. For example, in an emergency lane change, the stabilization and regulation of the vehicle motion after the lateral displacement has been accomplished is essential. Further, those vehicle handling parameters involved in the final closed-loop stabilization and regulation stage may be more critical than those which dominate the initial transient stage. In that case, the key handling parameters for emergency lane changes will be closed-loop rather than open-loop.

In vehicle handling studies, therefore, it is important to distinguish the limiting performance maneuvers which are substantially open-loop from those which have significant closed-loop aspects. For the former, the significant vehicle stability, control, and performance parameters are fundamentally a control power and vehicle alone dynamics nature. When closed-loop control is significant, the handling properties can still be expressed in vehicle alone terms, but the important properties will depend on driver control operations in particular frequency bands, i.e., the rapidity of the closed-loop response.

**DRIVER MODELS**

Current models for driver dynamic response originally derived from the more general human operator models in the field of manual control. This has been an active area of investigation since World War II, beginning with studies of fire control systems, maturing in the area of pilot control of aircraft, and broadening into other vehicular control areas during the past decade.

The types of models proposed and investigated in general span the control engineering field (see Refs. 17-24 for review articles). The closed-loop control model forms include:

- Linear transfer functions
- Describing functions
- Sampled data models
- Adaptive and optimal control models.

Each has potential application, but some have proven more useful than others. In their contemporary form, the common properties of these models are that they:

- Apply to learning or skilled control behavior
- Do not model higher order driver activity (e.g., navigation)
- Are strongly adaptive to controlled element (vehicle) and input properties
- Include some performance criterion
- Include a pure time delay
- Are generalizable to multiple feedbacks
- Use existing modeling techniques
- Contain a neuromuscular subsystem.

Additional classes of models include the following:

- Discrete
- Decision theoretic
- Statistical/empirical catalog.

These relate more to open loop operation as well as the higher order (decision and judgmental) processes involved in driving. They tend to be more descriptive, ad hoc, and multidimensional; and they are generally more qualitative than the closed-loop models. The theory for closed-loop operation is well developed and quantified, by comparison, and (to date) the describing function models have been most useful in vehicle handling applications.

**Dual Mode Controller Concept**

Combined open-loop/closed-loop driver control behavior can be characterized using the dual mode control model of the human operator shown in Fig. 2 (adapted from Ref. 25). The feedforward element accounts for open-loop and pursuit-like control. It operates on discrete inputs from the environment (such as a series of curves in the road) or provides inputs induced by a learned internal command repertory within the driver. The closed-loop control path is the vernier component, also referred to in Fig. 2 as the quasilinear steady state model. These loops are used for stabilization, following random
path inputs, regulating against disturbances, controlling the small perturbation dynamics of the vehicle in turns and other maneuvers, stably concluding the more drastic maneuvers initiated in the feedforward element, etc. The dual mode controller is, in general, a multi-loop structure, so the single blocks shown usually have several feedbacks and internal connections. Accordingly, the vehicle dynamics output, m, should be considered as a vector quantity reflecting several motion variables. These feedbacks can be perceived by the driver in both visual and motion (acceleration) terms. The dual mode model is pertinent to both directional and speed control.

The nature of the switching and the feedforward element is such as to divide the total driver behavior into temporal phases, each having a different system organization. As an elementary example, consider the typical system step response (e.g., lane change) shown in Fig. 3. During the initial period or time delay phase, nothing happens. This is followed by a rapid response phase and, finally, by a more or less oscillatory, error reduction phase. The feedforward element provides the major component of the driver's output during the rapid response phase. The quasilinear steady state model component is predominant in the error reduction phase (and in general during the time delay phase if the system is continuously excited by random disturbances or inputs other than the step assumed here).

In a more expanded view, the output of the feedforward element for a skilled driver is peculiar to the specific vehicle dynamics. With a skilled driver, under ideal conditions, the output of the feedforward can resemble that of a single input, single output, time optimal control system with an amplitude limit. For a heading angle change, c(t) is a single steer pulse, while for a lane change the ideal steer angle will be a double pulse. The amplitude limit may represent either a physical limit on the control deflection or, more likely, an implicit restraint imposed by the driver for the given situation. Man/machine system theory is not well enough advanced at the present time to specify this quantity for a variety of vehicle dynamics and maneuver situations.

Describing Function Model

As previously noted, the describing function models for closed loop operation are the best developed and most useful models currently available. These take into account a combination of:

- Guidance and control requirements related to good stability and path following, regardless of the type of controller
- Driver centered requirements which account for the preferences and limitations of the human driver.

As part of the dual mode concept, the describing function models are applicable to directional and speed control.

The driver responds primarily to a composite of visual stimuli derived from the full visual field. These stimuli are selected such that the driver's control action serves to fulfill the guidance and control needs of the driver/
vehicle system. Motion cues may be used by the driver in connection with large amplitude maneuvers or disturbances, but their advantageous use is generally limited by sensor lags and physiological washout properties.

The quasilinear model consists in general of three components: a set of describing functions with parameters which depend on the system and situation; a set of rules which tell how to adjust the parameters; and an additive remnant. In its most complete form the describing functions contain gains, indifference thresholds, time delays, equalizers, and neuromuscular dynamics. The indifference threshold is a higher order effect that can either be ignored, when the inputs are large, or accounted for approximately by using decreased driver gain. The neuromuscular system dynamics are based on low and high frequency data, and can be approximated at the midfrequencies of interest in driving as a first order lag or, even more simply, as an added increment to the time delay.

The rationale of driver equalization can be discussed most simply by using an approximate “crossover model” (e.g., Refs. 23, 24, and 29). Experimental data for a wide variety of both single and multiloop situations show that the driver adjusts his describing function \(Y_p\) in each loop such that the open-loop function \(Y_p Y_c\) in the vicinity of the gain crossover frequency \(\omega_c\) for that loop has the approximate form:

\[ Y_p Y_c = \frac{\omega_c e^{-j\omega \tau}}{j\omega} \]

Here \(Y_c\) represents the vehicle dynamics, and \(\tau\) is an effective pure time delay which includes the neuromuscular dynamics as well as any net high frequency vehicle lag. The crossover frequency \(\omega_c\) is the product of the driver and vehicle gains. In multiloop situations the effective controlled element dynamics \(Y'_c\) will include the effects of all the other loops closed. The form of Eq. 1 emphasizes that the driver characteristics in each loop are tailored to the specifics of the control situation and the vehicle. In addition to the time delay, the driver describing function \(Y_p\) in Eq. 1 contains:

- Driver gain, \(K_p\), which determines the amount of steering correction for a perceived level of heading angle or lateral deviation error;
- Equalization, \((T_L j\omega + 1)/(T_I j\omega + 1)\), which tailors the form of the driver’s response to suit a given vehicle’s handling dynamics.

Equation 1 states that if the effective \(Y_c\) transfer function has more lag than \(K/s\), some driver lead equalization, \((T_L j\omega + 1)\), will be required; while if \(Y_c\) is more like \(K\) than \(K/s\), some driver lag equalization, \((T_I j\omega + 1)\), will be used to achieve good driver/vehicle system response and performance. The parameters \(\omega_c\) and \(\tau\) in the crossover model depend on the disturbance or path input bandwidth and on the driver equalization. Data show that the crossover frequency is greatest and the driver time delay is least when his equalization is a low frequency lag. At the other extreme, \(\omega_c\) is least and \(\tau\) the greatest when the driver must generate low frequency lead. In fact, the major “cost” of equalization is this increase in time delay. Both \(\tau\) and \(\omega_c\) can vary with driver skill and level of attention to the control task. Experimentally based values for the crossover model parameters for several dynamic forms and input bandwidths are given in Refs. 23 and 29.

The remnant is that part of the driver’s output which is not linearly correlated with the input, and its major source appears to be nonstationary in behavior. When the driver’s control output is treated as a power spectrum, the remnant can be considered as a driver-induced broadband random “noise” injected at his output. For a skilled driver, and vehicle control situations involving reasonable handling dynamics, the remnant will generally be small compared to that part of his response involved in regulating against the external disturbance. For that reason it can often be neglected in making performance estimates, although some evidence of remnant is seen in the full scale comparisons, shown subsequently.
Driver/Vehicle System Structure for Directional Control

As noted above, multiloop control involving more than one feedback stimulus is appropriate to satisfying the guidance and control, and driver centered, requirements. Prior automobile control studies (e.g., Refs. 11, 16, and 26) have shown that the system of Fig. 4 is representative for steering control. This involves a primary feedback loop of vehicle heading angle ($\psi$), plus an outer loop of lateral deviation ($y_1$). These perceptual cues are operated on by the driver describing functions ($Y_{p\psi}$ and $Y_{p\psi}$) to produce a steer angle correction ($\delta_w$). The driver describing functions in Fig. 4 can be quantified using the models and rules outlined above (and detailed in the references). The analysis procedure involves a sequential application of the crossover model; beginning with $Y_{p\psi} Y_c$ in the inner loop and then considering $Y_{p\psi} Y_c$ in the outer loop. Typically, for well behaved cars, the required equalization is accounted for in $Y_{p\psi}$, and the driver time delay, $\tau$, is included there, also, by virtue of the “series” structure in Fig. 4. The outer loop describing function ($Y_{p\psi}$) is often a simple gain ($K_{p\psi}$).

EXAMPLE APPLICATIONS

The procedures and models outlined above have been used to investigate the response and performance of a variety of driver/vehicle systems, and two examples are highlighted below. The first of these involves a full sized station wagon operating in the presence of aerodynamic disturbance inputs. This is followed by an analysis of the effect of adding a travel trailer to the station wagon. Full scale data correlates are shown.

Station Wagon Performance with Aerodynamic Disturbances

The driver/vehicle response properties ($Y_{p\psi} Y_c$) for heading loop control of a late model station wagon are shown in Fig. 5. The vehicle dynamics are given by linear equations for heading rate, lateral velocity, and roll angle. A Pade approximation is used for the driver time delay, $e^{-\tau \omega}$. Driver lead equalization ($T_L$) of 0.14 sec is used in Fig. 5, and the amplitude ratio of the frequency response plot shows that this satisfies Eq. 1. For this lead, and with no input, the driver time delay ($\tau_0$) is about 0.35 to 0.4 sec; and the corresponding (zero phase margin) crossover frequency, $\omega_c 0$, is 4.2 rad/sec. The presence of a gust disturbance increases driver neuromuscular tension and reduces $\tau$ to about 0.25 sec, giving the stability margins shown.

Closing the heading loop results in an open outer loop effective controlled element ($Y_c^*$) which is combined with the lateral deviation describing function ($Y_{p\psi}$). Again applying the crossover model gives the driver/vehicle frequency response properties for lateral deviation control, shown in Fig. 6, and the broad region of $K/j\omega$-like amplitude ratio which allows the driver to use proportional control ($Y_{p\psi} = K_{p\psi}$).

Selection of the outer loop crossover frequency in Fig. 6 depends on several factors. Within limits, higher crossover frequencies give wider driver/vehicle system bandwidths which improve performance. The penalty associated with this is an increase in driver workload. If the crossover frequency becomes too high, performance will deteriorate because of reduced path damping and stability margins. For some vehicle handling dynamics, the quality of the response becomes poor for crossover frequencies well below the stability limits, as a result of undesirable interaction between the closed-loop heading and roll modes.

These considerations and subsequent full scale data correlates lead to the estimate $\omega_c 0 = 0.46$ rad/sec for the station wagon, which corresponds to $Y_{p\psi} = 0.005$ rad/ft. For
this relatively low gain the lateral deviation and heading mode roots are well separated (Fig. 6). This gives relatively simple response qualities, dominated by the lateral deviation mode. If $\omega_{c_y}$ were increased, the closed-loop roots of the lateral deviation and heading modes would approach each other (see the root locus), and the driver would find the resulting fourth order response undesirable. More gust sensitive vehicles require higher crossover frequencies to maintain a given range of performance, but this factor does not override these response quality considerations for the station wagon.

Estimated driver/vehicle properties plus aerodynamic disturbance data (e.g., Refs. 27 and 28) can be used to compute time responses for a given situation. These are compared with example full scale data in Fig. 7 from Ref. 27. The aerodynamic disturbance shown results when the station wagon passes an intercity bus, at a relative speed of 7 MPH, in the presence of a strong crosswind. In Fig. 7, $\delta_w$ is the front wheel steer angle, $r$ is the heading rate, and $|WV|$ and $\mathcal{X}WV$ are the magnitude and angle of the wind relative to the moving car. The results show good agreement. The higher frequency "noise" in $\delta_w$ and $r$ data is modeled by the remnant. This comparison supports the choice of outer loop crossover frequency shown in Fig. 6, $\omega_{c_y} \approx 0.46$ rad/sec.

Similar analyses and experiments have been done with other vehicles (e.g., Ref. 27). Vans show low stability margins and high crossover frequencies, just the opposite of the station wagon, and these differences depend on the aerodynamic and handling properties. For sedans of conventional design, the results show outer loop crossover frequencies of about 1 rad/sec and phase margins of about 60 deg. These values give good path mode
stability and overall performance, simple response qualities, and relative insensitivity to changes in driver gain.

Station Wagon Towing Trailer

Addition of a single axle travel trailer to the station wagon discussed above has a considerable effect on both the basic handling dynamics and the response of the driver/vehicle system to an aerodynamic disturbance (Ref. 27).

Root locus and frequency response plots for the heading loop driver/vehicle dynamics are shown in Fig. 8. Compared to the station wagon alone,* the main effect of adding the trailer is to increase the midfrequency phase lag of the vehicle dynamics which tends to reduce the attainable driver crossover frequency. Application of the previously noted driver model rules results in a heading loop driver lead (T_L) at 0.33 sec, and a driver time delay of 0.25 sec. Comparison of the open-loop heading roots of the station wagon (Fig. 5) with the wagon plus trailer (Fig. 8) shows that the trailer results in two additional modes (trailer roll and tow angle). The trailer tow angle mode is seen to be very lightly damped, and it rapidly goes unstable as the driver increases his inner-loop crossover frequency. Note that the station wagon heading mode remains quite well damped for all values of driver gain. Physically this means that the driver may be relatively unaware of large oscillations of the trailer. This analytical interpretation has been demonstrated in full scale tests where the driver's comments indicated he was unaware of the typically large, disturbance-induced trailer oscillations.

From a design standpoint, increasing the trailer tow angle damping would move the trailer tow angle pole-zero pair to the left in the Fig. 8 root locus. Then, driver heading

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*The velocity difference (65 MPH vs. 60 MPH) with the station wagon alone has only a minor effect on the vehicle dynamics shown.
control would ultimately drive the station wagon heading mode unstable while the trailer mode would no longer be a nuisance. Simple analytical procedures would allow the optimum design configuration to be developed, a priori, from such considerations.

The characteristics of the outer-loop driver/vehicle response properties for the wagon plus trailer are shown in Fig. 9. Again, simple gain control \( K_p \gamma \) is adequate in the outer loop, and the crossover frequency \( \omega_c \gamma \) is limited by the vehicle's handling dynamics. In this case, increasing the outer-loop gain would result in an undesirable interaction between the lateral deviation and trailer tow angle modes (rather than the heading mode as in the case of the station wagon). Although increasing the outer-loop gain does improve the trailer mode damping, the driver is unlikely to do this for the reason just cited as well as the substantial increase in workload and attentiveness which would be required.

**Figure 7.** Comparison of analytical and full scale results, station wagon passing bus

**Figure 8.** Driver/vehicle response properties for heading control, station wagon plus trailer at 65 MPH
Typical analytical and full scale results are compared in Fig. 10, and the agreement is seen to be good. The lateral deviation trajectories* ($y_{lt}$) in Fig. 9 show that the trailer (and car) tends to move toward the bus with this disturbance, while the station wagon alone (and other non-articulated test vehicles) tended to move away from the bus. This is due to the aerodynamic disturbance pulse at the front of the bus which is in a direction to both push and turn a single vehicle away from the bus. With the trailer attached, the yaw moment on the wagon peaks in the opposite direction, and the negative yaw moment on the trailer causes a large negative force at the hitch point. These combined positive yawing moments on the wagon turn it into the bus.

Together these examples illustrate the application of driver/vehicle analyses to han-

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*y$_{lt}$ refers to deviation of a point on the rear bumper of the trailer, and this accounts for the effect of trailer tow angle on lateral deviation.
Handling problems and highlight the importance of considering the closed-loop properties which result when the driver is in active control of his vehicle.

CONCLUDING REMARKS

Driver factors are clearly important in vehicle handling research, and driver/vehicle models have been developed for some classes of driving situations and tasks. The engineering approach to characterizing driver control and performance emphasized here has application in handling research and vehicle design, and utility in the quantification and standardization of vehicle handling properties.

Acknowledgements

Many of the concepts, models, and results discussed here derive from research accomplished by the combined staff of Systems Technology, Inc., and others, and this author's objective has been simply to review and summarize selected elements.

References


MICHAEL CHI, RESEARCH INSTITUTE:
I have a general question, if you don't mind. Would you care to explain how you obtained the constants used in your analysis?

HERB SACHS, WAYNE STATE UNIVERSITY:
How did you determine the describing function for the driver? Is that an empirical model or is it based on some other experience background?

Yes, there are in the simple describing models for the steering control case two or three parameters which are important and which are a function of the task variables. These include mainly the driver's time delay which is a kind of inherent time reaction-time delay thing. It varies from about a quarter of a second to a half a second and is composed of a variety of things. It's composed of processing delays when the driver has to generate equalization or compensation and that increases the time delay. Part of the time delay is related to simply the neural conduction times within the body, and part of the time delay is a mid-frequency or low frequency effect for the driver's high frequency neuromuscular dynamics which occur in the arm-hand actuation system at about two cycles per second. That is about a tenth of a second in the mid-frequency range. So you'd have to say a tenth of a second due to neuromuscular properties for the hand, another tenth of a second or so for neural delays, and another .05 seconds up to, say, .25 seconds for processing delays. So much for the time delay. The gain, as I indicated, is a more involved thing. It relates to efforts to achieve given levels of performance and, in fact, to satisfy those various kinds of requirements that I outlined. Then there is the equalization, of course, provided by the driver in order to overcome any deficiencies in the handling characteristics of the vehicle. So if he has a good handling vehicle, he doesn't have to work as hard. You can achieve higher levels of performance because he's not paying the penalty for processing delays. The compensation and equalization and the gains are really a combination of kinds of basic control theory considerations for what you do with the controller, whether it's a man or an auto pilot or what, as well as a large body of generalized manual control research data and specific data that's been taken in driving tasks, simulation results, and full scale data.

Well, the describing function model is a kind of general model form, as I indicated, and the general form of the model results from two different things. It results from the requirements that the man control the vehicle. So it's a general guidance and control need to have certain dynamic forms. And, in addition, because of the inherent limitations of the man as a controller he has limited band width, limited rates at which he can move his hand. He has visual limitations, processing limitations, etc. There are other factors which are rather further requirements or limitations on what the man can do and what the driver describing functions capabilities are or what the model's capabilities are, which relate to the man and which are, in that sense, driver centered. So, as I tried to indicate in the requirements slide, it's a combination of basic controlled considerations and then further limitations related to the driver which are not unlike auto pilot application actuator lags or, you know, hardware controlled system limitations of one sort or another.
Can you measure those describing functions?

Yes, a large number of describing function measurements have been taken both in general manual control situations and in driving tasks. This research dates back about 20 years or longer. The first measurements of that sort were made about 1946 in the United Kingdom. A great deal of research was done in the aircraft area starting in the middle '50's and early '50's and since about 1965 we've been concerned with the "fallout" of that technology into the driving area. Initially this was derived from the aerospace thing, but in the last few years we've done a number of different kinds of studies related directly to driving tasks which have extended these describing function models and these kinds of measurements into that driving area.

GRAHAM ALEXANDER, BATTelle MEMORIAL INSTITUTE:
Essentially are you relating, then, better handling with more open-loop type control? In other words, to reduce the driver on feedback requirements?

Yes. One view is to say that handling involves both open-loop type maneuvers in the sense I was using the word "open-loop" driver control reactions and it also involves a closed-loop operation. A good handling vehicle clearly should have satisfactory characteristics with respect to both aspects. Now, it turns out that the closed-loop properties may, in many situations, be more important than the open-loop characteristics, especially in a precrash phase where if the driver is not doing a large maneuver he's not making an on-ramp or something like that—he's just driving along, he's primarily a closed-loop operation. There has been a body of research that's looked into the rate at which the driver or the human operator can change from one control motion to another. It takes a few seconds; so, if you get him into a very rapidly developing accident situation, he's going to retain his control characteristics and the control process he was using before he got into that problem for a short period of time into the situation. So that's another way in which closed-loop characteristics can get into what normally might be considered an open-loop maneuver situation.

BOB ERVIN, UNIVERSITY OF MICHIGAN:
Could you comment as to the prognosis for the availability of driver models which grip with vehicle control under large side slip conditions? Have you given any consideration to the driver's sensitivity to the side slip response of the vehicle in addition to, say, lateral displacement at any angle of whatever?

Yes, the models aren't available now but we have worried about this and thought about it and certainly when you get into limiting acceleration situations, the kinesthetic views become more important, if not as a direct feedback, as an alerting device or some kind of limiting device or other non-linear operation. Another place you get into that kind of situation is in racing where, in fact, in large amplitude rapid type maneuvers, the drivers may be using heading rate feedbacks more than, say, heading angle. And, of course, again, the nature of the vehicle's dynamics gets into it too. And the race car may have sufficiently different dynamics so that different feedbacks are required. I think that the general guidelines in these models are pertinent to any kind of a situation and the same kinds of requirements would be applied and you'd have to develop the analytical models for the vehicle dynamics if you wanted to do an analysis and then run appropriate full-scale experiments to see how well the analyses track with the data. It could be done but it hasn't been done.
A Critique of Vehicle Safety Programs from the Viewpoint of a Consumer Advocate

Lowell Dodge
The Center for Auto Safety

ABSTRACT

Motor vehicle safety standards established to date under the 1966 National Traffic and Motor Vehicle Safety Act have been critically inadequate. Even though research completed by NHTSA would support improvements in many standards, the findings of this research have too often been neglected.

This paper explores the Congressional mandate authorizing the Secretary of Transportation to engage in vehicle safety research and measures the performance of NHTSA’s research efforts against that mandate. It concludes that the research effort should be integrated thoroughly with efforts to improve the motor vehicle safety standards.

The strengths and weaknesses of the current vehicle safety research program, as seen from a consumer viewpoint, are described and briefly analyzed. The paper’s recommendations include suggestions that the relative emphasis among certain current research plans be reassessed and redirected, that new funds be allocated for at least two programs, that NHTSA give more visibility to significant research findings, and that NHTSA establish mechanisms to ensure utilization of research findings in improving safety standards.

INTRODUCTION

On September 9, 1966, the National Traffic and Motor Vehicle Safety Act (the Act) was signed into law, setting in motion a process for the establishment of federal motor vehicle safety standards.

An analysis by Dr. Carl Nash* has shown that the vehicle safety standards program to date has been critically inadequate. While some welcome attention has been given to establishing priorities in the standards effort, several important aspects of vehicle design (for example, energy managing structures, vehicle handling, and pedestrian protection) are as yet unaddressed by standards. The Nash analysis shows that other aspects are at best poorly covered by current standards.

To ensure the promulgation of well-conceived and properly formulated standards, Congress also established, in the same Act, a vehicle safety research authority, residing in the Secretary, but in practice delegated now to the Research Institute of the National Highway Traffic Safety Administration (NHTSA). The Act specifically requires the Secretary, in prescribing standards, to:

consider relevant available motor vehicle safety data, including the results of research, development, testing and evaluation activities conducted pursuant to this Act (Sec 103(f)(1))

The research obligation of the Secretary is set forth in Section 106(a).* It is a broadly stated grant of authority, requiring the Secretary to conduct research, testing, development and training necessary to carry out the purpose of Title I of the Act. Title I is entitled: Motor Vehicle Safety Standards. Thus, it is important to note that the clear intention of Congress was that all research activity should ultimately be directed towards establishing new safety standards (or, after the issuance of the initial standards, improving standards already in existence). At the same time, Congress sought to insure that within these limits, the research effort would be “broad-scaled.”**

This paper attempts to reply to the question: How effectively has NHTSA utilized its research authority? This paper does not attempt to evaluate specific research efforts of NHTSA in detail; it is necessarily limited to a consideration of some of the broader questions which must be a part of any evaluation of NHTSA's research program. Moreover, it is limited to a consideration of the vehicle-oriented portion of the Research Institute's total program; it does not address research conducted under PL 98-564, the Highway Safety Act of 1966.

A SUMMARY ASSESSMENT OF CURRENT VEHICLE RESEARCH PROGRAMS: SOME GENERAL OBSERVATIONS

Low Visibility

The efforts and accomplishments of the Research Institute (RI) of NHTSA are among the least publicized activities of the NHTSA. While defect notifications receive relatively wide press attention, and developments in safety standards are regularly published in the Federal Register, there is no comparable availability of information about the day-to-day workings of the Research Institute. Even the most publicized of the RI's programs, the ESV program, has not received especially wide coverage outside the trade press. While this low visibility may make it possible for decisions and operations of the RI to proceed with relatively little outside interference, it also makes accurate evaluation of its efforts relatively difficult for consumer groups and Congressional committees.*

The Growing Importance of the Research Function

Ironically, at the same time that the RI's activities maintain relatively low visibility, it is clear, for several reasons, that they deserve considerably more attention from consumer groups than they have received to date.

First, a relatively large share of NHTSA's resources for motor vehicle programs is directed to research.**

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*Section 106(a) of the Act reads in pertinent part: “The Secretary shall conduct research, testing, development, and training necessary to carry out the purposes of this title, including but not limited to:
  (1) collecting data . . .
  (2) procuring experimental safety vehicles . . .
  (3) selling or otherwise disposing of test vehicles . . .”


This section requires the Secretary to undertake a broad-scale research, testing, development and training program for the purpose of acquiring information and knowledge necessary to relate directly motor vehicle and equipment performance characteristics to accidents involving vehicles and the resultant deaths and injuries.

The Senate Report, (U.S. Senate, 89th Congress, 2nd Session, Report No. 1301, June 23, 1966, to accompany S. 3005) states at p. 9:

The Secretary is given broad authority to initiate and conduct research, testing, development, and evaluation . . . .

Note that Title I of the Act also includes defect notification and compliance testing authorities, so that research designed to facilitate these programs is clearly contemplated under the scheme of the Act.

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*Not much is available publicly which summarizes or evaluates the efforts of the Research Institute. The annual reports of NHTSA are outdated by the time they are available. Indexes of research reports are available. Aside from these, the best source is the hearing record of the Committee on Appropriations for the House of Representatives covering the NHTSA budget. These records are large volumes published annually and available in Room H-218 of the U.S. Capitol.

**Out of a total NHTSA budget for FY 1972 of $73.1 million, $24 million was allocated to Research and Analysis. The total for safety standards (Motor Vehicle Programs) in the same year was $7.8 million, and the total for motor vehicle research contract programs (a part of the above $24 million) was $12.7 million.
Second, most of the safety standards incorporating known safety technology have already been established. Upcoming standards will have to rely more and more on the outcome of research and development efforts.* Thus, the role of the RI will become more critical.

Finally, the pervasive weaknesses and vaguenesses of many of the current standards, which render too many of them unenforceable, suggest the need for specific research and development efforts to save the standards and enforcement programs from slow deterioration—perhaps even ultimate self-destruction. While it may be true that some existing standards were ill-conceived and should be allowed to die,** and others will give way to broader systems performance standards,*** several critical standards which will survive are in desperate need of repair.† Such repair efforts could benefit greatly from the input of research findings.

A Mixed Mission

According to the language of the 1966 Act, all research, testing, training, and development activities of the NHTSA, in the vehicle area, are ultimately justified only to the extent they aid the Secretary in establishing, amending, and revoking new safety standards. A further aim is set forth in the Senate Report‡ on its version of the auto safety bill in 1966: “A principal aim is to encourage the auto industry itself to engage in greater auto safety and safety-related research.” This goal, however, is one which is ascribed to the entire act, not just the research activities authorized under it.

To direct the research efforts towards new and improved standards makes sense in reason as well as in law. The automakers have never shown themselves to be receptive to new technology developed outside their ranks. The only sure route for NHTSA to bring about improved vehicle safety designs is through the standards. Research and development results not reflected in the standards may never see the light of day.

This Congressional mandate has been loosely interpreted by the RI. In its reports to Congress, various research efforts are described sometimes as directed, as in the case of vehicle structures research, at proving “to industry and to the motoring public that substantially improved levels of protection are not only theoretically possible, but also technologically feasible.”* Efforts oriented toward industry and the public may assist the Secretary by removing the grounds for opposition to a standard, and in this way, may contribute to the establishment of standards. But in fact, such efforts can be viewed as totally unnecessary. The Sixth Circuit Court of Appeals in deciding the passive restraint case in December 1972, upheld the authority of the Secretary to make use of the standards to force the auto companies to develop new safety technology.** Thus, research directed merely at proving the feasibility of a safety design constitutes an unneeded assumption by NHTSA of a burden which the agency can and should place on industry. Under the Act, the RI might well limit its research efforts in the vehicle area to the minimum needed to

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*Passive restraint rulemaking is an apt instance of this.
**An example is the current Standard 208, which is a design standard specifying safety belts. Active systems are probably not advisable in the long run as a universal and required means of achieving occupant restraint. Some form of passive system should ultimately displace the original 208 entirely.
***Examples are Head Restraints (FMVSS 202), Side Door Strength (FMVSS 214), and Indirect Visibility (FMVSS 111).
†Examples, taken from the Nash work cited above, include FMVSS 101, the standard for control location, identification, and illumination; FMVSS 213, child seating systems; and FMVSS 301, fuel system integrity.

**Chrysler Corporation et al. v. DOT et al., Nos. 71-1339, etc., United States Court of Appeals for the Sixth Circuit, Decided and Filed on December 5, 1972. At p. 21 of the slip opinion, the Court states:

In summary, the Agency (NHTSA) is empowered to issue safety standards which require improvements in existing technology or which require the development of new technology, and it is not limited to issuing standards based solely on devices already fully developed.
support the formulation of a notice of proposed rulemaking. Thus, once reasonable safety performance parameters could be set forth in an area where rulemaking was contemplated, the task of the RI is completed. At that point, the NHTSA, through issuance of a proposed rule, can effectively shift the remaining development burden to industry. (See Recommendation (b), below, for further discussion.)

Even more difficult to justify is development work directed solely at improving the compatibility of already proven research designs with mass production techniques.* This research is arguably an illegal use of taxpayers funds to perform work that is clearly the responsibility of industry itself.

However, on a practical level, the agency may view all of these activities as necessary to create a favorable political climate for the acceptance of a new safety standard idea. But this consumer advocate, for one, would place a much lower priority on such efforts, relative to those leading directly to the definition of minimum performance levels to serve as the basis for drafting notices of proposed rulemaking. (See Recommendation (a) below.)

Allocation of Resources

The allocation of the 24 million research dollars spent by the RI in the fiscal 1972** seems to correspond to notions held by consumer groups of the relative importance, generally, of various auto safety countermeasure areas. Roughly half went into contracts for motor vehicle research, an eighth into traffic safety research, a sixth into accident investigation and data analysis, and the balance into salaries and supporting costs.

We find much less comfort in current and projected future allocations which show major increases in areas such as improved driver performance (driver training, problem driver correction, licensing, etc.) where we have seen little evidence of pay off. The Research Institute’s “Five Year Research and Development Plan, FY 1973 Through FY 1977” indicates that the RI will devote over $4 million to this area in Fiscal 1973 (the largest single “level 1 activity” expenditure outside ESV program), more than three times what it will put into occupant packaging research, and more than twice what it will invest in data collection through accident investigations.*

Moreover, the Five Year plan projects large increases in the budget for “Improved Driver Performance” over the next four fiscal years.**

The RI sets forth, as a major component of its research objectives the “improvement of transportation R&D effectiveness*** and projects an increase from 16% to 18% over the next several years in the proportion of its resources devoted to this objective. The primary components of this category are Accident Investigations, mathematical analysis, and data systems. There is no explicit subcategory directed at assessing or improving the extent of application of research results to the process of generating new safety standards or improving old ones.

So far as this author has been able to determine, there is no systematic, publicly available assessment of the extent to which NHTSA’s motor vehicle programs make use of the results of research activities.

STRENGTHS OF THE CURRENT PROGRAM

Volume of Output

One cannot help but be impressed by the number of research contract reports both in vehicle and non-vehicle areas generated by RI efforts over the past six years. As measured by the volume “Technical Reports of the National Highway Traffic Safety Administration; A Bibliography, 1967-1971” and by

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**“Safety 71,” p. 54.

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**“Five Year Research and Development Plan,” p. 43.
***Ibid., p. 43.
****Ibid., p. 17.
the volume "Research Reports of the National Highway Traffic Safety Administra-
tion 1967-March 1971" the output is truly monumental.

Evidence of Research Program Planning

Both the annual reports of the activities of NHTSA and the RI's Preliminary Five Year
Plan are strong evidence of efforts to adjust the priorities of research efforts to match
known areas of pay-off and to ensure that the various components of the program are inter-
related and coordinated with each other. They also reflect efforts to exert rational
control over the allocation of available re-
search dollar resources.

The Experimental Safety Vehicle Program

An investment to date has been the
catalyst for an overall investment by foreign
auto companies and their governments ex-
ceeding $150 million.*

The pay offs—in terms of visible results
(vehicles incorporating hundreds of new saf-
ey designs, many of them highly significant)
and in terms of spurring the automobile
manufacturers to reallocate more of their own
manpower and financial resources in the
direction of safety research—have been start-
tling and dramatic.

Automotive Recorder and Air Bag Fleet
Testing Programs

The RI has played a role in facilitating the
development of air bag fleet testing opera-
tions, critical for generating real-world experi-
ence to support occupant restraint rulemaking
in Standard 208.

An automotive recorder program, while
currently suffering a funding setback in Con-
gress, promises ultimately to provide elusive
pre-crash and crash phase data, and will
enable researchers, among other break-
throughs, to begin to correlate fatality data
with crash severity data.

*Statement of Solchi Kawazoe, Executive Vice Presi-
dent, Nissan Motor Corporation in U.S.A., before the
Subcommittee on Commerce and Finance, U.S. House of
Representatives, April 16, 1973, p. 3.

Accident Investigation

In-depth (and relatively high cost at over
$2,000 per accident) reports by multidiscipli-
ary terms on vehicle crashes, including
MDAI special studies, are now being accumu-
lated in large enough numbers to permit
evaluation of the effectiveness of safety stand-
dards. For example, the payoff of FMVSS 205
has been measured, and shown to be signifi-
cant, through statistical analysis of injury
sources. Similar analyses have been used to
provide guidance in selecting areas of research
and development which promise high payoff.
MDAI* studies have also generated valuable
recommendations for needed compliance test-
ing, defect investigations, and upgrading of
weak safety standards. They have led to the
recommendation that the exemption from
Standard 201 granted to multipurpose passen-
ger vehicles should be eliminated.

Technical Reference Section

Special credit has to go to the Technical
Reference Library, which consistently does its
best to keep abreast of available materials and
to make them available as conveniently as
possible to members of the public, as well as
to Agency personnel.

While there are undoubtedly other
strengths among RI vehicle-oriented pro-
gams, this representative sampling should
underscore the value seen by consumer groups
in the current research activities of the RI.

WEAKNESSES OF CURRENT VEHICLE
SAFETY RESEARCH PROGRAMS

The Center for Auto Safety and other
consumer organizations we have consulted are
in agreement on several fundamental weak-
nesses in the current programs of the RI.

Unavailability of Data

Although NHTSA research is among the
more adequately funded of NHTSA’s higher
priority efforts in general,** we believe that
more funds are desperately needed in at least

*Multidisciplinary Accident Investigations (MDAI)
**See Note**, p. 186(r).
two areas. First, the RI is still unable to respond adequately to requests for some items of basic data. Still unavailable, for instance, are fatality probabilities for various crash modes, angular crash configurations, and impact speed levels. Data on injury severity for different modes and speeds of crashes are lacking. While crash modeling may enable researchers to short-cut their way to conclusions otherwise difficult or expensive to reach, eventual confirmation by "hard" data is essential.

Second, to allow the automotive recorder research program to go unfunded is to perpetuate the system of guesswork which now pervades much accident reporting and investigation particularly with regard to impact speeds. We doubt that vehicle deformation analysis alone will ever adequately meet the data needs of rulemaking decisions, such as whether to go 50 MPH barrier test speed for Standard 208. We therefore recommend increased amounts of new funding for these efforts (see below, Recommendation (d)).

**Underutilization of Research Findings**

Weak and vague safety standards continue in existence, despite the completion of research which would support upgrading and clarification of these standards. Disregard for this research can mean, among other things, that some of the research is poor quality and cannot be used, or that there is no functioning mechanism to ensure that the results of good research are translated into improved standards, or both.

For example, completed research would support clarification or upgrading of the standards covering control location and identification, child restraint systems, seat anchorage strength, fuel system integrity, and rear lighting systems. If the payoff of research is in saving lives, by reflection of research into improved and new standards, then much completed research must be regarded as largely useless, and the funds expended for it, wasted.

The ESV program has generated wide ranging evidence which could be used to support new areas of rulemaking. However, there appears to be little in Vehicle Safety Standard Program plan books reflecting what has been learned in the ESV program. This is true despite pleas from many manufacturers, especially some of the importers, to see the fruits of their ESV labors reflected in planning for future motor vehicle safety standards.

Finally, much RI research has been completed which would appear to be sufficient to support rulemaking in areas that are at present totally uncovered. One example is rulemaking in the area of energy managing structures.*

**Misallocation of Dollar Resources**

The Research Institute's large and increasing commitment of resources to driver performance seems to be proceeding in total disregard of research, including several studies of the Insurance Institute for Highway Safety, suggesting that approaches to avoiding losses which involve modification of human behavior show little if any promise of payoff. The discovery that the RI projects an expenditure of $12 million in FY 1977 for improved driver performance, as compared to $8 million for vehicle structures research, and only $3 million for occupant packaging, is astonishing and totally unsupportable by anything this writer has been able to discover. While acknowledged high payoff rulemaking has progressed in occupant packaging, rulemaking for energy managing structures has not even commenced. If rulemaking for Standard 208 provides any guidance at all, it indicates that industry may be counted on to raise innumerable technical objections in the course of any rulemaking action requiring substantial changes in vehicle design. Reaching answers to such questions may require additional research; if funds are not allocated in anticipation of this, then the rulemaking may well be delayed, as has been the case with both fleet testing of air bags and dummy development in the passive restraint rulemaking.

Lack of Current or Planned Research in Areas of Potentially High Payoff

It is mystifying to consumer groups to be told that exterior protrusion rulemaking is currently being held up until research is completed,* and then find no reference in RI plans to research related to this rulemaking. Some vehicle/pedestrian research is in progress.** Fully one-fifth of the traffic fatalities in the U.S. involve pedestrians, and additional fatalities involve collisions between motor vehicles and riders of bicycles and motorcycles. Why so little concern for what can be done to the vehicle to eliminate or reduce the toll in this area?

Similarly, the concept of vehicle aggressivity, if extended, might lead to defining new research needs. For instance, one taking a systems viewpoint (rather than a vehicle occupant viewpoint) might well judge the larger vehicle which causes injury to the occupants of the smaller vehicle as the one with the "unsafe design." Yet comparative crashworthiness testing, which showed promising results in this area in the late 1960's, has been suspended, for now, by the RI.*** If it were resumed, and could support rulemaking limiting car size or mass (assuming the research program realizes its promise to find ways of building safety into smaller vehicles to protect occupants when the vehicle strikes stationary objects), then we might as a Nation avoid much of the current drain on our natural resources devoted now to building and powering larger vehicles.

Non-Objective Allocation of NHTSA Research Contracts

The NHTSA contracting system has in the past tended to excesses in favoring certain contractors over others because of their known support or opposition to certain systems or approaches. To a distressing extent, this practice has alienated significant segments of the vehicle research community, and in some cases, caused research organizations to fold. Moreover, the practice has increased opposition in some quarters to the air bag restraint system despite evidence that this system has high life saving promise.

RECOMMENDATIONS

These recommendations follow from the assessments offered above.

(a) The connections between research and standards need to be made much more explicit, and mechanisms which would function to improve coordination between planning for research and eventual improvement of safety standards need to be developed and made operational. It is not enough to justify an ordering of research priorities by citing data showing that deaths and injuries may be avoided or reduced by the development of given countermeasures. The mechanism by which the government most directly generates lived-saved payoff is the safety standards. Even the most cogent and brilliant research in an area of known high payoff will be useless unless it is translated into enforceable standards language.

Therefore, we recommend that the RI should devote 5% of its resources to show how the remaining 95% might be applied to the formulation of safety standards and to involve the RI in much more aggressive efforts to see that good research results are utilized in generating standards.

Evaluation of RI programs and reporting of RI payoff should be reoriented and described primarily in terms of the impact research results have had on the process of setting motor vehicle safety standards.

Efforts to view research programs and to plan research priorities in a more "integrated" framework should include integration with the standards-generating process. Integration of research programs in isolation from end

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*Ibid., p. A-14, and from many statements by former NHTSA Administrator, Douglas Toms.
**No indications can be found in the Research Institute's Five Year Plan of any intentions to increase the research effort in this critical area. Some pedestrian and motorcycle research is currently being conducted by the Office of Vehicle Structures Research, RI, NHTSA.
***The RI plans to re-institute comparative crashworthiness programs under the new Motor Vehicle Information and Cost Savings Act of 1972, Title II.
results may make life simpler and comfortable for the Rl, but it's not going to do the job of saving lives and reducing injuries as well as might otherwise be the case.

The Administrator (when he is appointed) should undertake a critical evaluation of Rl efforts not primarily oriented toward improving the safety standards. He should also take steps to make sure that mechanisms located either in his office, in MVP, or in the Rl (or in all three) are operating effectively to ensure utilization of good research results in the standards process. For instance, the program plan for vehicle safety standards should be keyed more broadly to projected research plans.

(b) Rl should eliminate research programs which perform work or develop knowledge or techniques for which responsibility under the 1966 Act is assigned to industry. A standard need only set forth performance parameters, and should avoid design specifications. Yet the Rl involves itself in design research going far beyond proving feasibility. It is a mystery to consumer groups, for instance, why the Rl undertakes development work directed at improving the compatibility of research designs with mass production techniques when the feasibility of achieving a desired performance level has already been demonstrated. Such expenditures are of highly doubtful legitimacy under the 1966 Act.

The NHTSA, and the Rl in particular, would be well advised to undertake a close reading of the 1966 Act and the U.S. Court of Appeals decision in December 1972 on passive restraints.* The act and the decision make it clear that NHTSA may force the automobile manufacturers to develop new safety technology by means of the safety standards. Once a concept has been shown to be practicable, through research or demonstration projects, a proposed standard may be issued. At that point, the Agency effectively shifts the development burden to industry. For example, now that 50 MPH survivability has been demonstrated through the ESV program, notably with Volkswagen's "ESVW"* it is entirely appropriate for NHTSA to proceed and to issue an NPRM setting a 50 MPH barrier crash test speed. Further research is not needed.

The Rl would also be well advised to direct contract funds, in so far as possible, away from industry groups, such as the Vehicle Research Institute recently formed by the Society of Automotive Engineers. Such groups may be under pressure by the employers of participants in research done for VRI to reach research conclusions favorable to the interests of such employers.

(c) The Rl should give more prominent display and broader dissemination to its research findings. Some research results are fairly dramatic and need not be buried in the last pages of "Highway Safety Literature" in the form of turgidly written executive summaries. Greater public exposure for useful research findings would also assist in bringing pressure to bear on those responsible for upgrading existing vehicle safety standards and for generating new standards. Wider exposure would also assist consumer groups interested in pressing for application of research findings to improvement in the standards.

(d) The Rl should place more emphasis on data gathering and analysis. (Specific needs in this area are outlined above.) In addition, fatality data and accident involvement data by make and model should be supported in greater measure to assist the efforts of the Office of Defects Investigation, as well as the standards engineers.

(e) The current emphasis in Rl planning on increased research expenditures in the area of driver/pedestrian performance and other safety countermeasures which depend for their effectiveness on modification of human behavior, and the support for enforcement activities which have a significant impact on accident causation, are consistent with this report's recommendations. The data base for an integrated performance-related countermeasure decision-making system should be built up incrementally. Additional research in these areas is needed. NHTSA's investment in research should reflect an understanding of its role in the process of moving from the research to the regulation stage in vehicle safety standards. 

*VW has produced a 3200 pound vehicle it believes to be practical and which it says can be mass produced. See Report on the Third International Conference on the Experimental Safety Vehicle Program, beginning at page 2-211. VW states that in front, side, and rear tests at 50 mile per hour barrier test crashes, specifications for injury criteria set by NHTSA are met or exceeded.
behavior should be reassessed. We believe the emphasis presently placed on vehicle structures, occupant packaging, biomechanics, fleet tests, and experimental safety vehicles should be retained.

Finally, we look forward to further opportunities to learn more about the work of the Research Institute and to participate in meetings such as this.
Questions & Answers

TOM GLENN, RESEARCH INSTITUTE:
Have you any suggestions as to how we might improve our press image?

Well, for one thing, we see precious little, in the way of releases generated, out of work done by the Research Institute with the exception of the Experimental Safety Vehicle program. On the other hand, if you read the press releases that come from the office of the Secretary, it seems that every time the Urban Mass Transportation Administration or the FAA issues a contract, that's made news of or at least issued in the form of a press release. It might be useful just in that way to give some visibility to contracts as they are let. It's a piece of news, I think, when Cornell gets a contract to work on 60 mile an hour survivability and it's again news when the target speed gets dropped as I learned this morning from 60 to 50. Yet you have to go to sessions like that or go into the technical reference section of DOT to find out these things. But I think, more basically, if there were some systematic way in which the results of good research that's completed can be disseminated, some way more systematic than the current executive summaries which are buried at the back of the literature survey, I think that would commend itself highly.

HANK JEX, STI:
Near the end you summarized a point by saying NHTSA could drop some of the research when it was shown to be feasible, and then later in a similar paragraph, you say that when once things are shown to be practicable they could be dropped. Now, there's a huge distinction there and I think you should clarify that point.

Well, the word "feasible" I use more as a word in common usage which I think is less subject to ambiguities than the word "practicable." The word "practicable" is the one which is used—perhaps unfortunately—in the Act as drafted by Congress. Now, in looking for guidance in how to interpret what Congress meant by the word "practicable" we can only go to the decisions of the Court. The leading decision is the Six Circuit decision on passive restraints and one light that's thrown on the definition of the word "practicable" by that decision is that NHTSA need not waste its resources on proving how industry may go about adjusting its mass production processes to incorporate safety measures. The feasibility need only be shown.

RON ESHLEMAN, IIT RESEARCH INSTITUTE:
Am I right that you say you advocate the issuance of standards without technology base or where new technology is required?

That's true. That's what I'm suggesting and that may sound like an irrational, or an impossible, situation but it depends how you conceive the purpose of the safety standards. If you see the safety standards as a way of reflecting what's already been proven and a way of incorporating into the existing production of technology what's already known, then you would disagree with that. If you view the safety standards as a way to provoke industry, a way to require or force industry into developing new technology which is the way Congress set up the Act, then you can view the safety standards in that light. As a tool, in other words, of generating, of encouraging the development of new technology. That's true.

Yes, but the development of new technology is very risky for one thing. I would think in developing safety technology this way by industry, especially new technology, that it's extremely cost ineffective because you've got everybody running around trying to gather this technology. And it seems to me that if they issued standards in this manner, that it would lead to a big credibility gap.

You might argue, I guess, that there's been a credibility gap with respect to passive restraint rulemaking on NHTSA and it could be argued, I guess, that the pace which NHTSA set in the passive restraint rulemaking has been a hot one. On the other hand, we don't see that as necessarily harmful. It may be that when you have people running around, more people than you might otherwise have, when the pace is hot, that you spend more money than you might otherwise have spent. But we're out to save lives and it seems to me that some of these developments in safety technology are long overdue. We have a hard time knowing how much is on the shelves in Detroit, and one way we can smoke it out is by issuing a
safety standard and finding out what kind of comments come back. I can answer it maybe in a flip way by saying we're not engineers, we're advocates and we're in this game to push it. We're in this—it's not really a game it's a matter of life and death—and we're in it to move things along more quickly than they've been moving. I think the history of the industry is such that it's not too difficult for us to show that there's been a lot of excessive laxity in the pace in the past. Our role in the whole situation is to accelerate the process. We do have to observe rational limits and we hope that we do that. We wouldn't propose that radar brakes be instituted in vehicles within the next few years. A lot of work needs to be done on that. Similarly with other on-board vehicle diagnostics; a lot of work needs to be done on that. At the same time, if there isn't somebody pushing for an accelerated pace, things will go about half as fast as we think they ought to go. There needs to be somebody holding up that side and that's how we view our role in the situation.

**GEORGE JOHANNESSEN, HAMILL MANUFACTURING COMPANY:**

Considering that the rational basis for the requirement for passive restraints was the inability to get occupants to use an effective, available restraint system and considering further that the Australian experience has indicated that there is a means for getting occupants to use the systems, what do you see now as the rational basis for mandating passive restraints?

Well, I would challenge your presumption that we can transfer the Australian experience whole cloth to this country. It may be that with mandatory belt usage laws we can increase belt usage rates considerably in this country. We don't yet have an equipment standard such as they have in Australia which requires a non-detachable upper torso portion and their enforcement is eased considerably by being able to check on whether that upper torso portion is in place. You don't have to look in everybody's crotch the way you would have to in this country. And without getting into the debate as to whether the American character is comparable to the Australian character, I'd simply raise the question as to whether we're certain enough that the characters are enough alike to be able to rely on that. But I think as my ultimate fallback in answering this question I'd turn to Dr. William Hadden—and we're four square behind Bill in his position—that countermeasures which depend for their effectiveness on modification of human behavior are in the long run not the way to go, that passive restraints or passive systems, those which don't depend on cooperation of humans or changing human behavior, are really the only way to get the kind of payoff that we're seeking in a reduction in the number of lives lost of in a reduction in the number of injuries.
Biomechanics and Crash Survivability
-A Status Report

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ABSTRACT

Development of biomechanics as applied to vehicle crashworthiness is presented. Historical precedents for this work are described. Applications of biomechanics in predicting tolerance to aircraft emergency loads led to modeling techniques which permitted prediction of injury probability from acceleration data. Similar techniques, developed for other injury mechanisms, are discussed. Kinetic models have been developed for predicting motion of the human in a crash environment and the injury models are used to evaluate the sensitivity of the human to the crash. Both of these models require experimental validation. Selection and description of a test subject for these experiments pose many difficulties. Limitations and advantages of human, cadaver, animal, and dummy tests are presented. A final application of biomechanics is the development of suitable dummy performance requirements for evaluation of crash injury reduction systems. Anthropometric data must be determined for a representative population to describe both sizes and capabilities. Body properties must be established to permit duplication in the dummy. Modeling techniques for relating injury to dummy response must be developed and validated. Finally, reliability and validity of the dummy performance in the specific crash environment must be established.

INTRODUCTION

Improved transportation systems have traditionally developed through exposure of the users to risk of injury or death. Although history does not record the first death from horse-drawn transport or from sinking of a ship, more modern forms of transport are better documented. The first air transportation fatalities were Pilatre de Rozier and P. A. Romain in 1785 when their balloon exploded during an attempt to cross the English Channel. Shortly thereafter, between 1793 and 1802, parachute descent techniques were developed for egress from balloons. The development of suitable power plants at the end of the 19th Century increased activity in more rapid forms of transportation. The fatal crash of Otto Lilienthal's glider in 1896, the first automotive fatality in 1899, and the first fatal powered-aircraft accident in 1908, reflected this activity and gave evidence of the hazards associated with these new modes of transport.

The military were among the first to recognize the high costs of deaths and injuries from crashes. In particular, the need to maintain an effective supply of trained pilots for warfare during World War I provided one of the first opportunities to reduce crash injury through interior delethalization and improved restraint. Indeed, the manual of Air Service Medical (1919) reported that a cowl change to provide increased clearance for the head "practically eliminated" injuries caused by striking the head against the cowl; and that incorporation of a shock absorber on the safety belt had "decidedly reduced" injuries to the upper abdomen and ribs. Operational problems were found to be the cause of 90% of the pilot losses during this period so that medical research, training, and vehicle improvements were directed toward "accident prevention" rather than crash injury protection. Efforts were made toward understanding the effects of operational prob-
lems such as long duration, low-level accelerations, altitude, sensory alterations, temperature, emotion and physical fitness, etc. Protective flying equipment (goggles and sunglasses, cold weather flying suits, oxygen supply systems, and parachutes) was developed to aid the pilot in accident prevention. The solution to crash injury was to avoid the crash environment by parachuting from the aircraft before impact. Nevertheless, even though continual improvements were made in aircraft and in pilot selection, training and maintenance, pilot losses in crashes continued. Maximum efforts toward crash prevention failed to eliminate crash injuries and deaths. Analysis of "survivable" crashes (those in which the pilot's cabin remained relatively intact) continued to show that the prevalent causes of injury and death were head and facial impacts with the aircraft interior as the pilot jackknifed forward over the lap belt during the crash. Armstrong (1939) conducted an early comparative evaluation of the performance of lap belts and lap belts with shoulder restraints. Although details of the tests are not given, he concluded that a sudden deceleration of 8 g's or more could cause the head to strike the aircraft interior with such force that "the skull would probably have been fractured." With the shoulder belt, decelerations up to 15 g's were tolerated "without any displacement of the body and without significant discomfort." The tests were terminated at 15 g's because that happened to be the limit of the available recording instruments; nevertheless, Armstrong predicted that one could live through 30 to 50 g's deceleration with lap belt and shoulder belt restraint.

It was clear as early as 1939 that escape from aircraft traveling at speeds greater than 175 knots would be feasible only if the pilot could be forcibly ejected from the aircraft. Several firms in Germany were commissioned by the German Air Force to develop such an ejection system. The results of tests of early German ejection seats, as reported by Glaister (1965), were not generally satisfactory; the seats caused a high incidence of vertebral fractures. German research, described by Ruff (1950), to investigate human tolerance to brief acceleration was the first major effort to apply biomechanical techniques to impact tolerance of the human body. The research included dynamic tests of human and animals and determination of mechanical fracture properties of fresh sectors of cadaver spinal column. One of the results of these tests was the recognition of time dependence of tolerable acceleration levels. (See Figure 1.)

**DYNAMIC MODELING**

Post-war developments continued to stress the importance of ejection systems as a means of escape from high performance aircraft. Performance of the ejection seat was evaluated by subjective reactions of the human test subject. Fracture of the spine, head flexure, and minor back injuries continued to occur. In an attempt to better understand the relationship between subjective reactions and the performance parameters of the ejection seat, it was natural for the development engineer to consider a dynamic analytical model of the system. Kroeger (1946), working at Frankfort Arsenal on the development of explosive charges for ejection seat catapults, modeled the pilot as a 200-lb. mass resting on a spring made up of elastic properties of the seat, cushion, parachute, etc., all resting on a 100-lb. seat. The system had a resonant frequency of 11.1 Hz, and Kroeger was able to demonstrate the effect of the thrust time curve of the catapult on causing "overshoot" of the acceleration as measured on the man. Latham (1957) compared the results of a similar model to actual measurements made on human test subjects and was able to demonstrate the importance of seat cushion rigidity in reducing dynamic overshoot. (See Figure 2.)

Modeling techniques at this period relied heavily on subjective response as a correlating factor. Kornhauser (1954), while working at the Naval Ordnance Laboratory, developed a simplified method of displaying the response of inertia-operated devices used in ordnance applications. He used, as an example, a simple
spring mass model, the mass of which must move a prescribed distance against a restraining force (the spring) during transient acceleration in order to perform its function (switch closure). (See Figure 3.) He was able to derive a sensitivity curve based on velocity change and average acceleration of the transient input which gave a boundary between "go" and "no go" performance of the device. The area to the left of the sensitivity curve represents those conditions where the acceleration level cannot sufficiently overcome the force of the spring so that the mass does not move the prescribed amount, no matter how long the acceleration is applied; i.e., no matter how great the velocity change. The area below the curve represents the conditions where high accelerations applied for short durations do not present sufficient energy to actuate the switch. Kornhauser also discussed the importance of the shape of the transient acceleration excitation pulse in determining the sensi-
tivity curve, particularly in the lower acceleration region.

The application of this technique to human tolerance to impact is obvious. If the injury mechanism of the body can be represented as compression or elongation of the spring, and if the body can adequately be modeled as a simple spring mass system, then a sensitivity curve can be established for the body. Kornhauser and Gold (1962) presented data obtained from 329 animal tests to support the possibility that a sensitivity curve did exist for man. Based on data available at that time, a human impact sensitivity curve was predicted. (See Figure 4.)

Payne (1962, 1965) and Stech and Payne (1969) investigated a variety of models for the spinal loading problem and concluded that a simple damped spring mass model was adequate to predict overall spinal injury probability for emergency ejection from aircraft. Using vertebrae breaking strengths reported by Geertz (1946) and Perey (1957) and mechanical impedance measurements by Coerman (1961), a limit of spring force and associated allowable spring deflection was established. This enabled computation of a Dynamic Response Index (DRI) which was adopted in USAF Military Specifications (1967, 1970) as a means of determining acceptability of acceleration profiles for ejection seats and ejection capsules. Brinkley (1968) found good agreement with the predictions of this model and the results of 321 successful operational ejections from USAF aircraft. (See Figure 5.)

Although the simple lumped parameter model appears to give good overall indication of probability of injury, it cannot describe the injury mechanism. The qualifying assumptions that have permitted the use of such a simple model include factors of spinal position, application of loads, seating and restraint systems, etc. To understand the effect of deviating from these assumptions and to better understand the mechanism of injury, it was necessary to develop more representative models. Hess (1956) and Lombard (1958) modeled the head and trunk as a homogeneous elastic rod and compared acceleration at the end of the rod with human head accelerations measured on ejection seat tests. Liu and Murray (1966) modeled the spine as a uniform elastic rod supporting a rigid mass at the head end, considered the effect of reflected stress waves, and discussed the site and sequence of the maximum axial load along the spinal column. Terry and Roberts (1968) applied viscoelastic criteria to the uni-axial rod model for the spine and discussed the possibility of using multiple mass spring dashpot elements. Toth (1967) developed a 9-mass model to consider the response of individual vertebrae from T-12 to L-5, requiring extensive experimental data to specify the properties of the vertebrae and inter-vertebral disks. These uni-axial models cannot be used to express responses associated with spinal curvature or bending of the vertebral column shown by Vulcan, King and Nakamura (1970), Ewing, King and Prasad (1971), and Fitzgerald (1972). Orme and Liu (1969), Li, Advani, and Lee (1970), and Lii (1971) Benedict (1972) developed models capable of responding to both axial and lateral loading as encountered in the ejection seat. These ta-
Figure 4. Prediction of overall human tolerance to impact based on sensitivity curve analysis by Kornhauser and Gold (1962)

...pered, curved, viscoelastic rod models and multiple mass discrete parameter models represent degrees of complexity which are, perhaps, ahead of confident experimental validation by carefully controlled whole-body impacts with adequate description of all input parameters. Yet recent work by Kazarian, Boyd and von Gierke (1971) and Kazarian (1972) indicates that the mechanism of spinal fracture may be even further complicated by torsional reactions.

Development of injury prediction models for the axially loaded spine has been successful because of the relative simplicity of the problem. Operational experience demonstrated the consistent site and nature of a primary structural injury without complicating concurrent soft tissue damage. Thus the problem was amenable to a comparatively straightforward structural analysis, based upon mechanical properties of the vertebral elements obtained in a manner familiar to the structural engineer. These data could then be incorporated in a simple, useful model. Of other components of the body, perhaps only the head can be treated in such a similar straightforward manner.

HEAD INJURY MODELS

The Wayne State tolerance curve for head injury, reported by Patrick, Lissner and Gurdjian (1965) has formed the basis for...
\[ m = \text{mass (lb-sec}^2/\text{in}) \]
\[ \delta = \text{deflection (in)} \]
\[ \zeta = \text{damping ratio} \]
\[ k = \text{stiffness (lb/in)} \]
\[ z = \text{acceleration input (in/sec}^2) \]

\[ \text{DRI} = \frac{\omega^2 n \delta_{\text{max}}}{g} \]

\[ \omega_n = \text{natural frequency of the analog = } \sqrt{k/m} \text{ (radians/sec)} \]

\[ g = 386 \text{ in/sec}^2 \]

Figure 5. Dynamic response index model used in USAF specifications for ejection seats and capsules

much of the tolerance analysis which has been applied to head injury. This curve was based on an extended program of animal and cadaver forehead impacts on a hard, flat surface. Like the Kornhauser sensitivity curve, points lying above the curve are assumed to be dangerous, points lying below the curve are assumed safe. A further similarity to the sensitivity curve should be noted. Low accelerations acting over long periods of time imply relatively great changes in velocity, so that the abscissa of duration could also be plotted as change in velocity without changing the shape of the curve. (See Figure 6.)

Gadd (1966) suggested that a straight line approximation to the Wayne State Curve, when plotted on a log-log plot, would be sufficient to indicate tolerance. Using this approximation, he defined an injury threshold of

\[ I = \int a^{2.5} \, dt = 1000 \]

which also agreed with the summary of tolerance data presented by Eiband (1959) and the crash injury reconstruction measurements by Swearingen (1965). This became the well known Gadd Severity Index which was adopted by the Society of Automotive Engineers (1966) as a criterion for head injury. Versace (1971) made an extensive review of the Severity Index and the Wayne State Curve and proposed an alternative formula for Tolerance Limit:

\[ T.L. = \frac{1}{T^{1.5}} \left( \int a \, dt^{2.5} \right) \]

Versace also recognized the inherent limitations of an index to describe the nature of closed-head injuries and suggested the application of dynamic models of a brain-skull system.

Numerous models exist for the response of the head to direct impact. Early models by Anzelius (1943) and Güttinger (1950) represented the head as a rigid sphere filled with a nonviscous liquid. Elgin (1969) considered an elastic two-dimensional shell and Benedict, Harris and von Rosenberg (1970) considered a two-dimensional membrane in place of the
shell. Lee and Advani (1970) considered the rotation of a sphere to evaluate injury due to rotational motion. Hickling and Wenner (1973) considered a three-dimensional spherical shell with brain, having linear viscoelastic properties, and were able to evaluate damping in the skull and brain, and provide a scaling formula for negative pressures in the brain.

Lumped parameter models have also been extensively developed. The simple damped spring mass model was proposed by Slattenschek and Tauffkirchen (1970), Slattenschek, Tauffkirchen and Benedikter (1971), Brinn and Staffeld (1970, 1971), Fan (1971) and Stalnaker and McElhaney (1970). The model of Stalnaker and McElhaney is of particular interest since the model constants were derived from impedance measurements of the human head rather than through curve-fitting techniques based upon the Wayne State Curve and other singular tolerance data points. This model postulates a mean strain limit as an injury threshold and has had extensive efforts applied to validation through animal testing and scaling (McElhaney, Stalnaker, Roberts and Snyder, 1971). (See Figure 7.)

The problem of loads transmitted to the head through the neck, and conversely, are of increasing importance as the occurrence of direct head contact with the interior of a vehicle during a crash is reduced. The work of Ommaya and his associates (1964, 1966, 1967, 1970, 1971, 1972, etc.) has well documented the importance of head angular
rotation. Injury models are now being developed to predict the occurrence of injury to the head and neck from this motion. These models range from the simple rotational system proposed by Martinez, Wickstrom and Barcello (1965) and confirmed with human test data by Becker (1972) to complex two and three-dimensional models proposed by Roberts, Ward and Nahum (1969), Freyler (1970), McKenzie and Williams (1971), and Bowman and Robbins (1972).

These models and the numerous others that have been proposed for injury prediction for the human body have demonstrated a sequential development which is characteristic. First, an injury is observed, either in operational use of a system or in laboratory testing. Then a simple method that relates an easily measured parameter, such as acceleration, to the occurrence of the injury is developed. This model is found lacking in its ability to explain the injury mechanism so more complex models are evolved. These models require a more comprehensive statement of the constituent properties of the system and an accurate statement of the boundary conditions. Often, these data are not available in the literature in quality (or form) required by the model, so assumptions are made to exercise the model. Lack of confidence in the assumptions then leads to further research to better define the unknowns.

It should be noted that the simple model may predict occurrence of injury as well as can the complex model. If information regarding the detailed injury mechanism is not required, the problems of specifying all of the input data for a complex model make the expense of such a model excessive. Moreover, any model is a simplified and limited statement of the problem and cannot represent conditions beyond its original intent. For an extreme example, consider an “energy absorber” composed of a bed of sharply pointed nails. If a “head” consisting of a rigid sphere impacts this bed, the design of the nails could undoubtedly be configured so that the acceleration of the sphere could be controlled. Thus, an injury prediction model based on acceleration could show that the “bed of nails” was a suitable protection device, simply because the model did not consider all critical parameters (such as area of load distribution) and was used irrationally. Injury prediction models must be used with a full understanding of their limitations, recognizing that injury mechanisms not represented by the model can occur.

**KINETIC OR KINEMATIC MODELS**

One other major modeling task is important in crashworthy analysis. The prediction of motion of the body in a crash is a great assistance in establishing the effectiveness or need of injury preventive systems. Dye (1949) attempted to predict the motion of a pilot during a crash by constructing a jointed, full-scale, two-dimensional manikin (called “Thin Man”) of weighted sheet metal. (See Figure 8.) The manikin was placed in a two-dimensional frame simulating a cockpit that was accelerated to simulate crash conditions. Tests were conducted on fellow workers to establish muscular restraint factors, which were simulated by joint friction in the model. Further progress along these lines resulted in the perfection of the sophisticated test tracks now in use throughout the world for evaluating crashworthiness systems, but deviated from Dye’s goal of providing low-cost data. In particular, a means of estimating impact velocity of the body with the vehicle interior and the reactions of the body to variations in seating and restraint systems was...
desired. The availability of high-speed computers provided the solution to the problem. McHenry (1963) formulated a 7-degree-of-freedom mathematical model of the human body, seat and restraint system for programming on an IBM 704 computer. Although the lack of comprehensive parameter data and experimental response prevented validation of the model, the results were sufficiently encouraging to warrant further refinement. McHenry and Naab (1966) presented an improved model (Figure 9) with 11 degrees of freedom that enabled determination of interior contact forces as well as providing improved body simulation. Both these models were two-dimensional in the sense that they indicated response only to a fore and aft crash vector. A comparative study was also presented which showed the response of the model relative to that of sled tests using a dummy. Naab (1966) measured inertial properties and dimensions of the anthropometric dummy as was necessary for the mathematical model. This study is one of the first critical analyses of an anthropometric dummy and noted variations between two different models of dummies and cadaver data published by Dempster (1955). A similar model was independently developed by Turnbow (1967), primarily for use in evaluating aircraft restraint systems. Roberts and Robbins (1969) presented both two and three-dimensional model results and Robbins, Bennett, Henke, and Alem (1970) presented comparative performance data between these models and anthropometric dummies. The three mass, three-dimensional model of this study possessed 12 degrees of freedom and sensed occupant to vehicle contact by up to 10 ellipsoids attached as contact surfaces on the body and 20 contact surfaces representing the vehicle. This was subsequently expanded to a six mass model for increased realism (Robbins, Bennett, Bowman, 1962). Robbins, Snyder, McElhaney and Roberts (1971) compared results of the two-dimensional model with a human impact test and discussed the difficulties encountered in attempting the comparison. The most complete kinematic

Figure 8. "Thin Man" model developed by Dye (1949) in an attempt to obtain low-cost kinematic data
A mathematical model developed to date has been described by Bartz (1971). This three-dimensional model consists of fifteen body segments resulting in a system with 40 degrees of freedom and has been validated against dummy tests. Injury criteria and a three-dimensional graphic display are other features of this model. This model; because of its complexity, may approach the response of a human more than simple models, but this refinement is at the expense of ease of use. (See Figure 10.)

VALIDATION OF MODELS

The application of kinetic models to analysis of crash injury prevention techniques has been generally accepted and several basically similar models have been developed. The general considerations discussed in regard to injury models apply to the kinetic models as well. In particular, the problems of adequate validation of a mathematical model must not be underestimated. Injury models must be validated through the use of surrogates for the living human. These surrogates, whether they be animals or human cadavers, must somehow be related to the living human. Early work using embalmed cadavers has been criticized because the preservation and storage techniques altered the material properties of the specimen. And, of course, soft tissue injury could not be evaluated with those specimens.
because of gross changes in tissue properties that occur during embalming and subsequent long storage. The recent availability of "fresh" unembalmed cadaver material for this research has alleviated many of these problems and the technique of artificial pressurization of the cardiovascular system used by Voigt and Lange (1971) and others, and techniques of staining to show injury will enable soft tissue rupture to be documented. Injury mechanisms involving physiological responses, such as concussion, require the use of living subjects and thus generate the need for animal subjects. Relationships between the results found in tests with animal surrogates and effects that would be seen on a living human evoke the use of scaling techniques. Presently proposed techniques range from the straightforward mass and angular acceleration relationship used by Ommaya, Yarnell, Hirsch and Harris (1967) in order to relate concussion in the monkey to concussion in man to the seven-parameter, four-dimensionless ratio group developed by McElhaney, et al. (1971). These scaling techniques make basic assumptions of the importance of the various parameters used, but cannot assure that all factors have been considered. Application of results from tests of surrogates is also limited by the complexity of this type of testing which, in turn, limits the quantity of tests due to cost factors. Because of normal biological variations in the test specimens, confidence in the results of a limited number of tests is low. A final factor only recently recognized is that the facility or test device may possess inherent performance characteristics that must be considered in evaluating test results. Johnson (1972) demonstrated potential differences in results when using different techniques for simulating a crash, and Chandler (1971) emphasized the importance of considering pre-impact, impact, and post-impact environment in simulating aircraft crashes.

The entire question of tolerance endpoints for the biological system has not been discussed to any extent in this paper, yet it is of major importance to the researcher. A review of the reference cited will indicate the
wide variety of factors considered, and Snyder (1970) presented an excellent and comprehensive review of the state of the art.

DUMMY SURROGATES

The first "anthropometric" dummy for evaluating restraint systems was developed by Swearingen (1951). To simulate human behavior, this dummy provided adjustable joint friction, weight distribution in accordance with the best available data, a thorax and abdomen designed to simulate human forward and lateral flexion and tissue properties and a flexible neck. In the intervening years since Swearingen's work, much effort has been expended to improving the dummy as a test device. Severy (1964) presented a synopsis of the early developments in this field.

Emphasis on anthropometric parameters guided much of these early efforts. The military services provided the most detailed measurements available and their measurements established the sizes of the dummies. Most applications during this period were associated with military requirements and, as the dummies were used as development tools rather than as acceptance devices, no major problems (other than maintenance) were encountered. Emphasis on testing for populations other than the military caused problems in defining those populations. Classical anthropometric measurements are most often obtained on large populations to serve as growth and development indicators. These dimensions do not usually provide the information required for dummy fabrication. Studies for other specialized purposes, such as clothing dimensions, are also misleading in many instances. The measurement of thigh depth, for example, made on standing subjects cannot be applied to a dummy in the seated position without correction because of the tendency of the thigh to flatten against the seat. If this error were undetected, the excessively deep thigh could prevent proper displacement of the seat belt and cause a false indication of submarining. In the absence of adequate data describing the population, value judgments must be made in specifying dummy characteristics.

Even if adequate population anthropometry were available, the selection of appropriate values for the dummy is not an easy task. Concise statistical statements of the data, as usually presented, are not the final answer. Although 50th percentile measurements can be defined, the existence of a 50th percentile individual who fits a composite of these measurements is remote. Similarly, although 95th (or 5th) percentile measurements of each segment of the body can be defined, these measurements cannot be combined to describe a 95th (or 5th) percentile man. Indeed, the optimum selection of dummy properties would be that composite that most severely tests the protection system under consideration and still remains representative of the population.

The mathematical model previously described may provide the only feasible method of resolving these problems. The descriptors for the kinetic man model can readily be varied so as to demonstrate the significance of that variation in the specific problem under analysis. If, for example, the model were to indicate that a system performed marginally with a child occupant and with a large occupant, it would be unwise to limit development testing to the use of a 50th percentile dummy.

Other requirements for dummies not directly concerned with biomechanical characteristics are currently well recognized. Reliability of performance is an obvious need. Ease of maintenance and of use should be provided to aid in obtaining the required reliability. Manufacturing techniques must be developed to assure consistency among similar components and specifications must be carefully written and confirmed to assure that they adequately describe the device. But the question of validation of dummy performance remains largely unanswered. It is obvious that the performance of a dummy should represent the living human. Unfortunately, this endpoint is largely undefined and is likely to remain so. There is no acceptable way to
directly measure living human dynamics under crash environments approaching the lethal levels. The techniques that are available, either through computer simulator or crash reconstruction, require significant assumptions to be made.

SUMMARY

The ability to specify tolerance to injury by a consistent analytical method has been greatly enhanced through the use of dynamic injury models. Complex models that can be used to investigate and describe the mechanism of injury as well as the occurrence of injury are becoming available. Kinetic models are available to predict the motion of the occupant during a crash and, when combined with an injury prediction model, can provide an accurate prediction of crash response.

Problems continue to exist in validation of these models and in recognizing their limitations. The users of these models should understand that every model is a simplified representation of reality. The simplifying assumptions necessary to create the model may place stringent limitation on its application. Validation of these models, likewise, requires a number of assumptions. Research is underway to provide data on the parameters required for these models, but as yet these data are far from complete.

The mechanical model, or dummy, suffers from many of the same limitations as the mathematical mode. In addition, problems of reliability and reproducibility due to mechanical variations must be solved. The mathematical model can aid the development of the mechanical model by predicting areas requiring the greatest improvement.

References


Questions & Answers

LARRY PATRICK, WAYNE STATE UNIVERSITY:
We've heard several times in the last two days about the use of civilian volunteers and the variation in human tolerance. It has been my contention for some time that we're not going to be able to protect everyone if we're going to do the best job. Now Dick mentioned the little old lady that cannot withstand the impact, and, if we try to protect her, in the long run, I think, we're going to lose lives and produce more injuries than if we use the average human tolerance—protect the most people from the most accident conditions. So when we talk about a tolerance, we can't talk about a single line like we have seen so many times. And I would suggest that we attempt to come up with some criterion for the individuals that we're going to design for. Do you have any comments on that, Dick?

HERB SACHS, WAYNE STATE UNIVERSITY:
I would like to know whether anybody has attempted to determine what the minimum number of lump mass systems is to represent realistically a torso or human?

Yes, I can only agree wholeheartedly. The value judgment that must be made and will undoubtedly be made will establish that population segment which can reasonably be protected. I mentioned the variation in energy absorbing systems with occupant size. That's certainly a problem that all of you have been aware of and is certainly one of the first decisions that will have to be made. Testing with the fifty percentile dummy does not conclusively prove the adequacy of a system for all population. And the testing at low levels with healthy young volunteers does not prove the adequacy of the system for you or me. Even more important, I think we have to make the decision—are we going to protect these people who are weaker and will it be at the expense of the protection of those who are not. These are very difficult decisions. I can't agree with you more, Larry.

Well, you get what you pay for. The single lump mass system which I showed adequately represents, for its intent, the human torso. Its intent, say, in the ejection seat problem is to evaluate the probability of injury. It is not intended to define the mechanism of injury. Now, how well you demand your definition, what resolution you demand, then governs the complexity of your model. If you want to look at pressure distribution through the cardiovascular system during impact, you'll have a very complicated model. If you're willing to be content with mechanical loads on the skeletal system, perhaps your model may be simpler. If you want to look at both of them, of course you pay for this in complexity of your model. I don't think there will ever be a determination of what is best because what is best depends upon what you are after.
Motorcycle Crash Safety Research

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ABSTRACT

This paper reviews the general problem of safe operation of motorcycles on highways, streets, and off-road and describes the past and current research work aimed at defining the motorcycle accident environment and improving the safety of motorcycles. The major portion of the paper describes a research program, "Dynamics of Motorcycle Impact," being performed by the University of Denver, Denver Research Institute, under contract to the National Highway Traffic Safety Administration. This program was begun in July 1969; the work includes performance of full-scale crash tests of motorcycles with anthropometric dummy riders/passengers and development of a digital computer simulation of the post-impact motion of the motorcycle and dummy rider. Results of the 41 crash tests run to date are presented. These tests include 1) perpendicular and angled impacts of motorcycles into barriers and the front, rear, and side of cars, 2) broadside impact of car into motorcycle, 3) rear impact of motorcycle by car, and 4) impact of motorcycle equipped with airbag into front and side of car. The present status of the digital computer simulation is reviewed and results showing the use of the computer simulation to perform parametric studies of the post-impact dynamics are presented.

The basis for specific recommendations made to US-DOT-NHTSA is discussed in terms of injury-producing phenomena identified by the crash test results. These recommendations include 1) criteria for gas-tank and filler-up integrity, 2) revised configuration and design of handlebars, steering head, control levers, instrumentation, fuel tank contour, and mirrors, and 3) modification of crash bars to provide protection in side-on impact and skidding/falling/sliding incidents. High speed movies of crash tests of preinflated and actively inflated airbag impact attenuators are shown; these tests demonstrate the feasibility of the airbag in impacts into the side or the front of a slowly moving or stationary car.

A review of other past and current research directly related to motorcycle safety is included. The present state-of-the-art in motorcycle safety is summarized and an attempt to define requirements for future research is made.

INTRODUCTION

Since World War II, there has been a dramatic rise in the number of motorcycles in use in the United States. The growth in numbers (≈200K-1945 to ≈2000K-1966) was accompanied by an alarming increase in the number of injuries and fatalities resulting from accidents involving motorcycles. As a result, the U.S. Department of Transportation in 1967-68 initiated a series of programs aimed at establishing safety performance standards for motorcycles and equipment/accessories for motorcycles and motorcyclists. (Probably the most widely publicized aspect of these programs was the research pertaining to head-injury/head-protection and the resulting passage of laws requiring motorcyclists to wear protective helmets.) Among the research contracts which pertained directly to motorcycle safety were the following: 1) FH-11-6543, Motorcycle Safety Study, Airborne Instruments Lab.; 2) FH-11-6903, Performance Requirements for Motorcycle Helmets, Airborne Instruments Lab.; 3) FH-11-6940, Face and Eye Protection for Motorcyclists, Denver Research Institute, University of Denver; and 4) FH-11-6955, Research in Occupant Interior and Pedestrian/
Cyclist Exterior Vehicle Impact Protection, Cornell Aeronautical Laboratory.

In the mid-1960's, Drs. P. W. Bothwell (University of Birmingham, U.K.) and D. M. Severy (UCLA-ITTE) began running crash tests of motorcycles with anthropometric dummy riders. Bothwell's proposal for motorcycle crash tests appeared in The Lancet, October 8, 1960, pp. 807-9; his article, "The Problem of Motorcycle Accidents," (in The Practitioner, 188, 1962, pp. 474-488), documented the statistics of injuries and fatalities, mechanisms of injury, and methods for reducing hazards. Results of Bothwell's U.K.-funded motorcycle crash test program were described in the August 1968 issue of Cycle World magazine; the article also described a conceptual-prototype Experimental Safety Motorcycle which had smoothed contours and an integral double-skin fairing which was intended to "restrain the rider under medium impact so he will remain with the machine and thus suffer little or no injury." In a 1970 paper, Severy discussed Vehicle Exterior Safety—Motorcycle Crash Protection and proposed developing a passive restraint system for the motorcyclist. The proposed system was intended to protect the rider from serious injuries "during most frontal impacts" and consisted of an energy absorbing "structure" across the motorcycle in front of the rider's pelvis and down each side in front of his legs plus additional "padding" on the steering head/instrument area.

It should also be noted that other USDOT-NHTSA sponsored programs on head injury criteria/impact tolerance, pedestrian/occupant impact, computer simulation and design of anthropometric dummies, modeling of vehicle crash dynamics, accident statistics, and driver education/human factors contain significant components of research which can be related to the problems of improving the safety of motorcycles.

CONTRACTS FH-11-7307 AND DOT-HS-126-1-186: DYNAMICS OF MOTORCYCLE IMPACT

In July 1969, Contract FH-11-7307, "Dynamics of Motorcycle Impact," was initialed to determine and investigate the injury-producing mechanisms of the motorcycle crash environment. The objective of the program was to establish the role of the various aspects of motorcycle design (e.g., handlebars and fuel tanks) in producing injuries and to provide the safety performance standards required to reduce/eliminate the hazards to the motorcyclist/motorist/pedestrian in a motorcycle accident. The work on the contract consisted of two parallel efforts: 1) a series of 27 motorcycle crash tests conducted by Dr. Bothwell in the U.K. at the Motor Industries Research Association Crash Test Facility (MIRA-CTF), and 2) development by DURDRI of a digital computer simulation of two-dimensional motorcycle crashes.

Experimental techniques for conducting motorcycle crash-test experiments using anthropometric dummy riders had been developed during the period 1964-68 by Dr. Bothwell at the University of Birmingham and MIRA-CTF. Experimental head-on motorcycle crashes against barriers and automobiles had demonstrated the feasibility and validity of this type of accident simulation. The significant coupling between the motion of the dummy rider, the motion of the motorcycle, and the characteristics of the obstacle had also been demonstrated.

The interdependence of the dummy rider motion, motorcycle motion, and accident/obstacle geometry implies that the degree of hazard present in a motorcycle crash is dependent on a large number of variables—e.g., motorcycle weight, geometry, and structural stiffness; rider weight, height, and initial position; obstacle motion, mass, geometry, and stiffness; and impact velocity and impact angle. Therefore, parametric studies are required to establish the relative importance of these variables in producing injuries/fatalities in motorcycle accidents. The cost of using actual crash tests to make these parametric studies would be very high. It is, therefore, reasonable to consider the alternative of using a digital computer to make analytical predictions of the post-crash dynamics of the motorcycle and rider. The non-linear nature of the equations of motion of the motor-
cycle-rider system makes a closed form solution impossible. Therefore, the development of a digital computer simulation of a two-dimensional, ten degree-of-freedom (DOF) system was undertaken as the first step in constructing a 3-D simulation.

The series of 27 motorcycle crash tests was run at the MIRA-CTF during the period July 1969 to July 1971. The content of this test program is summarized in Appendix A.

Between July 1971 and October 1972 under Contract DOT-HS-126-1-186, an additional 14 motorcycle crash tests were performed by Dr. Bothwell at the MIRA-CTF. (This series of tests is summarized in Appendix B.) During the same period, a digital computer simulation of the 3-D motion of a 9-DOF model of the motorcycle was developed by DU-DRI. (The work on the computer simulation is summarized in Appendix C.)

RESULTS OF RESEARCH ON DYNAMICS OF MOTORCYCLE IMPACT

In the 41 motorcycle crash tests run to date, a representative group of accident situations has been investigated. The results of these tests provide a clear definition of many of the hazards present in the motorcycle crash environment. In a near-90° impact, these hazards range from 1) the initial pelvic impact on the fuel-tank, through 2) the leg/pelvis impact with handlebars/steering head and the lacerating contact of the body with sharp protuberances on the contour of the motorcycle, to 3) the contact with opposing vehicle/obstacle and the final impact with the obstacle or the roadway.

The high speed movies of the crash tests document the kinematics of the dummy rider (and passenger) and the motorcycle. Analysis of the movies indicates specific aspects of the motorcycle design which are hazardous. For example, one major result of Contract FH-11-7307 was the definition of the extreme fire hazards created by flip-top gas caps and fiberglass gas-tanks.

The accelerometer data provides a quantitative estimate of the “injury-productivity” of a particular accident situation and motorcycle configuration. Table 1 gives the maximum g-levels recorded at selected positions in the dummy in the first 27 tests. Table 2 gives the peak resultant g-levels and head injury severity indices determined from the head accelerations which occurred in the tests described in Appendix B. The final report on the tests contains much additional information of the g-levels observed.

Work on Contract FH-11-7307 resulted in the following recommended safety design standards for motorcycles:

1. Because of their performance in impact situations fiberglass tanks should be eliminated unless fitted with flexible bag tank and safe-foam liners.

2. Monza-type, flip-top filler caps were found to open under impact and release fuel violently. Confirmation of leaking of Monza caps even without opening was obtained. This was sufficient to soak riders and the opposing automobile. Thus, only screw-down or tight-fitting bayonet caps should be allowed.

3. Confirmation that the tank line should not rise above the level of the loaded seat was repeatedly obtained. The tank shape should be revised to minimize the pelvic impact loads.

4. Tank top attachments such as parcel grids, welded seams, and filler caps should be eliminated or recessed not to rise above the general profile.

5. Impact of the steering head by the pelvis was frequent. This impact produces injury and also accelerates pitching of the torso which increases the angular momentum of the head. Head impact with the target automobile is thus aggravated. The steering head should not rise above the smooth contour of the fuel tank.

6. The motorcycle fuel tank and filler cap system should be required to pass separate shock-loading tests simulating a head-on 30 MPH crash (50 g) and a side-on 30 MPH crash (75 g). The tank should be filled with simulated fuel before testing. The test jig should support the tank in the same way it is installed in the motorcycle. If the tank contour is not required to eliminate pelvic
Table 1. Maximum g-levels Encountered at Selected Positions in Dummy

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Table 2. Peak g-levels Recorded in Dummy Head and Associated Severity Indices

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F&A = Fore and Aft; V = Vertical L = Lateral; R = Resultant G.I. = Gadd Index; HIC = H.I.C. Index

*Anomalous events in test affected acceleration levels.

impact, the tank should be simultaneously impacted on the rear hump by a mass representing the dummy/rider pelvis.

7. The attachments for windshields should "knock-off" without leaving trauma-producing ends. Toughened glass shatters and disperses apparently innocuously and appears to be the best current proposition.

8. Lacerating projections (e.g., brake and throttle levers, switches, lever clips, and screws) should be eliminated. The levers should be prevented from trapping the fingers by a guard. Mirrors should "knock-off" without leaving sharp edges.

9. The tendency of the bars to impact the face or body indicates that ball ends to close the handle-bar-end should be required. To eliminate impact with the dummy's face and chest, the handlebars should not rise over 6" from the current tank top height—i.e., at the outer ends. It is obvious that excess width is a hazard in traffic and a width of 25" is suggested as maximum.

10. Everything about the Chopper is contra-indicated (i.e., Ape-hanger handlebars, Seat, Sissy Bars, and Exhaust Stacks). The seating position which radically alters the front/rear weight distribution produces significantly lower loading on the front wheel. All these have implications for degrading crash survivability except for the temporary protection afforded by the seat-back in rear-end impact.

11. In rear impacts the kick-starter was a hazard to the leg. The kick-start mechanism, both crank and pedal, should on the evidence
be retractable to lie inside the space swept by the rear moving leg.

12. The chopper exhaust is the extreme but it is obvious that exhaust pipes rising out of the horizontal or projecting outside the general envelope of the motorcycle can be injury producing and should be eliminated.

13. Ignition coils should be fitted as remotely as possible from the fuel tank so they are not in a position to spark off a fuel fire. This area can be drenched with fuel and the wiring is often disorganized after impact.

14. In the sliding tests and broadside impacts it is apparent that the footrest is one of the few (perhaps the only) potential protectors of the foot. In slides a folding footrest would not protect at all. The slightly unexpected conclusion is reached that for the road motorcycle footrests should a) not fold, b) be very much stronger than they are to resist deformation, and c) should have outer ends which promote “non-dig-in” sliding. The footrests should be required to survive a 30 MPH slide on concrete.

15. The whole design, strength of, and fixings for crash bars appear to be woefully bad. They can be regarded as totally ineffective except perhaps in very mild slides where their role is somewhat beneficial. In side impacts and rear impacts they were useless. Design criteria are needed.

16. Seats appeared to detach and fly very readily. Although they did not hit the rider, they flew at 30 MPH through the air and constituted another potentially lethal flying hazard for the bystander. Stronger anchors are indicated. Seats should stay intact and in place at 50 g from 30 MPH.

17. A general feature of the tests is the strong indication that general smoothing of the outer contour all over the motorcycle is a desirable feature.

As described in Appendix B, crash tests of motorcycles fitted with heavy duty crash bars were run. These crash bars furnished significant protection from some of the injury producing mechanisms but sometimes created severe leg impacts of their own. Further work is needed to establish design criteria for crash bars. The final report on Contract DOT-HS-126-1-186 will be issued in the very near future. It will contain additional data which reconfirm and amplify the above recommendations. In addition, it will document 1) the creation of increased hazards to the rider by the presence of a passenger behind him, 2) the ability of heavy duty crashbars to prevent rotation of the bike in angled impacts, and 3) the marked decreases in acceleration levels which were produced by fitting an airbag impact attenuator to the motorcycle.

CONCLUSION

Work on a third contract on “Dynamics of Motorcycle Impact” is just beginning. A crash test program of 16 tests is planned. These tests will evaluate the airbag impact attenuator in angled impacts with moving vehicles and will include baseline tests of moving motorcycles hitting moving cars. Several motorcycles will be modified in accordance with the results of the crash tests; these modified motorcycles will be crashed to determine the injury-hazard reductions.

The development of the computer simulation of the 3-D motion is being continued. The CAL-3D occupant simulation is being modified to provide a model for the motorcycle rider and passenger. The 9-DOF motorcycle model currently provides a tool for estimating the effects of motion of the target vehicle on the 3-D post-impact motion of the motorcycle. It is anticipated that this program will be used to obtain guidelines for redesigning the airbag shape to provide protection for the rider in 3-D impacts.

There is a significant need at the present time for additional data on the statistics of the specific types of motorcycle accidents. Since safety improvements for one type of accident can increase hazards in another type of accident, a trade-off may be required to determine the optimum modification of the motorcycle. In addition to the statistical data, detailed documentation of individual motorcycle accidents would be very useful. These “real crash-tests” could be reconstructed, compared, correlated, and analyzed vis-a-vis crash tests and computer simulations of simi-
lar events. This activity would serve to validate (or suggest modification of) the crash test methodology and/or the computer simulation which would in turn increase the credibility of the research results and the associated recommendations for safety standards.

Acknowledgements

The authors wish to recognize the important contributions made by a number of people to the work reported here: especially, Mr. Arthur E. Hirsch (US-DOT-NHTSA); Dr. A. A. Ezra (DU-DRI); Mr. Lewis Buchanan (US-DOT-NHTSA); Mr. David Bean (Caliber Design, Ltd.); Mr. G. A. Rowell (DU-DRI); Mr. C. J. Temus (DU-DRI); and Mr. R. E. Stirley (MIRA).
DR. WILLIAM KING, NHTSA: I prepared the first notice on the control location uniformity for motorcycles and I helped to prepare the actual rule, Standard 123. I notice something that is a philosophy in this research, that is, I notice from the ramps that you have on those tanks occasionally. My guess is that your philosophy is to clean up the vehicle so, as the fellow becomes airborne, he doesn't get hurt so bad—doesn't get cut up too much. My point that I would like to ask here is, the bulk of the research shown in the automotive crashes, etc. indicates that if you can keep that person tied down so he can ride down that crash impact, he is more likely to survive. What I'm thinking is that people that ride these choppers are already sitting in a semi-fetal position, and if we could put a little more mass up there is front of them and have some kind of—I was interviewed by Cycle News West, May 15th, and my comments are in there—but by feeling is that, if we can get something today that people are buying, and make it so it would be a little more crashworthy, such as these choppers which have these springers on them, they would absorb some of this impact. You know that Norman Severy out there experienced perfectly survivable time histories with the rear axle of choppers when they were prying into the side of vehicles. What I'm suggesting, what I'm asking is, why have you elected to go for the philosophy of driving them airborne faster rather than keeping them aboard?

The air bag attenuator shows we are not trying to accelerate them off the bike. In the DOT report, we included a series of what we called recommendations for safety standards, and I put an abbreviated version of that in preprint. One of the main issues involved in that list is the clean-up, the smoothing up of the configuration of the motorcycle.

The chopper, however, has some handling problems associated with it, which are—well, I see you are shaking your head no, but, I guess that is a philosophical discussion.
ART HIRSCH, RESEARCH INSTITUTE:
Let me just catch one point on what Dr. King just said. Yes, we want to clean the bike up but I think in reference to using a bike as a mechanism for the management of the energy. The problem is it is fine with an automobile where you can tie your man down and use the car. With the motorcycle it is difficult. We tried a belt to hold the man on there. It is very hard to do because it confines him to the bike. That is why we have explored the feasibility of using an air bag where we can use this travel distance that he has. So we are looking into the use of the bike itself as a mechanism for reducing the energy, but also, as an interim step for present regulations where the bag can't be introduced. The cleaning up of the bike is a very important thing, because there are numbers of injuries that occur as a person rides over the tank, which you well know, some injuries which are quite severe. This is the reason for that.

OTTO T. WEINREICH, BMW:
You only showed tests where the bike and the rider were in the perpendicular situation. This is actually a very unusual situation in the motor bike accident. If you, by experience, run into an accident with a bike, you lay it down and this is probably true of 90% of all accidents. I wouldn't say that the perpendicular situation cannot happen, but to 90%, you lay the bike down if you run into an accident. Have you taken that into consideration?

I guess first of all I'd ask you where the number 90% comes from but, apart from that, we have run skidding and sliding incidents. We have run angled impacts—the one you say. I did show you two angled impacts, 67½°. We've also run 45° impacts both with single riders and with two dummies. So, I couldn't show you everything. I showed you what I thought was a representative sample.

Well, as I say, we have run skidding and sliding incidents. We do that by locking up the rear wheel and launching the bike off of the trolley. It turns out that the locked up rear brake—as I guess all motorcycle riders know—will make the bike unstable and it will skid and fall. Now, in those incidents the g levels are generally “very low.” There's also considerable evidence that many accidents happen in which the rider does not have time to lay the bike down. And that, of course, is . . . . You know, if a guy has time to lay the bike down or get around an obstacle, he's home free. The kind of accident that we're showing you here is a fatality. I mean, these dummies are getting killed every time.
I said in the beginning that I believe that these types of accidents happen and the 90%, that was my own judgment. I don't want to say that is a true figure. But, as to my judgment, about 90% of the accidents—the rider has a chance to lay his bike down.

Well that, I think it's probably true. At least, I had a lot of informal discussions with individual motorcycle riders and if a fellow is very experienced, then usually he can cite an instance in which he has indeed evaded a collision by laying a bike down. But he's also walking around uninjured and he's not the guy that got killed. You bring up an associated point, though, which is very important—that as we study, how do we modify a motorcycle and make it more safe? You've got a bag of worms on your hands because of the fact that the accident geometry is highly variable and you can protect the guy on a side-impact with crash bars but you've got problems when he hits something head-on or when he tries to get off the bike because if you try to package him on the bike, you can create problems for him.

JON MCKIBBEN, AGBABIAN ASSOCIATES:
First of all, I disagree with our colleague from BMW. I've ridden a couple of motorcycles—I've done my crashing—at least I hope, for a while. First of all, I think that most motorcycle safety teachers these days, including myself and my lecturers at USC, don't advocate laying a bike down because the bike will decelerate a lot faster on rubber tires than it's going to, if you lay it down and pick up a couple of hard contact points. And, presumably, if you're going to crash, the lower you can get the crash velocity down, the less you're going to get hurt. I wanted to ask a question, though, I noticed on several of the crash films—on some of them—you had extremely high handlebars. California style high-risers, I suppose. Was that done for a specific purpose? And my second question, the crash bar installations that you've got, what do you feel the value of them to be relative to perhaps a problem that crash bars are well known to cause, and that is they effectively make the motorcycle wider and decrease your ability to miss something.

Well, the latter comment, the latter point; this is Bothwell's key concern. That is, when he looks at these crash bars, we have shown, for example, they will prevent the bike from rotating around and trapping the rider's leg in a 45° collision with the front of the bike. And you saw in the 67½° which had a much less violent yawing motion, the rider's leg was trapped. So they do that. But that doesn't necessarily mean that they're a very good thing. There is—and that is the trade-off I was mentioning—when you do one thing to try to change the design to protect the guy in one accident, you may be creating other problems for him. We hope to be able to do much more in the future here on actually getting at this problem of the validation of our tests and our computer modelling vis-a-vis the real accident situation which, of course, is an extremely important thing.

Now, on the high handlebars, we were essentially trying to demonstrate the hazards and indeed we did. Once the guy puts the high handlebars on and he goes into any kind of an angled impact, he gets the handlebar right in his face. This is described in some detail in the DOT report.
Appendix A

Summary of Motorcycle Crash Test Program Conducted Under
Contract FH-11-7307 (July 1969 to June 1971)

A1. Introduction

During the period July 1969 to June 1971, a series of twenty-seven crash tests using Alderson CG-50 anthropometric dummy riders was run at the Motor Industries Research Association Crash Test Facility (MIRA-CTF), Nuneaton, Warwickshire, England. These motorcycle crash tests were performed by the BSA Research Est., BSA Company, Ltd., under subcontract to the University of Denver, Denver Research Institute; the crash testing was directed by Peter W. Bothwell, M. D., Head of Bioengineering, BSA. The results of this motorcycle crash test program were described in detail in Volume II of the Final Report on Contract FH-11-7307 (Report No. DOT-HS-800 587, dated July 1971).

A2. Summary of Tests Conducted

The twenty-seven tests were divided into five categories:

Test Series 1: Head-on Perpendicular Impacts with 3 ft. Barrier—11 tests.
Test Series 2: Impacts with 67½° Angled Barrier—3 tests.
Test Series 3: Impacts of Motorcycle into Stationary Automobile—8 tests.
Test Series 4: Skidding and Sliding Incidents—2 tests.
Test Series 5: Broadside Impact of Static Motorcycle by Automobile—3 tests.

The relatively large number of tests in Series 1 is due to the use of this simple crash geometry to establish the basic factors of technique, trajectory, behavior and repeatability. Table A1 gives the basic details of the tests including the configuration of each motorcycle.

A3. Test Track, Instrumentation System, and Test Technique

The MIRA-CTF is described in detail in the DOT report noted above. The facility has a rail-guided vehicle accelerator powered by a linear motor and complete, modern electronic and photographic instrumentation.

The instrumentation system for the dummy rider consisted of 10 accelerometers (usually three sets of two each in head, chest, and pelvis plus four variably placed in the limbs depending on impact geometry) plus a three-axis rate gyro in the chest. A single accelerometer was placed near the c.g. of the motorcycle. High speed movie cameras (1,000 fps and 250 fps) and an Arriflex camera (40 fps) were used to photograph the motion.

The accelerometer and rate gyro signals were brought out from the back of the flying dummy on an umbilical cable which was stored on the four-wheeled trolley used to carry the motorcycle down the test track.
Table A-1. Summary of Twenty-Seven Motorcycle Crash Tests Conducted During 1969-71  
Under Contract FH-11-7307

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Type of Motorcycle</th>
<th>Motorcycle Configuration</th>
<th>Speed at Release (mile/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H.22</td>
<td>BSA 650</td>
<td>Steel gas tank – Standard handlebars</td>
<td>–</td>
</tr>
<tr>
<td>A1-1</td>
<td>Triumph 650</td>
<td>Free-flight of dummy off motorcycle with no forward obstructions</td>
<td>30</td>
</tr>
<tr>
<td>A1-2</td>
<td>BSA 650</td>
<td>Steel gas tank – Snap filler cap – Semicowhorn handlebars</td>
<td>30</td>
</tr>
<tr>
<td>A1-3</td>
<td>BSA 650</td>
<td>Steel gas tank – Screw filler cap – Standard handlebars – Windshield mounted</td>
<td>30</td>
</tr>
<tr>
<td>A1-4</td>
<td>Harley-Davidson 750</td>
<td>Steel gas tank and oil tank combined – Screw filler caps on gas and oil tanks – Standard handlebars – Crash bars installed – Windshield mounted</td>
<td>30</td>
</tr>
<tr>
<td>A1-5</td>
<td>Honda 50</td>
<td>Open frame – Gas tank under seat – Standard handlebars – No mirrors fitted</td>
<td>31</td>
</tr>
<tr>
<td>A1-6</td>
<td>BSA 650</td>
<td>Fiberglass gas tank – Snap filler cap – High-cowhorn handlebars – Crash bars installed – Windshield mounted</td>
<td>30</td>
</tr>
<tr>
<td>A1-7</td>
<td>BSA 650</td>
<td>Standing rider – Steel gas tank – Screw filler cap – Semicowhorn handlebars</td>
<td>30</td>
</tr>
<tr>
<td>A1-8</td>
<td>Triumph 650</td>
<td>Free-flight (re-run of Test A1-1)</td>
<td>30</td>
</tr>
<tr>
<td>A1-9</td>
<td>BSA 500</td>
<td>Honda-type “high hump” gas tank – Snap filler cap – High-cowhorn handlebars – Crash bars installed – Windshield mounted</td>
<td>30</td>
</tr>
<tr>
<td>A1-10</td>
<td>BSA 650</td>
<td>Handlebars instrumented to measure impact forces – Fiberglass gas tank – Snap filler cap</td>
<td>30</td>
</tr>
</tbody>
</table>

Test Series 2: Impacts with $67^\circ$ Angled Barrier

| A2-1        | BSA 650            | Fiberglass gas tank – Snap filler cap – Semicowhorn handlebars – Crash bars installed – Windshield mounted | 30                          |
| A2-2        | Harley-Davidson 750 | Standard gas and oil tank arrangement – Standard handlebars – Crash bars installed – Windshield mounted | 30                          |
| A2-3        | Honda 50           | Open frame – Standard gas tank under seat – Standard handlebars – Mirrors fitted on both sides of bars – Windshield and mud guards mounted | 30                          |

Test Series 3a: $67^\circ$ Angled Impact into Front of Car

<p>| A3-1        | BSA 650            | Alloy gas tank – Snap filler cap – Cowhorn handlebars – Crash bars installed – Windshield mounted | 30                          |</p>
<table>
<thead>
<tr>
<th>Test Number</th>
<th>Type of Motorcycle</th>
<th>Motorcycle Configuration</th>
<th>Speed at Release (mile/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Series 3b:</strong> Impact of Rear of Motorcycle by Front of Automobile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3-2*</td>
<td>Triumph 750</td>
<td>Chopper configuration (rear crash bars)</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Triple</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3-2A**</td>
<td>Triumph 750</td>
<td>Re-run of Test A3-2</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Triple</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3-3</td>
<td>BSA 750</td>
<td>Standard machine specifications — Steel gas tank</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Triple</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3-4</td>
<td>BSA 650</td>
<td>Steel gas tank — Standard handlebars — Front crash bars — Perspex windshield</td>
<td>30</td>
</tr>
<tr>
<td>A3-5</td>
<td>BSA 125 Bantam</td>
<td>Standard machine specifications — Steel gas tank</td>
<td>30</td>
</tr>
<tr>
<td><strong>Test Series 3c:</strong> Perpendicular Impact of Motorcycle into Front or Rear of Automobile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3-7</td>
<td>Triumph 650</td>
<td>Steel gas tank — Smoothed up ramp — Pivoting into rear handlebars — Standard handlebar fittings</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>into rear</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>of automobile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3-8</td>
<td>BSA 650</td>
<td>Steel gas tank — Stiffened front forks and frame — Standard handlebars</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>into front</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>of automobile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3-9</td>
<td>BSA 650</td>
<td>Racer specification — Fiberglass gas tank with bag type inner container — Perspex racing screen — Glass fiber racing fairings — Racing seat — Clip-on handlebars</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>into front</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>of automobile</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Test Series 4:</strong> Skidding and Sliding Incidents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4-1</td>
<td>Matchless 500</td>
<td>Standard machine specification</td>
<td>30</td>
</tr>
<tr>
<td>A4-2*</td>
<td>Triumph 750</td>
<td>Steel gas tank — Crash bars installed front and rear — Laminated glass windshield — Standard handlebars</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Triple</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4-2A**</td>
<td>Triumph 750</td>
<td>Specification as A4-2</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Triple</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Test Series 5:</strong> Broadside Impact of Static Motorcycle by Automobile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A5-1</td>
<td>BSA 650</td>
<td>Alloy gas tank — Crash bars front and rear — Laminated glass windshield — Cowhorn handlebars — left and right mirrors</td>
<td>30</td>
</tr>
<tr>
<td>A5-2</td>
<td>Honda 50</td>
<td>Open frame — Standard machine specification — No screen or mirrors installed</td>
<td>30</td>
</tr>
<tr>
<td>A5-3</td>
<td>BSA 750</td>
<td>Steel gas tank — Toughened glass windshield — Crash bars installed on front and rear — Standard handlebars</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Triple</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Test aborted
**Repeat of aborted test
Appendix B

Summary of Motorcycle Crash Test Program Conducted Under Contract DOT-HS-126-1-186 (July 1971 to March 1973)

B1. Introduction

During the period September 1971 to October 1972 a series of fourteen crash tests using anthropometric dummy riders was run by Dr. Bothwell at the Motor Industries Research Association Crash Test Facility (MIRA-CTF), Nuneaton, Warwickshire, England. The dummy riders and motorcycles were instrumented with 14 accelerometers; five high speed cameras were used to record the crash event. This appendix summarizes this series of tests. The test results include identification of hazardous aspects of current motorcycle design and accident configurations. These findings confirm and amplify findings in the preceding series of 27 tests conducted under Contract FH-11-7307. The tests provide data on a number of safety design modifications (including the use of airbag impact attenuators fitted to the motorcycle).

B2. Summary of Tests Conducted

The crash test program investigated nine motorcycle accident situations:

1) Skid tests with one and two riders on the motorcycle
2) 45° frontal impact into a static automobile
3) 45° frontal impact into a static automobile using two dummies on the motorcycle
4) Perpendicular frontal impact into a static automobile using two dummies on the motorcycle
5) Impact of a moving motorcycle hit broadside by a moving automobile
6) Perpendicular side impact into a static automobile
7) Perpendicular side impact into a static automobile: pre-inflated airbag
8) Perpendicular side impact into a static automobile: actively inflated airbag
9) Perpendicular frontal impact into a static automobile: pre-inflated airbag

The tests with both vehicles moving required development of a new technique. Two runs were needed to establish correct timing. The tests with two dummies on the motorcycle were new in concept. See Table B1.

B3. Test Track, Instrumentation System, and Test Technique

The MIRA-CTF is described in detail in DOT-HS-800 587. The instrumentation system in this series of tests was similar to that used in the earlier series. However, the rate-gyro was removed in favor of additional accelerometers (with the exception of Test A3-6). Three triaxial sets of accelerometers were used—in head, chest, and pelvis. Four accelerometers were variably placed in the limbs; one was placed near c.g. of motorcycle. In tests of two dummies, only the rear dummy was instrumented with accelerometers because of probable tangling of two umbilical cables.
Table B-1. Summary of Fourteen Crash Tests Run Under Contract DOT-HS-126-1-186

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Type of Motorcycle</th>
<th>Motorcycle Configuration</th>
<th>Speed at Release (mile/hour)</th>
<th>Test Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A4-3</td>
<td>BSA 750 (470 lbs.)</td>
<td>Revised crash bars</td>
<td>30</td>
<td>Skid simulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>One dummy</td>
</tr>
<tr>
<td>A4-4</td>
<td>BSA 750 (470 lbs.)</td>
<td>Revised crash bars</td>
<td>30</td>
<td>Skid simulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Two dummies</td>
</tr>
<tr>
<td>A6-3*</td>
<td>BSA 650 (425 lbs.)</td>
<td>Revised crash bars</td>
<td>20</td>
<td>Broadside impact of moving motorcycle by moving full-sized 1959 Chevrolet</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>(motorcycle)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>(automobile)</td>
</tr>
<tr>
<td>A6-3A**</td>
<td>BSA 650 (425 lbs.)</td>
<td>Revised crash bars</td>
<td>This test aborted due to trolley failure</td>
<td></td>
</tr>
<tr>
<td>A3-10</td>
<td>BSA 750 (500 lbs.)</td>
<td>Revised crash bars</td>
<td>30</td>
<td>45° impact into front of full-sized 1959 Chevrolet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pivoting handlebars</td>
<td></td>
<td>Smoothed tank ramp</td>
</tr>
<tr>
<td>A3-11</td>
<td>AMC 350 (250 lbs.)</td>
<td>Pivoting bars</td>
<td>30</td>
<td>45° impact into front of full-sized 1959 Chevrolet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smooth top contour</td>
<td></td>
<td>Smoothed tank ramp</td>
</tr>
<tr>
<td>A3-12</td>
<td>AMC 350 (250 lbs.)</td>
<td>Pivoting bars</td>
<td>30</td>
<td>Two dummies on motorcycle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smooth top</td>
<td></td>
<td>Perpendicular impact into front of full-sized 1960 Ford</td>
</tr>
<tr>
<td>A3-13</td>
<td>BSA 650 (420 lbs.)</td>
<td>Pivoting bars</td>
<td>30</td>
<td>Same as A3-12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smooth top</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3-14</td>
<td>BSA 750 (500 lbs.)</td>
<td>Revised crash bars</td>
<td>30</td>
<td>Two dummies on motorcycle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pivoting handlebars</td>
<td></td>
<td>45° impact into front of full-sized 1960 Ford</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smooth top</td>
<td></td>
<td>Perpendicular impact into side of 1953 Studebaker</td>
</tr>
<tr>
<td>A3-6</td>
<td>BSA 650 (420 lbs.)</td>
<td>High bars</td>
<td>30</td>
<td>Perpendicular impact into side of 1953 Studebaker</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tempered glass windshield</td>
<td></td>
<td>Fiberglass tank with bag liner</td>
</tr>
<tr>
<td>A7-1</td>
<td>BSA 650 (430 lbs.)</td>
<td>Revised crash bars</td>
<td>30</td>
<td>Perpendicular impact into side of 1953 Studebaker</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Airbag with forward projection pre-inflated to 0.8 psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A7-2</td>
<td>BSA 650 (430 lbs.)</td>
<td>Airbag without forward projection pre-inflated to 0.5 psi</td>
<td>30</td>
<td>Perpendicular impact into side of full-sized 1959 Chevrolet</td>
</tr>
<tr>
<td>A7-3</td>
<td>Honda 750 (520 lbs.)</td>
<td>Airbag with forward projection pre-inflated to 0.5 psi</td>
<td>30</td>
<td>Perpendicular impact into front of 3-litre Rover</td>
</tr>
<tr>
<td>A7-4</td>
<td>BSA 650 (430 lbs.)</td>
<td>Airbag with forward projection equipped with Olin hybrid active-inflation system</td>
<td>30</td>
<td>Perpendicular impact into side of 3-litre Rover</td>
</tr>
</tbody>
</table>

*Two preliminary runs using a motorcycle without dummy rider were made to establish this technique.

**A6-3 and A6-3A were to be identical tests but A6-3A failed when the trolley latching mechanism broke during the run up.
The umbilical cable which transmits the data from the dummy to the recording apparatus is stored behind the motorcycle on the trolley. During the tests the payout of the umbilical cable was modified to allow a high payout with a shock-damped movement built into the pivoting tube. This was of help in reducing fouling of the cable, but there were still instances where the umbilical snagged on the motorcycle. Further development is needed to eliminate this problem.

The skid technique established in Contract FH-11-7307 was used again in Tests A4-3 and A4-4. There was no tearing out of leads as had occurred in previous tests. However, a restriction to 11 channels was necessary in order to reduce the weight of the long umbilical.

A schematic of the apparatus used to perform the tests of a moving motorcycle and moving car is shown in Figure B1. The motorcycle was mounted in the standard manner on the trolley and pulled by the linear motor so that the motorcycle was ejected onto the concrete apron at the rear of the track. The motorcycle was not braked so that the wheels rolled freely. The linear motor was also coupled to a cable which was led via pulleys to the automobile. The automobile was thus pulled at right angles to the linear motor guide rail. The cable lengths were adjusted so that the desired impact geometry was produced.

The pre-inflated airbags in Tests A7-1, A7-2, and A7-3 were mounted on a plate which was attached to the gas tank. These airbags were designed and supplied by American Safety Equipment Corporation. The active inflation system and the airbag used in Test A7-4 was designed, developed, and constructed by the Energy Systems Division of the Olin Corporation. The details of the airbag geometry and installation are shown in the photographs of the respective tests. A pressure transducer was installed to measure the pressure in the bag before and during the test.

B4. Description of Motorcycle Crash Tests

In this section, each of the motorcycle crash tests is briefly described. In the Final Report on Contract DOT-HS-126-1-186 these tests are described in much more detail: pretest photographs, essential frames of the Arriflex 25 millisecond (ms) interval films, and post-test photographs are included to document the test configuration, post-impact motion and damage of the automobile, motorcycle and dummy rider; a narrative of the specific events occurring during each test is given; time-histories of resultant acceleration, head injury indices, and a table of peak g-levels are included; the coverall diagram for each test indicates the contact which occurred between the dummy and the motorcycle.

B4a. Test A4-3: Skid Test with One Dummy

The objective of Test A4-3 was to evaluate the revised crash bar design in a skidding and sliding incident. Of specific interest was the ability of the revised crash bars to prevent trapping of the dummy’s leg between the falling motorcycle and the concrete skid pad. The dummy was held in place on the motorcycle by elastic straps and locked elbow joints. The fuel tank was fitted with a Honda-750 flip-top filler cap. Four gallons of fuel substitute were placed in the tank.

REMARKS: Ejection of motorcycle from trolley occurred successfully. Bike skidded about 70 feet, fell to left, ejected rider cleanly, spun around, flipped over onto its right side. Modified crash bars operated successfully and prevented further rolling of motorcycle when they contacted concrete. Terminal positions of motorcycle and dummy are shown in Figure B2. Motorcycle came to rest on apexes of right-side crash bars and right footrest. Kickstart pedal, brake pedal, and footrests intruded into leg-escape space provided by revised crash
bars. Cable to accelerometer in lower left leg was cut by abrasion between left knee and concrete. Heavy scoring from abrasion by concrete was apparent on contact points of revised crash bars. Left footrest was also scored. Neither footrest broke off. Both crash bars remained intact without deformation or bending. For solo rider revised crash bar design contours limited rolling of the bike and preserved a leg extraction space. Fuel tank, fitted with a Honda-750, flip-top, filler cap, remained intact with no leaking of fuel. Physical damage to dummy was similar to previous skidding experiments emphasizing need for knee and elbow protection and for face protection. Left knee and elbow of dummy were scored. Nose and chin had made sliding contact with pavement.

B4b. Test A-44: Skid Test with Two Dummies

The objective of Test A4-4 was to determine the effectiveness of the revised crash bar configuration in a skidding incident when the motorcycle was carrying a rider and a passenger. The BSA-tank with the Honda-750 flip-top filler cap was used. Turn-indicator lamps were mounted on the front and rear of the motorcycle. Two Alderson CG-50 dummies were seated on the motorcycle—one rider and one passenger. The elbow joints of the rider were tightened so that the rear dummy could lean on the back of the front dummy (the rider). Both dummies were biased to the left to make the motorcycle fall to the left.

REMARKS: Ejection of motorcycle from trolley occurred correctly at 30 MPH. However, rear dummy was apparently thrown forward onto front dummy when motorcycle contacted concrete and was decelerated by friction on tires. Rear dummy then “bounced back” off front dummy. Also, tension in umbilical pulled dummy passenger backward. As a result, rear dummy can be seen leaning back over rear wheel in high speed movies. Motorcycle went into skid, fell to left, spun around, but did not flip over. Dummies both remained on motorcycle and did not detach. Front dummy made sliding pelvis contact with rear portion of fuel tank. Honda cap remained closed with no loss of fuel. Extra weight apparently caused rear wheel locking strut to be pulled out of its anchor. One muffler tore off and jammed into rear wheel. Bike slid well on crash bars which did not fail. Motorcycle was prevented from overturning by crash bars. Dummy heads made no contact with concrete. Leg space between motorcycle and road was still present at end of test. Final positions of dummies and motorcycle are shown in Figure B3. Both dummies finished up with legs beneath bike. Rear crash bars were not in contact with pavement; bike was resting on legs of two dummies; feet were trapped beneath motorcycle. Several artifacts were present which modified motion: 1) position of passenger after ejection from trolley was unnatural, 2) rear wheel-locking strut broke loose (freeing wheel), and 3) detached muffler subsequently jammed rear wheel. Damage to dummies was confined to knees and elbows, particularly rider. No head markings were observed. Turn-indicator lamps were broken off leaving jagged edge. If dummies had come off bike, rear crash bar contour would probably have deflected legs and feet out around broken fixture.

B4c. Test A6-3: Broadside Impact of a Moving Motorcycle by a Moving 1959 Full-Sized Chevrolet

The objectives of this test were 1) to determine the changes produced in the post-impact motion of the moving motorcycle and dummy by the motion of the automobile, 2) to evaluate the revised heavy crash bars in protecting the rider’s legs in a broadside impact by a moving car, and 3) to demonstrate the feasibility of using a cable/pulley system to achieve a desired impact geometry for the moving automobile and
moving motorcycle/dummy rider. In Test A6-3 the impact speed for the system was limited to 20 MPH for each vehicle.

REMARKS: Motorcycle ejected correctly from trolley. Rendezvous of moving car and moving motorcycle occurred as planned. Moving car struck front half of motorcycle broadside. Motorcycle was pushed ahead of car. Crash bar was very severely bent and fractured at a weld. Bike then rotated to side of auto. Dummy was ejected off bike and pitched head long into vertex impact with side of one of cars used as a crash stop. He then bounced off sideways to come to rest on fractured ends of front crash bar (see Figure B4).

NOTE: Test A6-3A was intended to be exactly the same as Test A6-3. However, the trolley did not release from the towing motor correctly and the test aborted.

B4d. Test A3-10: Impact of 500-Pound Motorcycle at 45° Angle into Front of a Stationary 1959 Full-Sized Chevrolet

The objective of this test was to determine how well the revised heavy-duty crash bars, pivoting handlebars, and revised tank configuration would function in a 45°-angled impact of a 500-pound motorcycle into the front of a car. The automobile was placed at 45° to the path of the motorcycle. The geometry simulates an automobile turning left in front of an oncoming motorcycle.

REMARKS: At impact front wheel of motorcycle rotated to left. Dummy slid up "tank-ramp" without severe pitching. Energy-absorbing handlebars pivoted on impact with leg and chest of dummy. Dummy ejected face-down horizontally over car hood. Right leg was not trapped in impact; it did hit right front crash bar and impacted car hood leaving a dent. Dummy scraped head, face, and chest across hood. (See Figure B5.) Dummy passed over car (missing windshield) and landed on its left side (with legs spread apart) at side of indoor crash pad. There was a lateral impact to head on landing. Although emergency brake on car was engaged, car moved backward about 10 feet and off the pad. Fouling of umbilical cable on rear of motorcycle deflected dummy's trajectory downward and away from car. Surface at base of tank-ramp was scored by contact with dummy pelvis. Front wheel of motorcycle was intact, but forks were bent. Crash bars were essentially undamaged. Handlebars pivoted in joints as designed. A chrome strip on top edge of right front fender of car was broken off by impact of face.

B4e. Test A3-11: Impact of a 250-Pound Motorcycle at 45° Angle into Front of a Stationary 1959 Full-Sized Chevrolet

The objective of this test was to determine the effectiveness of the revised heavy-duty crash bars, pivoting handlebars, and revised tank. The automobile was placed at a 45° angle to the path of the motorcycle. Chocks were placed behind the wheels of the car to prevent rearward motion after impact.

REMARKS: Ejection of dummy involved relatively little pitching. Dummy's right knee hit right front crash bar and front edge of hood of car. Handlebars pivoted correctly. Dummy's right leg was not trapped between car and motorcycle. Dummy flew head-first over hood; helmet scraped across surface. Dummy completed path across hood without major head impact (see Figure B6). As dummy fell to side of car, umbilical fouled on rear of motorcycle. Dummy was thus pulled back toward front of car by stretched umbilical cable.
B4f. Test A3-12: Perpendicular Impact of a 250-Pound Motorcycle with Two Dummies into Front of a Stationary 1960 Full-Sized Ford

The objective of this test was to determine the effects of the addition of a dummy passenger on the post-impact motion of the dummy rider and the motorcycle in perpendicular collision with the front of a car.

REMARKS: The two dummies ejected together; passenger pushed rider up tank-ramp into front of car. Front dummy's legs hit edge of hood. Both dummies pitched forward and off motorcycle. Front wheel of motorcycle rotated to left and wedged under bumper of car. Rear of motorcycle pitched up to 30°. Then it rebounded and fell to floor in front of car. Rider's head impacted hood of car; passenger's head hit back of rider's head. Dummies continued to pitch slowly and moved head-first across hood of car (see Figure B7). Both dummies made vertex head impacts with windshield. Front dummy's face was pushed down into windshield/cowl junction and his feet pitched up. Rear dummy suffered hypperextension of neck as his feet continued to pitch up after vertex head impact with windshield. Front dummy bounced back and came to rest on hood and left front fender of car. Rear dummy yawed and rolled as it pivoted on its head off the windshield—then fell backwards onto floor at side of car. Motion of dummies off windshield was affected by umbilical cable which fouled on rear of motorcycle and was stretched back through legs of rear dummy. Dummy rider was held down onto hood by taut cable.

Front forks of motorcycle were bent back and twisted; front wheel was intact. There was heavy scoring on tank-ramp. Left handlebar was broken off at one of welded joints. Magneto casing (in front of engine) was fractured. Windshield of car was fractured but was not penetrated by head impacts. Nose and chin of rider showed scoring from contact with hood of car. Rider made heavy contact with ramp of motorcycle. Handlebars pivoted forward on impact. Rider's lower legs hit bumper on car and left knee hit hood. Passenger's foot contacted left handlebar; passenger's lower right leg hit kick-starter pedal, splitting rubber and exposing bare metal.

B4g. Test A3-13: Perpendicular Impact of a 420-Pound Motorcycle with Two Dummies into the Front of a Stationary 1960 Full-Sized Ford

The objective of this test was to determine the post-impact motion of a dummy passenger and its effect on the motion of motorcycle rider in perpendicular impact into the front of a stationary car.

REMARKS: On impact with car bumper, front wheel was deflected downward and wedged under bumper. Dummy rider and passenger moved forward up tank-ramp. Rider's lower legs impacted car bumper and head/torso pitched violently downward—front of helmet and face impacting car hood. Passenger used rider as energy-absorber and drove lower half of rider into car. In ejection off motorcycle, lower right leg of passenger hit kick-starter pedal. Passenger's head/torso pitched downward and heads made sliding impact. Passenger slid up on top of rider and two dummies moved head-first across car hood. Rider's face was scraped along surface of hood. Both dummies hit windshield. Rider's head did not penetrate glass and dummy rebounded to come to rest on car hood. Rear dummy's head penetrated windshield; dummy's body pivoted about head so that feet came to rest on roof of car producing severe hypperextension of the neck. Head and neck were still stuck in windshield (see Figure B8).
Forks on motorcycle were bent back. Front wheel was bent inward in third quadrant and wedged under front bumper so that motorcycle was standing up after crash. Pivoting handlebars were broken off at welded joint and were carried forward by dummy rider. In impact with passenger's lower right leg, kick-starter pedal tore coverall and cut into leg. Passenger's face had lacerations on cheek and mouth from penetration of windshield. Both dummies made heavy contact with tank-ramp.

B4h. Test A3-14: 45°-Angled Impact of a 500-Pound Motorcycle with Two Dummy Riders into the Front of a Stationary 1960 Full-Sized Ford

The objectives of this test were to determine 1) the changes produced in the motion of the motorcycle and dummy rider by the addition of a dummy passenger and 2) the effectiveness of the heavy-duty crash bars, smooth tank-ramp, and pivoting handlebars in 45°-angled impact.

REMARKS: On impact with bumper, front wheel turned to left and forks bent back. Rear of motorcycle swung slightly to right. Right front crash bar smashed into grill/bumper. Both dummies moved forward together. Rear dummy's hands were taped together in front of rider. In sequence right legs of the rider and passenger hit crash bar/bumper/car front. Impact of rider’s right leg with crash bar/auto ruptured weld at ankle joint. Both dummies pitched down. Rider's head made light frontal impact with hood. Rear dummy impacted rider; heads knocked together. Passenger slid up and over rider pushing him down onto hood. Legs came free of motorcycle; both dummy torsos slid up onto hood. Rider's face and head were scraped across hood. Rear dummy went into somersault with hands still taped around waist of rider. Car was knocked backward over wooden wheel chocks by impact of heavy motorcycle and two dummies. Hence, it was rolling backward as dummies came up onto hood near right front “corner” (see Figure B9). At same time, rear of bike was pitching up and bike was rolling to the left. Net result was that dummy rider came back down onto motorcycle. Rider was “pulled off” bike by attached somersaulting passenger as motorcycle rolled over onto its side. Dummies came to rest on floor beside wooden platform. Hands of passenger remained taped around waist of rider. Trajectories of both rider and passenger were certainly modified by this attachment. Also, umbilical cable fouled on right rear parts of motorcycle. These two factors contributed to violent terminal impacts of dummy passenger on edge of wooden platform and floor.

Motorcycle showed marks of contact between front right crash bar and car; but crash bar was intact. Motorcycle front forks were bent and twisted, but the front wheel was not plastically deformed in this 45° impact. Handlebars pivoted forward but still were hit by both dummies. There was no impact with windshield.

B4i. Test A3-6: Perpendicular Impact into the Side of a Stationary 1953 Studebaker

The objectives of this test were 1) to determine the motion of the dummy rider, motorcycle, and automobile in perpendicular impact of the motorcycle into the side of a stationary car and 2) to establish the impact levels for this geometry for use as a base-line for measuring the effectiveness of an airbag impact attenuator.

The rider was instrumented with 10 accelerometers plus a three-axis rate gyro (mounted in the chest cavity): three sets of two instruments each (one vertical and one fore-and-aft) in head, chest, and pelvis; three instruments in left leg—two in lower leg (one vertical and one fore-and-aft, one fore-and-aft in upper leg); and one accelerometer fore-and-aft in right upper leg.
REMARKS: Motorcycle struck car at bottom of door near middle. Dummy slid forward on motorcycle. In succession, pelvis hit rear of gas tank, gas cap, and the steering head/damper. Rear of motorcycle pitched up; tempered glass windshield shattered into a myriad of small "round/smooth" fragments. Dummy moved upward and off pitching motorcycle and violently impacted side of car. The upper chest smashed into and dented roof line of car. Torso impacted window and door with high handlebars sandwiched in between. Grips of handlebars were under armpits of dummy. Car was rolled to about 15° and moved sideways by impact of motorcycle and dummy (see Figure B10). As motorcycle continued to pitch up past 90°, dummy slid off car and moved down between car and pitching motorcycle. Rear fender of motorcycle came down and hit dummy on the back and head, knocking it into side of car. Fiberglass gas tank was ruptured, but simulated fuel did not leak out of flexible-bag tank liner (which was filled with safe-foam).

B4j. Test A7-1: Perpendicular Impact of Motorcycle Equipped with Pre-Inflated Protuberance-Type Airbag into the Side of a Stationary 1953 Studebaker

The objective of this test was to determine the effectiveness of a pre-inflated airbag (with a protuberance out over the handlebars) in attenuating the impact of the dummy rider in a perpendicular collision of a motorcycle/ rider into the side of a stationary car.

REMARKS: Front wheel hit lower part of door and rocker panel/side beam. Wheel dented in side of car. Front forks were bent back and wheel itself was buckled inward. Dummy began moving forward noticeably about 25 ms after impact. This movement caused airbag to pitch forward slightly before protuberance bumped up against roof edge and car window (about 40 ms after wheel impact). Dummy moved forward into bag with no tendency to slide off to one side. Bag reaction on side of car prevented both dummy torso and motorcycle from pitching forward. Crushing of front of motorcycle and side of car and compression of airbag by dummy continued to increase. At $\Delta t \approx 100$ ms blowout patches ruptured; maximum pressure recorded by transducer was slightly over 5 psi (see Figure B11). Bag did not collapse rapidly enough (after blowout patches functioned) to prevent rebound of dummy off airbag "spring." As dummy bounced back off airbag and motorcycle rebounded off car, rear of motorcycle began swinging around toward rear of car. At $\Delta t = 500$ ms, motorcycle was almost parallel to car. Rebound distance of motorcycle was large enough to allow dummy's right leg to escape being trapped/crushed between motorcycle and side of the car. Heavy-duty crash bars provided protection against leg-trapping, but motorcycle rolled about its longitudinal axis so that value of crash bars was decreased. Dummy somersaulted backward off motorcycle as motorcycle crashed down near rear wheel of car. Dummy rider then fell down and back over motorcycle.

Damage to left door of car in Test A7-1 was very nearly a mirror image of damage to right door in Test A3-6. Damage to edge of roof above door was eliminated by airbag. Damage to front wheel/front forks of motorcycle was also very much the same in the two tests. Airbag forces tore gas tank loose from motorcycle frame. Airbag itself was undamaged in test. Dummy was essentially unmarked and undamaged.

B4k. Test A7-2: Perpendicular Impact of a Motorcycle Equipped with a Pre-Inflated Prismoidal Airbag into the Side of a Stationary 1959 Full-Sized Chevrolet

The objectives of this test were 1) to evaluate the effectiveness of a pre-inflated prismoidal airbag in attenuating the impact of a dummy rider into the side of stationary car and 2) to determine the effects of the simple airbag shape (no forward protuberance) on the motion of the dummy and the motorcycle.
REMARKS: Motorcycle/dummy ejected from trolley onto outdoor concrete crash pad and struck car on lower left door and rocker panel/side beam. Front forks were bent backward and slightly twisted to left. Then wheel started to collapse. Forward displacement of dummy relative to motorcycle became visible at about 30 ms. As dummy slid forward into airbag, bag tipped forward and contacted rain gutter above window about 70 ms after impact. Lower rear edge of airbag caught dummy in abdomen and raised pelvis off motorcycle. During this dummy motion, rear of motorcycle pitched up to about 10°. Airbag was compressed between dummy torso/head and car-roof edge. At about 150 ms, airbag suddenly ruptured on right side and abruptly deflated. Tearing of bag was apparently initiated by pinching of bag material between blowout patch retaining rings and car-roof edge. Both blowout patches remained intact; pressure in bag had reached 5.2 psi (see Figure B12). Before bag ruptured, it decelerated forward motion of dummy and deflected dummy up and off of motorcycle. Elevated trajectory of dummy carried it up over side of car which was rolled over by impact of motorcycle. Dummy actually cleared side of car and was moving over roof when umbilical cable caught on rear of the motorcycle. Rear of motorcycle had pitched up to about 40° and had swung about 10° toward rear of car. As rear of motorcycle fell to ground, snagged umbilical dragged dummy down off top of car. Motorcycle came to rest on right side; dummy ended up lying across top of motorcycle with feet stuck under rear fender of car.

Left door was bashed in, but window was not broken; roof edge was not dented inward. Deformed front wheel and bent forks were typical for 30 MPH perpendicular impact.

Coveralls showed contact between dummy rider and motorcycle was limited to initial low-g bump of pelvis on gas tank and sliding contact between left leg and left handlebar.

B41. Test A7-3: Perpendicular Impact of Motorcycle Equipped with a Pre-Inflated Protuberance-Type Airbag into the Front of a Stationary 3-Litre Rover Sedan

The objectives of this test were to determine 1) the effectiveness of a pre-inflated airbag (with a protuberance out over the handlebars) in attenuating the impact of the dummy rider in perpendicular impact into the front of the car and 2) the motion of the dummy/airbag/motorcycle in the absence of a vertical surface for preventing forward pitching motion of the airbag. Except for the protuberance-type airbag, the motorcycle was in standard street trim.

REMARKS: The motorcycle ejected correctly from trolley and struck middle of front bumper of car. Front wheel pushed bumper up and back into grill; wheel was deformed and front forks were bent back. Dummy moved forward off seat; pelvis/thighs hit rear/sides of gas tank and dented it in; torso/head moved into airbag. Bag pitched forward and protuberance came down onto hood of car. Rear of motorcycle began to pitch up. Dummy made only slight penetration into airbag; blowout patches remained intact (see Figure B13). Airbag was "bent" across two supports—hood of car and attachment to gas tank. (Bag was not compressed as in Test A7-1.) As dummy, intact inflated airbag, and motorcycle bounced back off car, rear of motorcycle began to yaw around to rider's right. Maximum pitch of the motorcycle was about 30°. Forward motion of dummy off motorcycle was so restricted by airbag that dummy did not move off location pins in rear of pelvis. Therefore, as bike fell over, seat was torn from its attachment to frame. Motorcycle came to rest on his right side to right of car. Protuberance of airbag was resting on top of left front fender of car; bag remained inflated and attached to gas tank of motorcycle. Damage to front of Rover is
typical of 30 MPH head-on impacts. Only contact of dummy with car was on left hand. Only significant contact of torso with motorcycle was pelvic impact with gas tank.

**B4m. Test A7-4: Perpendicular Impact of a Motorcycle Equipped with Actively-Inflated Airbag into the Side of a Stationary 3-Litre Rover Sedan**

The objectives of this test were 1) to evaluate the effectiveness of an actively-inflated protuberance-type airbag in attenuating the impact of the dummy rider into the side of a stationary automobile, 2) to demonstrate the feasibility of installing an active-inflation system and airbag on the motorcycle, and 3) to determine the kinematics of the inflating airbag and its effect on the motion of the dummy rider and the motorcycle.

The Olin hybrid inflator unit (high pressure bottle and diffuser) was clamped on a cradle which was welded to the frame above the engine. The nitrogen cylinder was held in place by hose clamps. The gas tank was modified to fit around the cylinder and under the diffuser. The capacity of the nitrogen cylinder was 60 cubic inches. The system was fired by a squib actuator which was connected to a contact switch mounted on an extension of the front fender. The nylon-weave airbag was held onto the motorcycle by the base of the diffuser unit. A pressure transducer tube was inserted into the folded bag on the left side close to the diffuser tube (to try to prevent tearing out of the transducer during inflation). The bag was folded so that the rear section would be most likely to unroll and inflate first. The bag was then taped to the gas tank. The cylinder was charged to 2400 psi with nitrogen.

**REMARKS:** Motorcycle ejected from trolley and struck automobile near rear edge of left front door. Front wheel pushed into door; front forks bent back. At $\Delta t \approx 10$ ms after impact, inflation/deployment of bag was visible. As bag inflated, it pushed back against torso and head. Initial contact of dummy with airbag (at $\Delta t \approx 20$ ms) snapped dummy’s head back. Forward motion of dummy relative to motorcycle was visible at $\Delta t \approx 35$ ms. Airbag was almost fully inflated at $\Delta t \approx 50$ ms; dummy had moved forward about two inches relative to motorcycle; deployed bag filled space between dummy and side of car. Very early in inflation process, bag ruptured close to left end of diffuser tube. Large hole allowed bag to deflate rapidly as dummy moved into it. Penetration of door, deformation of front wheel and bending-back of front forks continued during inflation of bag. At $\Delta t \approx 75$ ms, fully-inflated forward protuberance of bag was against car window and compressed bag was decelerating torso. The dummy’s head/neck was still retroflexed; pelvis had struck gas tank. By $\Delta t \approx 125$ ms, dummy’s head had moved into bag and close to edge of car roof; arms were wrapped around rapidly deflating bag; bag contacted torso from waist up. Torso/head was pitching forward primarily because of pelvic impact on rear of gas tank plus dragging contact with seat/tank. Bag continued to deflate under penetration by dummy and by $\Delta t \approx 200$ ms dummy head contacted roof of car near left windshield/door-pillar. By this time, forward velocity of dummy was almost to zero; dummy remained in almost same position (left arm “leaning” on left front fender and head on roof edge) for about 100 ms. Dummy then began falling slowly to its left toward front of car as its right leg continued to move up and over motorcycle. Rear of the motorcycle also moved around toward front of car. Very little pitching of motorcycle occurred; rear wheel came off concrete about 6 inches. As motorcycle rebounded off car, it rolled to left and came to rest on left side. Dummy turned to its right as it fell back away to its left from car. Dummy continued to fall backward to left and came to rest on its back to left of motorcycle. See Figure B14.

Damage to door was typical of 30 MPH perpendicular side impacts. Airbag prevented violent impact of dummy into roof-edge, window and top of door; that area was thus
undamaged. Damage to front of motorcycle was also typical of 30 MPH perpendicular impact. Dummy was undamaged. Coveralls showed no significant markings. Dummy's left arm hit left front fender of car; head bumped top of car through airbag. Pelvis struck rear of gas tank. Torso and legs did not contact automobile.
Appendix C

Summary of Development of Digital Computer Simulation of Post-Impact Motion of Dummy Rider and Motorcycle

C1. Introduction

In the performance of Contracts FH-11-7307 and DOT-HS-126-1-186, three digital computer programs have been developed. The first was a two-dimensional ten degree-of-freedom (DOF) model of the motorcycle and rider. The motorcycle rider is represented by a seven-DOF system—three rigid body DOF and four internal DOF (shoulder joint, elbow joint, hip joint, and knee joint). The model of the motorcycle includes the three rigid body DOF for plane motion. This program is documented in DOT-HS-800-588. The second program is a modified version of the first. The seven-DOF model of the rider was replaced by a point mass moving against a nonlinear spring representing an airbag impact attenuator. The third program is the first part of a digital computer simulation of the three-dimensional impact; namely, a nine-DOF model for the three-dimensional post-impact motion of the motorcycle. The nine-DOF are the six rigid body DOF for translation of the mass center and rotation about the mass center and three internal degrees of freedom (rotation of the front and rear wheels and rotation of the front fork about the steering axis).

Work is currently underway to modify the CAL-3D-Occupant-Simulation for use as a model for the 3D motion of the motorcycle rider.

C2. Two-Dimensional 10-DOF Simulation

The configuration of the 2D-10DOF model of the motorcycle and rider is shown in Figure C1. The independent coordinates used to describe the position of the system at any time are also shown. Figure C2 gives the free-body diagrams which show the forces which act on various points on the motorcycle and rider. The Lagrangian formulation is used to obtain the coupled ordinary differential equations of motion. The Lagrangian formulation was selected since it is possible to include the forces of constraint in the generalized forces acting on the system along with the external applied forces and to retain the original Lagrangian without change. The numerical solution to the equations of motion is obtained using fourth-order Runge-Kutta formulas. The solution at any time \( t \) is a set of values of the coordinates, their first and second derivatives and any forces of constraint which are present at that time. This information is calculated using a FORTRAN IV program which delivers the output as a printout on the line printer and also constructs a magnetic tape containing all the data computed. This tape is used to provide input to another program which generates input instructions to a Calcomp plotter so that stick figures of the position of the rider at selected time intervals may be drawn. Graphs of any of the characteristics of the system vs. time may be drawn as desired.

This computer program was used to simulate free-flight tests (such as A1-1 and A1-8) for the case in which the angle of the tank-ramp on the motorcycle is 20° and the coefficient of friction between the dummy rider and the ramp is 0.2. Figures C3 through C6 are typical of the output which is produced by the Calcomp plotter.
C3. Three-Dimensional 9-DOF Simulation of Motorcycle

The mechanical model of the motorcycle is a system of connected rigid bodies with relative motion allowed. The motorcycle model is composed of the main frame and engine, the two wheels, and the front fork/handlebar steering mechanism. The system of equations required to describe the motion consists of nine scalar equations. These are the equations for six rigid body degrees of freedom plus the three equations required to describe the motion of the two wheels and the steering mechanism relative to the frame of the motorcycle.

Figure C7 shows the motorcycle in a fixed (Newtonian) frame (X, Y, Z) with a body-fixed coordinate system (x, y, z) located at the center of mass of the motorcycle. The rider is represented by a point mass rigidly attached to the motorcycle and located at the c.g. of a 50th percentile dummy seated on the bike.

The FORTRAN IV computer program uses fourth-order Runge-Kutta formulae to perform the integration of the differential equations. The output is on both the line printer and a magnetic tape. The tape is used to make plots on the Calcomp plotter.

A test run of the 9-DOF model of the motorcycle has been made. This run simulates the motorcycle (with rigidly attached "point mass rider") crashing at 30 MPH into an obstacle which is moving at 30 MPH in a direction perpendicular to the motion of the motorcycle. As expected, the forces exerted on the front wheel by the moving obstacle and the gyroscopic angular momentum of the wheels produced complex coupled rotations about the pitch, roll, and yaw axes.

This computer program will be used to determine effects of target vehicle velocity on the post-impact motion of the motorcycle.
Figure C1. Coordinate system for rider and motorcycle

Figure C2. Free body diagrams of rider and motorcycle
TIME = 0.000 SECONDS

Figure C3. Position of dummy rider on motorcycle at instant of impact

Figure C4. Superposed stick figures showing evolution of dummy motion with time
Figure C5. Trajectory of C.G. of dummy

Figure C6. Time history of force exerted on pelvis of dummy by the motorcycle

Figure C7. Inertial and rotating coordinate systems
Pedestrian Safety Research

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ABSTRACT

Automobile impacts with pedestrians continue to account for approximately 10,000 fatalities and 150,000 injuries on the nation's roadways annually. This remains an area of the total highway fatality and injury spectrum which is virtually unaddressed by present safety standards.

A review of past pedestrian impact research consisting of statistical analyses of accident data, experimental impacts utilizing vehicles and pedestrian surrogates, and development of various analytical pedestrian simulators reveals the areas and direction needed for additional research in pedestrian impact protection area.

The National Highway Traffic Safety Administration's pedestrian impact protection program is discussed and considered in relation to both the objectives of pedestrian injury mitigation and compatibility with the design considerations of the crashworthiness programs.

THE PEDESTRIAN PROBLEM

Automobile impacts with pedestrians account for a significant portion of the total number of motor vehicle-related fatalities and injuries occurring on our nation's highways yearly. Last year the National Safety Council (Ref. 1) reported that 10,600 pedestrian deaths and 150,000 injuries occurred within the United States in 1971. This represents 21.6 percent of all highway fatalities and 2.6 percent of all highway injuries. Yet to date, no substantial measures have been incorporated into the design of vehicles to effect a mitigation of pedestrian injuries and fatalities. In fact, present design trends, motivated by the objectives of achieving a more crashworthy structure, may well present a harsher environment in which the pedestrian must survive.

Detailed analysis of pedestrian accidents in the U.S. by Calspan (Ref. 2), and by Mackay and deFonseka (Ref. 3) in England both indicate that the pedestrian receives his injuries from two main sources: the vehicle and the road. Of these two sources, injuries resulting from vehicular contacts occur somewhat more frequently than injuries resulting from ground contacts, and the vehicular contacts produce more severe injuries than do ground contacts. The major injury producing components of the vehicle are the hood edge, the bumper, the forward hood, and the grill (listed in descending order of severity). The predominant injury to an adult pedestrian from vehicular contact is to the leg, followed by the lower torso, the head, arms, and the upper torso. Considering vehicular contact with children; head injuries become predominant, followed by legs, lower torso, arms, upper torso, and neck injuries. The predominance of head injuries among child pedestrians is attributable to the fact the head is exposed to direct contact with the front of the vehicle while this is not the case with the adult. Severe ground related injuries to the adult and the child pedestrian are to the head, followed by the legs, arms, and the torso.

It is also evident from the pedestrian accident statistics that 77% of pedestrian impacts involve the front of the car and that the majority of these impacts occur at velocities less than 20 MPH. Of the injuries
occurring in frontal impacts below 20 MPH, only 7% can be categorized in the serious-fatal range while 82% of the frontal impact injuries at greater than 20 MPH are serious-fatal. Furthermore, when considering all serious-fatal accidents, 89% occur at velocities below 30 MPH.

Impacts with the side of vehicles account for approximately 20% of all pedestrian impacts, and these impacts result in somewhat less serious injuries than front impact accidents. That is, while 15% of the front impacts were serious-fatal, only 5% of the side impacts were in this severity range.

It is evident from the above data that the pedestrian impact problem is indeed a severe one and that a significant effort should be made to reduce both the fatalities and injuries associated with this phenomenon. The obvious solution would be to entirely separate the pedestrian and the motor-vehicle: An enormous task with a considerable economic burden and a large inherent time delay.

A less ambitious preventative approach to the pedestrian problem would be to strictly control where and how pedestrians and vehicles interact. This is done by markings, signs, lights, and various other devices which not only make both the pedestrian and the vehicle operator aware of each other’s proximity but also limit their movement relative to each other.

However, to insure an adequate reduction of pedestrian injuries and fatalities, an alternative approach, one that assumes that a significant number of the pedestrian-vehicle impacts remain inevitable and that the impact effects to pedestrians must be controlled and minimized, should also be pursued.

But before this approach and any of its supporting research efforts are discussed, it is appropriate to consider past pedestrian research which will lend more insight into the solution of the total problem.

PREVIOUS RESEARCH

One of the earlier significant works was conducted by Severy and Brink (Ref. 4) of the Institute of Transportation and Traffic Engineering at UCLA. They conducted an experimental impact program utilizing dummies and actual vehicles. A total of twelve experiments was run attempting to correlate such parameters as impact speeds, size of car, pedestrian size, impact position, braking or not, and structural characteristics of cars. Some of the conclusions reached from these experimental runs were: 1) At speeds of 10 MPH, impact of the car tends to be of a severity comparable with the subsequent pavement impact. For speeds of 20 MPH and higher, the initial car impact is usually two to three times more severe than subsequent impacts with the pavement, 2) head accelerations resulting from vehicle impact with an adult increase exponentially with increases in impact speeds, while small children’s head accelerations increase linearly with speed, 3) compared with the pedestrian weight, the weight of the striking car, whether small or large, is not a significant injury factor, but the pedestrian-height-to-car-profile relationship determines, in a large measure, the struck pedestrian’s movement and injury exposure, and 4) sheet-metal provides an excellent energy absorber.

Cornell Aeronautical Laboratories (Ref. 2) conducted an investigation of the pedestrian accident problem under sponsorship of the NHTSA. This investigation became a three-part research effort consisting of investigations of pedestrian and cyclist accidents, development and application of a computer simulation to the dynamics of pedestrian impacts, and an exploratory experimental study of impact loadings and structural deformations. The accident investigation phase obtained data defining 265 pedestrian-vehicle impacts in the metropolitan areas of Buffalo, New York, and Toronto, Canada. Several of the significant results of this phase were incorporated in the previous discussion on accident statistics. The pedestrian-vehicle impact model, a two-dimensional, three mass, five degree-of-freedom simulation, confirmed the analysis of both Severy et al. and the accident data, i.e., the severity of injury increases exponentially with the impact speed.
and above 20 MPH the majority of impacts are serious or fatal. The model also gave indications that both the vehicle profile and its structural properties play an important role in both vehicle-related and ground-related injuries and that vehicle braking or the lack of it contributed significantly to the ultimate pedestrian kinematics. The third phase of the investigation, the impacting of actual vehicle components with various head forms, confirmed the greater hazard to head injury from the hood edge when compared with the top of the hood.

Another NHTSA sponsored pedestrian research effort was conducted by the Texas Transportation Institute of Texas A&M University (Ref. 5). This effort is now in its final stages of documentation. It consists of three major areas of investigation; the first being the development of an injury index based on the average strain-energy density in the various body segments and an empirical relationship which assesses the combinatorial effect of several simultaneous injuries of various levels of severity. The second area attempted to assess the relative significance of the approximately 50 parameters observed in the accident investigation statistics of the previous CAL contract and develop a functional relationship between these and the level of injury. This resulted in a relationship containing a linear dependence on pedestrian-vehicle height ratio and a non-linear dependence on the initial impact velocity.

The third area of investigation is an experimental verification of the ability of the three-dimensional TTI pedestrian model to simulate actual tests of a dummy dropped on a vertical vehicle buck. Preliminary results verify the model's ability to simulate some pedestrian-vehicle impacts but a great deal of attention must be focused on determining the pedestrian's (dummy's) initial conditions and the method with which contact forces are analytically generated.

Cook and Nagel (Ref. 6) conducted an investigation of impact injury to the knee joint. The experimental series included impacts to both bovine and fresh cadaver legs. They identified peak impact force as the dynamic variable that correlated most strongly with the degree of trauma produced, but insufficient data prevented formulation of a comprehensive injury tolerance criteria.

A combination of experimental and analytical investigations of pedestrian-vehicle impacts was conducted by the Japan Automobile Manufacturers Association (Ref. 7). This consisted of a series of 26 experiments with velocity of impact ranging from 10 km/hr through 40 km/hr and was one of the first experimental efforts which attempted to assess the effects of extreme vehicle modifications on pedestrian kinetics and kinematics. One such modification was the addition of a large wedge-shaped front end to the vehicle. This introduced a significant reduction in the leg accelerations of the pedestrian at initial contact, probably due in part to energy absorbing characteristics of the structure and in part to the lower point of contact of the structure with the leg. But this latter characteristic became extremely detrimental at higher impact speeds because the structure caused the dummy to acquire large rotational velocities and impact its head more severely at a stiffer area near the windshield.

Other additional investigative efforts [McLean et al. (Ref. 8), and Hall et al. (Ref. 9)] continue to affirm the same basic general facts about pedestrian-vehicle impacts that the previous efforts have. That is, 1) pedestrian impacts constitute a significant portion of the fatalities and injuries attributable to motor-vehicle accidents, 2) the majority of these impacts involve the front end of vehicles, 3) the predominant injuries (legs, lower abdomen, head) are attributable to impacts with either the vehicle or the road, but with vehicular impacts, in general, being somewhat more severe 4) the proportion of pedestrian fatalities increases sharply as the speed of collision rises, and 5) the shape and compliance characteristics of the vehicle's surface not only determine the trauma due to vehicular impact but contribute directly to the pedestrian's subsequent kinematics and resulting trauma from impact with the road surface.
PRESENT STATUS

The research efforts described above contribute to the general understanding of the pedestrian problem yet definitions of specific remedies for the mitigation of the problem are still unobtainable. This inability to pro-mulgate rational and effective performance standards for pedestrian impact protection is the result of, or more specifically, the lack of the following essential elements:

1. The lack of a comprehensive, active, data base, representative of the total pedestrian problem, and the techniques capable of analyzing this data base to locate the major problem concentrations and identify the levels of their significant defining parameters. (This data base could be used later for evaluating the effectiveness of any resulting standards or detect new problems if they should arise.)

2. The lack of quantitative injury measures and tolerances for assessing not only the seriousness of actual pedestrian injuries for input into the data base but the severity of experimental impacts when using pedestrian surrogates.

3. The lack of an accurate, economical method of characterizing and replicating real-world pedestrian accidents.

4. The lack of a systematic method of minimizing the overall hazard to the pedestrian by determining the optimum practical combination of the many controllable parameters which define the pedestrian-vehicle impact.

FUTURE RESEARCH

Cognizant of these technical deficiencies, the NHTSA has formulated a comprehensive research plan (Figure 1) which will address all the significant areas needed to effect a solution to the pedestrian impact problem. The emphasis of these planned efforts will concentrate in both the analytical and experimental areas.

In the analytical area, the modeling of the pedestrian in the impact environment will be done at two levels; gross-motion simulation and detailed structural modeling. The gross-motion simulation will determine the kinetics and resulting kinematics of a pedestrian-vehicle impact. It will allow an investigation of the relationships between the many parameters which define and control the outcome of an impact. A simulation of this type will necessarily sacrifice some of the details of the impact event in order to accommodate the larger scope of the investigation economically.

Therefore, to understand the impact phenomenon more fully, detailed structural analysis techniques are also being developed and applied to areas which will greatly benefit the pedestrian program. This includes finite element models of both the head and neck and the thorax. These models will contribute to the understanding of the prevalent injury mechanisms occurring during impact and to the development of realistic injury tolerance criteria. The finite element techniques will also be utilized in characterizing the vehicular structures that the pedestrian has contact with, i.e., the bumper, fender, hood. Additional efforts are being directed toward the development of general analytical techniques capable of determining the contact forces and their distribution between two impacting deformable structures. This will then allow merging of the human and vehicular finite element models to obtain a complete description of the vehicular response and the resulting human response and injury. This capability will also be extremely useful as a design tool in evaluating prospective vehicular materials and configurations.

The experimental areas will not only provide material parameters and validation data for both the gross-motion simulators and the finite element representations but supply the necessary data to formulate injury criteria, conduct tests to evaluate experimental modifications, demonstrate production feasible designs, and develop compliance procedures and devices.

Several research contracts for fiscal year 1973 address specific areas of pedestrian safety research. One contract, entitled "Body-Vehicle Interaction," will attempt to
Figure 1. Pedestrian protection program

quantify the forces, accelerations, velocities, and resulting injuries to the legs and lower abdomen of pedestrians being struck by automobiles. The research emphasis is on understanding the injury mechanisms and developing realistic injury tolerances for these body areas. To insure this, the use of unembalmed cadavers, placed in an experimental configuration which accurately duplicates the loading conditions of one of the several predominant pedestrian impact modes, is required. In addition, the program will investigate the material properties of candidate energy absorbing bumper coverings for their injury mitigating potential and the effectiveness of the most promising will be experimentally evaluated.

Another research contract entitled, "Contact Loads-Experimental Study," will attempt both the experimental determination and analytical characterization of contact forces during a pedestrian-vehicle impact. Initially, validation of the Calspan 3-Dimensional Crash Victim Simulator (Ref. 10) in a pedestrian configuration will be conducted. Since the entire motion and any resultant measure of injury calculated by this mathematical simulation is a direct result of the contact force algorithms used, it is imperative they receive the closest scrutiny and be completely validated to assure the accuracy of future simulations. To guarantee this, the validation phase will include not only a correlation with the dummy drop tests previously conducted at the Texas Transportation Institute, but it will also attempt correlation with an additional eight experimental pedestrian-vehicle impacts using extensively instrumented dummies and fresh cadavers. If the present contact force algorithms prove inadequate, they will be revised or alternative formulation will be constructed.

The contract also calls for a restructuring of the Calspan model so that when sufficient experimental kinematical data is inputted (i.e., accelerations, velocities, and displacements), the kinetic contact forces, which the motion was a result of, can be calculated as functions of time. This could eventually provide a good compliance technique because
it would eliminate the necessity of incorporating load cells in any vehicle being tested.

A third contractual effort, entitled, "Pedestrian Model Parametric Studies," addresses the problem of how to best utilize large analytical simulators when attempting to optimize a problem such as the pedestrian one. Since the complexities of these models require a considerable effort in constructing their input modules and each run results in a cost of several hundred dollars, it is essential that any optimization technique utilized must be capable of characterizing the desired objective function in the n-parameter space as quickly as possible and searching this resulting hyper-surface to determine the optimum point with a minimum number of iterations. The contractual effort will initially conduct an extensive review of optimization techniques. They will be ranked by their ability and efficiency to perform optimization and parametric sensitivity studies on complex non-linear models and objective functions. Then, if necessary, additional theoretical development will be pursued to develop a unified optimization technique capable of handling problems as complex as the pedestrian one.

Once this is achieved, the technique will be applied, utilizing the best available analytical pedestrian simulator and the most accurate injury assessing criteria, to determine the optimum combination of the many vehicle parameters which will minimize the overall injury producing hazard of vehicles to pedestrians.

Future NHTSA efforts will then attempt to validate experimentally the efficacy of the design changes determined to be most beneficial to pedestrian injury mitigation, and develop demonstrations of production feasible modifications of these specifications to present vehicles. Strong effective coordination will exist between the pedestrian safety research programs and the occupant crash survivability programs to not only insure that the resulting structural specifications of one program are not contradictory with the other but that they combine to give an optimum combination of specifications that mitigate the hazards of both crash environments.

To ensure effective application of the resulting pedestrian protection standards when promulgated, parallel efforts will develop both test equipment and procedures which will determine if any given vehicle design can comply with them.

CONCLUSIONS

The severity and magnitude of the national pedestrian-vehicle impact problem has been recognized and a significant effort has been undertaken by the NHTSA to effect a reduction of both pedestrian injuries and fatalities. This effort not only continues the accident avoidance approach now underway but specifically addresses itself to the problem of mitigating the effects of the actual pedestrian impact.

Deficiencies in the past efforts of pedestrian impact research that have prevented the establishment of effective vehicle standards have been identified and specifically addressed by new research efforts. These immediate efforts coupled with appropriate follow-on efforts will determine the feasibility of and hopefully result in the ability to design and specify general structural and geometric characteristics of vehicle fronts which will mitigate the pedestrian's extreme vulnerability to injury during impact.

References


Questions & Answers

CLYDE ROCKMORE, NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION:
I'll ask the question so the rest can hear it. In the past studies, either accident studies or research and development, has it been ascertained as to the extent to which protuberances like the old hood ornaments and things of this kind contributed to the percentage of injury as opposed to the contour or blunt trauma to the vehicle?

Reading through the literature, I've found there are contradictory opinions to this. Some say the elimination of some of the things—very strong things—like side mirrors and things like this—at least on the right side where the predominance of pedestrian impacts occur, on the side opposite of the driver—would seem to be desirable—or possibly breakaway things. But the direct correlation of injury to a specific type of ornament or something like that has not been made.

CARL NASH, PUBLIC INTEREST RESEARCH GROUP:
Right now the NHTSA has only one standard which could be considered to be a pedestrian standard and that's the one that eliminates wings on the wheels or hubcaps of cars. Is it a political decision or is it a lack of confidence in the NHTSA, or what, that doesn't allow similar kinds of standards to eliminate sharp protrusions on cars, sharp front edges such as on hoods which are relatively unyielding, and that kind of thing as an interim standard until all this sophistication which really seems to be akin to counting the number of angels that can be found on the head of a pin—well, you know, tens of thousands of people are dying and being injured by cars . . .

They tell me that these protrusions are the cause of tens of thousands of injuries but I see no direct correlation between these.

Can I have an answer to that question? Is it a political decision or . . .?

I can't answer that question.
DR. JOHN STATES, UNIVERSITY OF ROCHESTER:
I did want to comment on front-end design a little bit. We think we're going to see more lower extremity injuries because of the energy absorbing bumpers which have been moved away from the bodywork. The numbers that we have in our own hospital are still so small but I'm reluctant to talk about it. This in part begins to answer the questions that are raised in the back about the hazards of front-end design and I admit it's been a very difficult thing to get a hold of statistically. We have a problem at this point—we can't demonstrate effects statistically but believe there will be an effect from the new bumpers that have been moved away from the front end of the car and are a protrusion that sticks out further than it used to. I also wanted to raise the question of examination—determination of injury mechanisms. I think this is a key point in designing any of your programs and I noticed on your chart that it didn't begin until funding year 1974. This actually isn't true of Cornell. Of course, it tried to determine injury mechanisms in their cases and well, I think this is a key point in developing the program—the establishment of the injury mechanisms that the pedestrians sustain.

That's true, and predominantly it's the leg injury for which we have really no tolerances at all right now from the impact loadings that they see. So we definitely are pursuing it.
Status and Measurement of Vehicle-In-Use Defects

Fernando Oaxaca
Ulrasystems, Inc.

ABSTRACT

Over a period of nearly three years, Ultrasystems, Inc., of Newport Beach, California, has been involved in a series of research efforts leading to establishment and development of a reliable data base for studying the safety and performance status of the passenger automobile population of the United States. Two sequential programs, one of which is still in progress, were contracted by the Department of Transportation (DOT) to collect vehicle-in-use data from 7,000 automobiles in ten states having a variety of terrain and climatological characteristics, varying motor vehicle inspection laws, and varying vehicle usage characteristics, such as urban vs. rural. The majority of these data was collected through the utilization of privately owned, fixed-site diagnostic centers using uniform component test criteria. A seven-month program was also conducted in the last half of 1971 which resulted in the collection of in-use data of 3,300 automobiles, all being operated in the vicinity of Bloomington, Indiana. Data collection involved the use of a portable van test facility originally developed for NHTSA. To analyze the collected data a new computer program was developed for data storage, retrieval, and analysis that could support ongoing and future data collection efforts. The program included built-in analytical capability, automatic defect decision-making and categorization by the computer upon comparison of test data with specification values built into the computer program and a capability to automatically plot graphs and curves presenting outage frequency, percentages, and the like against vehicle makes, models, model years, vehicle mileage, and vehicle age at different hardware system levels. All research efforts have shown that certain vehicle components consistently display out-of-spec conditions. Such components or functions include brakes, steering components, parameters involving front wheel alignment, and tires. These findings appropriately support a variety of related research programs conducted by other contractors to assess the effects of such component degradation. Ultrasystems is now completing fabrication and assembly efforts for a second portable van system utilizing knowledge gained from the Bloomington effort to improve van construction and equipment. Also in progress is an eighteen-month project which began in June 1972, which involves data collection in six states using the original van and, eventually, the new van.

RESEARCH OVERVIEW

Ultrasystems Incorporated of Newport Beach, California, has been involved in a type of research for NHTSA which is significantly different from the many activities to be described by others in papers for this symposium. The two main distinguishing features of this work which Ultrasystems has been engaged in for the last three years are: 1) it has been typified by large-scale data collection and has involved samples of thousands of automobiles in dozens of locations around the United States; and 2) the information has been gathered at the end of the pipeline, so to speak, of the automotive industry, i.e., the privately owned automobile being operated by the consumer. This work and the work of others described in this paper has all been in support of the Vehicle-In-Use program of NHTSA which focuses on research activities involving motor vehicles after design, after manufacture, after distribution, and after they leave the new car dealer.

The efforts of two early researchers, TRW Systems of Redondo Beach, California, and the Automobile Club of Missouri of St. Louis, followed up by Ultrasystems in the last few years, have focused on the actual measurement of the functional and safety status of automobiles in actual operation on streets and highways through detailed and comprehensive
inspection of dozens of parameters and hardware elements and the formulation of that collected information into useful statistical data that can assist in safety standard design and validation, evaluation of motor vehicle inspection programs conducted by states, and support to other automotive safety related research of NHTSA. In general, a detailed and carefully structured inspection of thousands of automobiles through the use of both fixed and portable diagnostic facilities has led to the generation of a data base that now includes over 20,000 vehicles of 25 models and 13 model years. This massive compilation of information is now available to NHTSA in Washington, D.C. and a computer program is available for further data storage and retrieval purposes, as well as to conduct certain analyses on demand on the data sample.

Although other initial efforts had taken place in the United States and in Europe, the first comprehensive vehicle-in-use status measurement activity was done by the then NHSSB under contract with the Automobile Club of Missouri at the Auto Club diagnostic center from 1968 to 1970. This involved the collection of diagnostic data on approximately 12,600 automobiles involving eleven American makes and two foreign manufacturers. This study first revealed on a formal basis the nature of the most common automotive defects that could be revealed by diagnostic center inspection and first indicated in formal measured terms the degradation of vehicle status with age. Concurrently with the work at the Auto Club in St. Louis, TRW Systems conducted a vehicle-in-use status study which explored the possible effects on vehicle condition from other factors such as terrain, climate, type of vehicle usage, and other such parameters. Data was collected on more than 13,000 vehicles in addition to a baseline sample of 7,000 cars from the Auto Club of St. Louis study. The automobiles in the sample came from such diverse locations and environments as the hot and dry climate in Tucson, Arizona, hot and wet with salt atmosphere environment in Miami, Florida, cold and dry Denver, Colorado, hilly San Francisco, and rural Salem, Oregon. Also included were Riverside (California), Seattle, and Detroit.

The TRW study results, which were also examined by the John I. Thompson Company of Rockville, Maryland, again showed that the differences in defects per vehicle between makes of cars are slight but that the differences between model years are great. One other critical finding came from this study that led to changes in later work. The bulk of the TRW data samples was collected in the form of inspection reports provided at random by commercial diagnostic centers across the country from such organizations as were willing to provide the data to a federal research program. A striking difference was found between the percentage of defects per vehicle of the same make and model but inspected at different diagnostic centers. It seemed fairly clear that these differences from center to center could not be attributed to the parameters of geography, climate, or vehicle usage. This study thus also pointed out, through thousands of real data points, the need for significant uniformity in diagnostic center processing if the information collected from different centers was to be combined to forecast trends or identify particular problem areas by make, model, or other parameters. It also highlighted the problems of standardization in inspection procedures and processes for any universal motor vehicle inspection effort common across all states.

Ultrasystems began its research in this field in 1970 with what was to some degree an extension and refinement of the TRW effort. There were some important differences. There was significant attention paid to the question of diagnostic center uniformity, a serious effort was made to utilize previous research for the generation of a new set of inspection criteria, and the study focused not only on adding to the data base but on attempting to identify any differences in the condition of vehicles in four states with varying status as regards mandatory vehicle inspection. Approximately 2500 inspection
samples were collected and analyzed in California, Pennsylvania, New Jersey, and Washington, D.C. This new data was compared against 8,000 data sets from the Automobile Club of Missouri, still using ACM as a baseline data bank. More specific results are presented later in this paper.

Subsequent to this initial effort, Ultrasystems conducted a different project in Bloomington, Indiana, which involved the inspection and data analysis of approximately 3300 automobiles, with the major variation from previous work being that a portable diagnostic van developed by RCA was used for testing. This mobile inspection facility had been developed and supplied to NHTSA by RCA some time previously but had never experienced extensive field utilization until the Bloomington study by Ultrasystems. The Ultrasystems effort resulted not only in extensive experimentation with large-scale portable facility inspection, but in the collection of thousands of data points that tended to validate fixed facility results and which were added to the total data bank. Additionally, a significant number of improvements to portable facilities was suggested by the study, which culminated in a subsequent effort to build a new mobile facility for NHTSA. In June of 1972, Ultrasystems began the design and assembly of a new multipurpose mobile inspection van which reflected improvements and augmented capability developed by the Bloomington study, and that van is now (May 1973) about ready for operational usage.

Two other related and current studies are presently under way for NHTSA and being conducted by Ultrasystems. One involves further and extensive inspection data collection and analysis on approximately 3500 automobiles in several states new to the previous data base and with varying status of vehicle inspection laws. Additionally, a significant effort is under way using the original RCA portable facility for data collection in the states of California, Texas, Missouri, Illinois, Pennsylvania, and Maryland. The new van assembled by Ultrasystems will shortly join the other one in the state of Missouri and the two will work concurrently in that state as well as in Illinois, Pennsylvania, and Maryland. This collection process will add significantly to an understanding of vehicle status in states with different motor vehicle inspection laws and permit further study and validation of the concept that inspection data from fixed and portable facilities can be correlated and used jointly for research and for assistance to policy and legislative decisions.

TEST CRITERIA DEVELOPMENT

The preceding discussion is designed to provide an overview of the beginnings and the status of a very large and significant data base now available to NHTSA which provides realistic information on the functional and safety status of a very representative sample of the vehicle-in-use population in the United States. What follows will cover briefly some of the considerations taken into account during this research, some of the results and interesting findings, and certain factors arising from this effort which could impact future activities. Though this particular description may appear disjointed, there was a serious and thorough effort made to conduct these studies with continuity, integration, and maximum exploitation of previous efforts.

Inspection criteria is a good example of this evolutionary approach. Uniform criteria for inspection to be used by the automobile mechanics who conduct the actual testing is of course critical in order to draw conclusions with statistical validity when the sampling is made across a large variety of makes and models and over a wide geographical dispersion. The "granddaddy" criteria is the D-7.1 criteria generated by the United States of America Standards Institute of New York. The Automobile Club of Missouri, in its 1969-1970 work, put together its own criteria which incorporated some features of the D-7.1 and which was more rigorous in many areas. TRW in its research, utilized both of these criteria sets in the formulation of the overall specifications for their study. From
these prior efforts, Ultrasystems evolved criteria which are presently in use and which took the best elements of all and focused on improving the criteria in terms of minimizing human judgment in final results. The overriding concept in all criteria is that the vehicle condition be compared against a standard which in many cases is the manufacturer's specification. Since the data must be computerized because of its tremendous volume, and because a "go-no go" decision is necessary for each data point, many problem areas arise. It is difficult to write a firm and unambiguous criterion for how frayed a safety belt can be before it is unacceptable. It is similarly difficult to specify how loose a ball joint in the front end of an automobile can be before it is considered a defect. It is also clear that every manufacturer has different specifications and indeed there are countless variations even within different makes from the same manufacturer and even from one Ford to another or one Chevrolet to another. Ultrasystems and NHTSA today believe a pretty good set of criteria exists which is acceptable for standardized inspection on a national basis. However, there are still obvious areas for improvement and the manufacturers continuously add dimensions to the problem. Nevertheless, after four or five years, things have pretty much settled down and the criteria being used is considered quite satisfactory for research and other purposes.

DATA PRESENTATION AND ANALYSIS

The handling of tens of thousands of data samples is a problem common to many research programs today. The computer program available today to NHTSA is again a child of evolution. The early efforts of both the Automobile Club of Missouri and of TRW led to the generation of computer programs that would not only permit data storage and retrieval but some amount of categorization and analysis. In the last three years, learning from previous efforts and often encountering unforeseen needs, Ultrasystems has engaged in an almost continuous effort to provide a universal computer program that could not only handle immediate requirements but be amenable to growth and change as the data base grew, as different types of vehicles fed into the data base, and as different analytical requirements developed. As in the criteria area, things have settled down somewhat and the present computerized storage and analytical tool satisfies present and most identified future needs. The computer is now used as a tool for doing state-to-state comparisons, for producing extensive statistical analyses, and even for generating plots of interesting and useful data as required. One important feature of the existing program is that it has built into it the comparison capability of a number recorded by the inspecting mechanic against the manufacturer's specified number for that particular component or parameter. With the tremendously varying specifications for different makes and models, it can be appreciated how eventually such a program can just grow and grow. Thus it is essential to control such growth.

Figure 1, following, presents a summary of the analytical and statistical data treatment

- Chi-square tests for all major outage rate comparisons with a given file
- t-tests for "variable" comparisons
- linear and quadratic regression estimates for variables
- equivalent statistical comparisons for special outage rate indices
  - objective component index
  - safety sensitive component index
  - hot/dry component index
  - cold/wet/salt component index
  - stop-and-go driving component index
- overall "cross-file" statistical comparisons between given files of interest

Figure 1. Summary of computer software analytical capability
possible with the present computer program. Figures 2-4 are typical computer plots of research data which are presently within program capability. Figures 5 and 6 are typical results from computer program-assisted analysis which permits comparison of certain parameters under different situations or environments.

**FIXED TEST SITES**

It is fairly general knowledge that the diagnostic center industry has experienced much change in the last few years. At one time, a study by Northern Research and Engineering performed in 1969 indicated that to carry out a nationwide motor vehicle inspection system might require 7,000 diagnostic centers across the country. It is quite difficult to establish what a reasonable number might be considered to be today. However, the problems TRW encountered in 1969 were repeated for Ultrasystems through the years and they entail several specific areas that will always plague researchers in the field. They include:

1. Finding available diagnostic centers in the geographical area where it is desired to collect inspection data, not only in terms of a particular city but in terms of the neighborhood within that city where it is possible to attract the right vehicles of the right types.

2. Having located an appropriate center, convincing the center management

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**Figure 2.** Computer plot of component outage vs. model year

**Figure 3.** Computer plots of subsystem outages vs. vehicle age groups

**Figure 4.** Computer plot of vehicle model percentage distribution in overall sample
STOP-AND-GO DRIVING INDEX—ALL CARS (TABLED: OBSERVED OUTAGE RATE, %)

<table>
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<tr>
<th>Component</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>$\chi^2$</th>
<th>Sig. Code*</th>
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<td>2.0</td>
<td>9.61</td>
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<td>16.4</td>
<td>1.88</td>
<td>–</td>
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<td>Total Index</td>
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*Significance Code:
– = Not significant.
+ = Significant at 95% confidence level.
++ = Significant at 99% confidence level.
+++ = Significant at 99.9% confidence level.

Figure 5. Typical results from computer program-assisted analysis

that the research activity will not significantly interfere with the center’s normal business and convincing them to cooperate in terms of using appropriate inspection criteria, good mechanics, and other such features which they view as contributing to financial losses.

3. Finding centers that not only have appropriate quality in diagnostic and test equipment but have the other hallmarks of a competent near-laboratory environment such as cleanliness, organization, and good management.

4. Finding centers which do not use the diagnostic function solely as a come-on to attract unwary vehicle owners with the intent of selling them significant and possibly not totally necessary repair work.

5. Locating centers which permit the research organization to train their personnel to do inspection specifically against proper criteria and quality standards and which permit research organization personnel to implement a continuing program of training and surveillance of center effort to assure uniformity and consistency of quality work while research data is being collected.

The above parameters have made this element of research in the field a very difficult process indeed. This situation calls for great wariness and care on the part of the
# VARIABLES—COMPARISON BETWEEN STATES (TABLED: OBSERVED MEAN VALUES)

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<tr>
<th>Variable</th>
<th>Washington</th>
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<th>Arizona</th>
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<td>0.232</td>
<td>10.77</td>
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*Significance Code:
  ++ = Significant at 99% confidence level
  +++ = Significant at 99.9% confidence level

Figure 6. Typical results from computer program-assisted analysis
research organization in the selection of centers and then tremendous skill in negotiation and diplomacy to assure that a good center, once located and signed up, can provide consistently high quality data to the research effort over a long period of time.

MOBILE TEST SITES

Ultrasystems probably has more experience than anyone else in the country in the utilization of portable diagnostic facilities for research quality inspection data collection. From a data collection standpoint, the portable facility offers fewer headaches than the fixed diagnostic center site. On the other hand, in all its activities, Ultrasystems has always used its own mechanics and helpers and these individuals have generally traveled with the portable vans across the country. The problem in using local labor while moving from state to state is obvious. It is not only an economic problem but a data quality issue to have to train new people every time there is a move. Thus, it has been necessary for Ultrasystems to find not only competent mechanics and support personnel that were free to travel and be away from home for long periods of time, but, after training, promised some reasonable permanence on the job. A continuing concern, for obvious economic reasons, is to ensure processing of as many vehicles per day as equipment and personnel capacity will allow. Thus, when there is only one testing system, it is essential to maintain the equipment in a preventive sense and have a quick response capability when something breaks down. Additionally, the field effort is always subject to generally unforeseen problems such as weather, local traffic patterns, and the location of an appropriate site, and the very basic issue of attracting people to a facility that was not there the last time they drove by. When operating in a remote site, there are other logistics arrangements to be made such as installing a temporary telephone capability, hiring a receptionist to greet and comfort impatient vehicle owners, and hiring junior-level mechanics' helpers for helping process the automobiles.

A most recent Ultrasystems activity, in addition to the data collection process, has been the construction of a new portable van for DOT. Figure 7 shows an artist's rendering of this new van which is more formally called a mobile inspection facility. A consideration in this and all other Ultrasystems effort has been a continuing attempt to move towards maximum correlation capability between fixed and portable sites and to minimize variability effects in the data from the total different data collection problems that accrue to both approaches.

TEST VEHICLE PROCUREMENT

During the years, one important thing has been learned about separating a vehicle owner from his vehicle. This is that it is very difficult! Since inspecting a car in a fixed diagnostic center has involved a more comprehensive testing, the owner is usually deprived of his car for about an hour. Using a portable system, this can be cut down to about half an hour. Nevertheless, and it varies from state to state and site to site, people are interested in what NHTSA is doing; they are interested in the fact that research may be contributing to automotive safety, but their personal participation does create an inconvenience for them. Every practical technique has been used to

Figure 7. Mobile inspection facility
encourage public participation, ranging from newspaper and radio advertising to direct mail based on random sampling from computerized registration lists, and from random drops at commercial diagnostic centers to vehicles stopped by a law enforcement officer and waved into a portable test facility. Since the latter approach has always been on a voluntary basis, even that is not a positive way to ensure optimum utilization of facilities in a cost-effective sense. The direct mail process is expensive, not too productive, and more recently has been used only to fill in scarce portions of a preestablished data sample of certain makes, models, and model years. Newspaper advertising is reasonably cost effective but is rapidly saturated in a given locality. Such advertising also varies in effectiveness between small communities, where it is better, and in a large city. Setting up in shopping center parking lots and state fairs has been determined to be quite unproductive and not the way to go.

It has also been found that incentives do not really work with someone who does not have the time to cooperate. Ultrasystems has tried money, a full gas tank, free lubrication, etc., but the best solution is an interested vehicle owner who is willing to take time from his day-to-day life to contribute to what he considers an important governmental research activity. In some ways, the mobile facility can be quite effective because in effect it is taking the mountain to Mohammed, and people are intrigued by what is happening. It is important to summarize that procuring test vehicles has always been a most difficult part of this type of research.

INTERESTING STUDY RESULTS

Following is a small sample of some of the interesting findings that have come from Ultrasystems' research efforts. It is impossible to condense even the more significant results of three years of study activities in a paper of this type. However, the following charts may pique reader interest to the point of ordering some of the pertinent reports from the Technical Information Clearing House.

The first set of charts (Figures 8, 9, and 10) presents quantitative summaries of the makes, models, and model years of the vehicles inspected and presently included in the overall NHTSA data bank. Automobile data collected under Contracts FH-11-7525 and HS-094-2-253 come from inspection at fixed commercial diagnostic centers except for the sample of about 500 cars from Connecticut which were run through the RCA mobile facility. The Bloomington sample of 3,297 vehicles is all from the mobile system.

An interesting comparison of vehicle condition is shown below from the 2,476-vehicle sample of Contract FH-11-7525. It indicates the variation in component outage rates with PMVI characteristics of four states (Washington, D.C. is treated as a "state"). Pennsylvania has twice-a-year inspection through licensed stations. Washington, D.C. and New Jersey require once-a-year inspection at a state-operated facility, and California has a random system of inspection performed by State Police at roadside which is planned to test about 10-15 percent of the state vehicle population once a year.

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Figure 8. Quantitative summary by make, model, and model year
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Figure 9. Quantitative summary by make, model, and model year
This data has been normalized to allow for 18 components which are not inspected in Washington, D.C.

Another look at the same vehicle sample is provided in Figures 11a, 11b, and 11c, wherein individual component outages can be compared from state to state. Figures 12 and 13 identify the components found to be most frequently out of specification in the two fixed diagnostic center samples of 2,476 and 3,358 vehicles, respectively (see Figures 8 and 9 for distribution).

Figures 14, 15, 16, and 17 show comparisons of outage rates for different Make/Model groups and a summary of lowest and highest rates by make for selected components within the total sample of 2,476 cars tested in 1970-1971. Figures 18 and 19 show change with vehicle age and mileage of two variable parameters, comparing variability by state.

HS-094-1-130
DATA COLLECTION SUMMARY
Bloomington, Indiana

DEFINITION OF MANUFACTURER GROUPS

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| Total          | 57   | 95   | 183  | 222  | 367  | 398  | 388  | 451  | 473  | 401  | 262  | 3297 |

*Figure 10. Quantitative summary by make, model, and model year*
POSSIBLE FUTURE RESEARCH

From the above description of the efforts of other researchers as well as Ultrasystems, it is clear that vehicle-in-use research, like that done in many fields, only illuminates new questions and generates new and interesting research tasks. A few intriguing ones that are worthy of consideration are the following:

1. Conduct a new and comprehensive study of what is happening in terms of PMVI in every state in the nation and assess on a cost-effective basis, based on today's knowledge, the true impact of nationwide standardized PMVI.

2. Study carefully, particularly for purposes of nationwide PMVI concepts, the advantages and disadvantages of fixed vs. portable diagnostic facilities and the determination of how both of these concepts might be "frozen" at some acceptable quality level so as to permit such nationwide PMVI with maximum utilization of existing capital investment in such facilities.

3. Examine carefully the results of all vehicle-in-use data collected to date and from this analysis generate a comprehensive set of inputs to automotive design and/or safety standards that would eventually reduce vehicle defect rates and contribute significantly to a reduction in cost to the consumer of using his automobile in terms of reliability, maintainability, and endurance.

4. Analyze carefully research organization experience in projects such as those previously described and other

### STATE MOTOR VEHICLE INSPECTION OUTAGE RATE COMPARISONS

PMVI vs. RANDOM MVI

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<td>55. Turn Signal Lamp</td>
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<td>56. Brake Failure Lamp</td>
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<tr>
<td>Totals</td>
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<td>1410</td>
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</table>

Statistical Comparisons:
- Outage Rates: 6.28% vs. 13.28% vs. 9.23% vs. 12.88% vs. 6.58% vs. 10.25%

Chi-Square Test: 747.46 > 99.9
Significance Percentile 173.63 > 99.9

Figure 11c. Component outage rate comparisons
**COMPONENTS FOUND TO BE MOST FREQUENTLY OUT OF SPECIFICATION**

<table>
<thead>
<tr>
<th>Component</th>
<th>Components Tested</th>
<th>Outages Found</th>
<th>% Outages</th>
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</thead>
<tbody>
<tr>
<td>1. Air-Fuel Idle**</td>
<td>1402</td>
<td>830</td>
<td>59</td>
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<td>2. Brake Ratio**</td>
<td>2303</td>
<td>1283</td>
<td>56</td>
</tr>
<tr>
<td>3. Toe-In</td>
<td>1831</td>
<td>1015</td>
<td>55</td>
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<tr>
<td>4. Ignition Breakdown</td>
<td>1897</td>
<td>979</td>
<td>52</td>
</tr>
<tr>
<td>5. Dwell</td>
<td>2000</td>
<td>953</td>
<td>48</td>
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<tr>
<td>6. Ignition Timing-Basic</td>
<td>1986</td>
<td>896</td>
<td>45</td>
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<td>7. Tire Pressure Spare*</td>
<td>1988</td>
<td>833</td>
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<td>8. Air-Fuel Cruise**</td>
<td>1523</td>
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<tr>
<td>9. Headlamp Aim</td>
<td>2034</td>
<td>790</td>
<td>39</td>
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<tr>
<td>10. Ignition Timing-Advanced</td>
<td>1891</td>
<td>630</td>
<td>33</td>
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<td>11. Air-Fuel Power**</td>
<td>1712</td>
<td>507</td>
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<td>12. Tire Pressure LR*</td>
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<td>707</td>
<td>29</td>
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<td>13. Tire Pressure RF*</td>
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<td>14. Tire Pressure LF*</td>
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<td>21. Front Shock Absorbers</td>
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<td>19</td>
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<td>22. RF Camber*</td>
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<td>16</td>
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<tr>
<td>23. LF Camber*</td>
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<td>16</td>
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<td>24. R Shock Absorbers</td>
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<td>25. Brake Fluid Level</td>
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*Outage criteria modified on current contract
**Component deleted on current contract

*Figure 12. Out-of-specification components fixed diagnostic centers*

large data collection activities by agencies like EPA to determine the most cost effective methods for eliciting public response and cooperation where utilization of privately owned vehicles is essential to the research.

5. Survey and analyze inspection data collection processes and vehicle-in-use status data available in foreign countries and determine whether foreign experience can be exploited for research and PMVI implementation in the United States.

6. Utilize researcher experience and operational and technical problems previously identified to conduct a comprehensive survey, analysis, and feedback to diagnostic equipment manufacturers to help state-of-the-art improvement or possible establishment of quality and capability standards for diagnostic inspection equipment.
COMPONENTS FOUND TO BE MOST FREQUENTLY OUT OF SPECIFICATION

<table>
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<tr>
<th>Rank</th>
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<td>2</td>
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<td>Tire Pressures*</td>
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<td>Pedal Load A**</td>
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*Outage criteria made more stringent than on 7525 contract
**Component not assessed for outage in 7525 contract

*Figure 13. Out-of-specification components fixed diagnostic centers*

<table>
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<tr>
<th>Other Components of Interest</th>
<th>Chevrolet IMP</th>
<th>Chevrolet CHV</th>
<th>Chevrolet CVII</th>
<th>FAIR</th>
<th>GAL</th>
<th>MUS</th>
<th>BUI</th>
<th>CAD</th>
<th>DOD</th>
<th>OLDS</th>
<th>PLY</th>
<th>PONT</th>
<th>RAMB</th>
<th>VW</th>
<th>X²</th>
<th>Sig. Code*</th>
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<td>29 - Wheel Studs</td>
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<td>.012</td>
<td>.008</td>
<td>.000</td>
<td>.009</td>
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<td>.015</td>
<td>.021</td>
<td>.035</td>
<td>.015</td>
<td>.025</td>
<td>.016</td>
<td>.000</td>
<td>.000</td>
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<td>.107</td>
<td>.076</td>
<td>.130</td>
<td>.132</td>
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<td>.076</td>
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<td>.144</td>
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<td>.157</td>
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<td>.171</td>
<td>.156</td>
<td>.171</td>
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<td>.111</td>
<td>.084</td>
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<td>.108</td>
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<td>.122</td>
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<td>144 - Coil Polarity</td>
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<td>.063</td>
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<td>.578</td>
<td>.634</td>
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| Overall Outage Rates (%)                   | 11.73         | 9.92          | 9.39           | 11.00| 10.71| 10.21| 9.59| 9.92| 11.28| 10.54| 11.46| 10.82| 11.59| 11.01| 137.29| +++        |

Overall Outage Rates (%)
(Based on the above 65–plus 47 additional)

*Significance Code:

- = Outage rates between make/model groups are not significant
+ = Outage rates between make/model groups significant at 95% confidence level
++ = Outage rates between make/model groups significant at 99% confidence level
+++ = Outage rates between make/model groups significant at 99.9% confidence level

Figure 15. Comparisons of outage rates
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<th>Highest</th>
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</tr>
<tr>
<td>Front Brake Drum Cond.</td>
<td>Cadillac</td>
<td>5.0</td>
<td>Pontiac</td>
<td>15.7</td>
</tr>
</tbody>
</table>

*Figure 16. Comparisons of outage rates*
<table>
<thead>
<tr>
<th>Components</th>
<th>Lowest</th>
<th>%</th>
<th>Highest</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spare Tire Pressure</td>
<td>Chev II</td>
<td>3.38</td>
<td>Impala</td>
<td>51.0</td>
</tr>
<tr>
<td>Front Shock Absorber</td>
<td>Chev II</td>
<td>11.7</td>
<td>Dodge</td>
<td>30.8</td>
</tr>
<tr>
<td>Rear Shock Absorber</td>
<td>Chev II</td>
<td>8.3</td>
<td>Dodge</td>
<td>2.25</td>
</tr>
<tr>
<td>Ignition Breakdown</td>
<td>Cadilac</td>
<td>8.4</td>
<td>Cadillac</td>
<td>63.1</td>
</tr>
<tr>
<td>Radiator Hoses</td>
<td>Pontiac</td>
<td>9.6</td>
<td>Impala</td>
<td>28.0</td>
</tr>
<tr>
<td>Pressure Cap</td>
<td>Buick</td>
<td>10.9</td>
<td>Plymouth</td>
<td>38.2</td>
</tr>
<tr>
<td>Heat Riser</td>
<td>Chevelle</td>
<td>16.6</td>
<td>Impala</td>
<td>37.1</td>
</tr>
<tr>
<td>Dwell</td>
<td>Pontiac</td>
<td>38.2</td>
<td>VW</td>
<td>63.4</td>
</tr>
<tr>
<td>PCV Valve</td>
<td>Buick</td>
<td>5.2</td>
<td>Impala</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>Fairlane</td>
<td>5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall Total (%)</td>
<td>Chev II</td>
<td>9.39</td>
<td>Impala</td>
<td>11.73</td>
</tr>
<tr>
<td>(Based on 112 components)</td>
<td>Buick</td>
<td>9.59</td>
<td>Rambler</td>
<td>11.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Plymouth</td>
<td>11.46</td>
</tr>
</tbody>
</table>

*Figure 17. Comparisons of outage rates*

*Figure 18. Between state comparison of brake force ratio vs. mileage and age*

*Figure 19. Between state comparison of right front tire tread depth vs. mileage and age*
Servicing Vehicles in Tomorrow’s Environment

Karl-Heinz Keller
Josef Metz
Volkswagen of America, Inc.

ABSTRACT

The presence of wear and usage defects in vehicles is well known as is the fact that these defects affect both safety, economy, and operation. Volkswagen has a well defined service system, consisting of vehicle service and customer care, which is based on diagnosis or, "the inspection and evaluation of components and subgroups in order to pinpoint problem areas, both actual and potential." Service market research shows increased mechanic salaries, mechanic shortages, increased gas costs, higher depreciation rates, and higher maintenance costs. These have been combined with the concern for vehicle defects and the Volkswagen service system to indicate the need for the VW Diagnosis System. This system was developed in two steps evolving from an essentially manual system involving 48 checks in 72 minutes to a computer diagnosis of 82 checks in 51 minutes, with 24 of the checks being made automatically. The computer diagnosis system is in use in 3,000 dealerships in Europe and will be in practically all VW dealers in the U.S., by the end of 1973. There are a number of alternative diagnostic possibilities such as combined on-board/off-board computerized diagnosis, off-board test equipment, completely on-board diagnosis, pre-determined parts replacement, and extended parts durability. Of these, the on-board/off-board is the most attractive for the present, although the others are of use for particular circumstances. A universal application of computer diagnosis would require, for standardized equipment, uniform design of tested components, performance and quality standards, and requirements for specific test principles. Uniformity applied to component design would tend to stifle innovative vehicle design. There is an extensive list of components to be tested which can be categorized by repair operation, and test methods established. According to VW statistics, the public is very receptive of computer diagnosis but only regarding vehicle economy and reliability and not safety.

INTRODUCTION

Defective Vehicles

An evaluation of vehicle inspection statistics of various states (Ref. 1) indicates that every third vehicle would not pass annual inspection because of defective components. In fact, 26% had defective lights, 4% had defective directional signals, 4% had brake defects, 3% had tire defects, or combinations of these and other items (Ref. 2).

Through years of research in this field, we have come to realize that this is only the tip of the iceberg. We found that in addition to those items directly affecting vehicle safety, many others exist which affect the proper function of a vehicle, and thus create hazards to all traffic. These can also cause considerable damage to various vehicle components before any defective condition is realized by the driver.

This should indicate to you the very real importance of timely maintenance and especially, regularly-scheduled checking of systems and components. Vehicle tune-ups and general maintenance at pre-determined intervals, carried out by skilled personnel, are important contributions which the service industry can make in improving overall vehicle condition.
Even though we must accept the fact that not every vehicle owner appreciates this benefit, statistics show that with a program of regular maintenance, and through continuous quality improvements, the failure rate of vehicle components is decreasing.

<table>
<thead>
<tr>
<th></th>
<th>1966</th>
<th>1968</th>
<th>1970</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lights</td>
<td>60%</td>
<td>29%</td>
<td>26%</td>
</tr>
<tr>
<td>Brakes</td>
<td>9%</td>
<td>5%</td>
<td>4%</td>
</tr>
<tr>
<td>Steering</td>
<td>3%</td>
<td>1%</td>
<td>0.7%</td>
</tr>
</tbody>
</table>

Volkswagen has developed new methods in this field, and we are pleased to present and discuss the results of their application with you.

For openers, we'd like to give you the reasons behind Volkswagen's change in the concept of maintenance. Then, we will outline our new system "VW Computer Diagnosis." In the third part of this presentation, we will discuss alternative systems of diagnosis.

For our purpose here today, we will limit our comments to the theme of this meeting, and consider only the safety aspects involved. First, a few general clarifications: servicing, for the purpose of this paper, is a two-pronged concept consisting of troubleshooting, or diagnosis, and the actual maintenance functions. Our proposals here could have much broader application in the future. We are considering only passenger vehicles. Tomorrow's environment will stress our activities in regard to such services, with emphasis on improved safety and other important considerations which the industry should anticipate. Please understand that we are using only Volkswagen experience, because other vehicle manufacturers have not yet introduced similar programs.

Definition of the Volkswagen Service System

Our service system is established on two basic criteria: 1) vehicle service and 2) customer care. The components of these two terms are outlined in the following chart.

Since our theme today concentrates on diagnosis, let us now define that term.

DEFINITION OF DIAGNOSIS

The diagnosis system, as employed by VW, consists of: The inspection and evaluation of components and subgroups, in order to pinpoint problem areas, both actual and potential. Such investigations concentrate mainly on wear-and-tear items, and in predetermined areas of concern. To facilitate matters, data-processing means are applied. Defect causes are in many areas difficult to determine, especially since a given problem could be caused by any number of vehicle conditions, for example, excessive gas consumption could be caused by improper ignition timing, low or uneven compression, individual driving habits, or improper carburetor adjustments. Any of these possibilities or a combination of them must be pinpointed and corrected in order to solve the problem.

This makes the diagnostician the key man in the repair process and shows how vital precise diagnosis is to the success of the repair. It is one of the most important operative factors in the entire process. Current diagnosis procedures often rely on the simple observation of a defect. Such "seat-of-the-pants" diagnosis can lead to improper repairs and unnecessary replacement of parts, without probing further to find the heart of the problem. Frequently, this leads to comebacks and customer complaints.

Market Situation and Objectives

Our day-to-day experience convinced us that periodic checks at given intervals would
not bring satisfactory results in the long run, even though progressing technology might permit us to extend maintenance intervals further and eliminate some superfluous operations. Our service market research studies predicted:

- A growing number of sophisticated in-vehicle systems, many of them electronic (fuel injection, antiskid system)
- Increasing wages

$\text{$/hr.}$

---

\[
\begin{array}{c|c}
\text{YEAR} & \text{RELATION MECHANIC: VEHICLE} \\
\hline
1950 & 1 : 73 \\
1965 & 1 : 129 \\
1975 (EXPECTED) & 1 : 154 \\
\hline
\end{array}
\]

\text{FAVORABLE RELATION} & 1 : 80

Mechanics shortage (3)

### Increased gas prices (gas shortages)

- **REPRESENTS AVERAGE INCREASE OF LAST 5 YRS.**
- **REPRESENTS AVERAGE INCREASE OF LAST 2 YRS.**

\[
\begin{align*}
\%: \text{BASE 1970} \\
2.9 = 52\% \\
2.7 = 42\%
\end{align*}
\]

Government statistics for gas and oil increase per mile (without tax) (4)

### Higher depreciation rates due to additional equipment for safety and pollution

- **REPRESENTS AVERAGE INCREASE OF LAST 5 YRS.**
- **REPRESENTS AVERAGE INCREASE OF LAST 2 YRS.**

\[
\begin{align*}
\%: \text{BASE 1970} \\
9.2 = 187\% \\
6.8 = 115\%
\end{align*}
\]

Government statistics for cost depreciation per mile (4)

### Higher maintenance costs (parts and labor) for sophisticated equipment, and due to increasing wages.
development and introduction was divided into two phases: Phase 1) Diagnosis I; Phase 2) Computer Diagnosis II

DEVELOPMENT OF THE VW DIAGNOSIS SYSTEMS

Diagnosis Phase I

I think that we can all agree that the annual mileage will differ between a commuting business man’s and a housewife’s car. Market research has shown a wide variance between registered mileages on intermediate and compact vehicles within a specific time period. For example:

<table>
<thead>
<tr>
<th>MILEAGE/TIME RATIO FOR VW TYPE 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000 miles are reached by 54.8% within 8 months</td>
</tr>
<tr>
<td>11,000 &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  10 &quot;</td>
</tr>
<tr>
<td>12,000 &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  11 &quot;</td>
</tr>
<tr>
<td>13,000 &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  11 &quot;</td>
</tr>
<tr>
<td>14,000 &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  12 &quot;</td>
</tr>
<tr>
<td>15,000 &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  12 &quot;</td>
</tr>
<tr>
<td>16,000 &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  13 &quot;</td>
</tr>
<tr>
<td>17,000 &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  13 &quot;</td>
</tr>
<tr>
<td>18,000 &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  14 &quot;</td>
</tr>
<tr>
<td>19,000 &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  14 &quot;</td>
</tr>
<tr>
<td>21,000 &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  &quot;  15 &quot;</td>
</tr>
</tbody>
</table>

VW Statistics 1971

A comparison between maintenance requirements of different makes shows also that little consideration is given to varying environmental and driving conditions.

Analyzing maintenance procedures, we found that only a few items needed regularly-scheduled maintenance, for instance, breaker points or oil filters. On the contrary, extensive research demonstrated that a majority of items normally thought to require regular maintenance, actually needed it only on a periodic basis. Realizing this, we separated those items needing regular maintenance from those requiring periodic maintenance. Consequently, we reduced our corresponding regular maintenance requirement (in terms of positions checked) from the previous 30 to 8 positions. With the resulting time savings, we were free to devote that time to diagnosis

For Americans, the automobile has become integral to everything. At this time, public transportation systems have limited possibilities for offering alternatives in transportation. With this in mind, major increases in automobile operating costs are a matter of great concern to all of us. Therefore, we established the following working philosophy:

1. Customers need economical, reliable transportation throughout the lifetime of their vehicle.
2. People want a non-polluted environment and protection from vehicle accidents and injuries.
3. The service industry needs more effective systems and methods to match the increasing complexity of vehicle technology, and to reduce inefficiency.

Our diagnosis concept, therefore, not only had to fulfill requirements as defined, but also had to consider economic feasibility. It also had to fit in our organizational structure. Its
(check). Observed defects or necessary adjustments became normal repair items.

The VW diagnosis program consists, therefore, of two distinct phases:

Cost/benefit ratios require the highest possible information return. Therefore, as major criteria the diagnosis check-points were determined, based on the subassemblies showing the highest repair frequencies. To give you an example of the research involved: Statistics showed us that out of 30 items, the following had an above-average failure pattern:

<table>
<thead>
<tr>
<th>Item</th>
<th>Failure Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>5.0%</td>
</tr>
<tr>
<td>Fuel and carburetion</td>
<td>4.3%</td>
</tr>
<tr>
<td>Front axle</td>
<td>3.6%</td>
</tr>
<tr>
<td>Brakes (drums, linings, pads)</td>
<td>5.9%</td>
</tr>
<tr>
<td>Ignition/starter</td>
<td>7.3%</td>
</tr>
</tbody>
</table>

(Percentages are based on repair order total.)

Aside from the individualized approach and the time saved, certain additional benefits accrue:

1. increased maintenance capacity of the workshop,
2. a vehicle condition report provided for each customer.

In a Diagnosis I workstand, the basic modular setup for the subsequent computer diagnosis system is already in place. Of course, such changes in the total service concept can be implemented successfully, only if, at least one complete market participates. In the case of Volkswagen, this system has been introduced worldwide.

**Diagnosis Phase II (Computer Diagnosis)**

Customer response to Diagnosis I showed us that this concept was well-accepted and encouraged us to develop this system further. Our aim was to mechanize and automate the diagnostic part of the maintenance procedures to:

- reduce time required to the minimum,
- improve the accuracy of testing,
- minimize human error,
- provide better repair instructions,
- tighten organizational procedures (automatic printed test report).

The greatest information return for the considerable hardware investment can be achieved by cutting time. The most time-consuming checking operations were then determined, and the feasibility of automating these checks was studied. Actually, 24 out of
74 test operations, or 33%, are now performed automatically. As these checks are the most time-consuming, the time savings with this system are even more impressive. As an example: A check of the compression, regulator and generator voltages used to take 24 minutes. With computer diagnosis, we now do it in 1.2 minutes, a 95% time saving.

Positions not checked automatically are evaluated by the diagnostician. He uses a hand-held input unit which visually indicates all tests to be performed. By pressing a plus or minus button, he records his evaluation in the computer.

This concept is already in service with 3,000 VW dealers in Europe, and this year practically all 1,200 VW dealers in the United States will offer this system to VW customers.

Diagnosis II, or Computer Diagnosis is designed so that expansion of its test-range is feasible. This system will be complemented in the near future by including an ignition timing test device. The entire concept is, of course, under continuous development.

ALTERNATIVE POSSIBILITIES

I would like to outline the systems and methods, which we could consider viable alternatives:

Alternative Diagnosis VW Systems (Hardware)

On-Board/Off-Board Computerized Diagnosis data collection technique as developed by VWAG (Ref. 5) consists of the following components:

1. Sensors and a permanently-wired, in-vehicle test harness with a central access socket.
2. Non-contact equipment, such as an “optoelectronic” system for measuring camber and toe-in.
4. Electronic components for processing and evaluating data, and other complementary equipment.
5. Data display and printout units.

Electric signals are compared with parameters stored on a program card. Information about the condition of vehicle components is received from built-in sensors and probes, or by measuring resistance of current consumers using the vehicle’s normal wiring system. Visual checks are recorded with a handheld input unit. Similar methods are applied by the Tacon/AMC Test Institute (Ref. 6) and Hamilton Industries (Ref. 7).

Off-Board Test Equipment is designed to measure the performance of a specific vehicle unit, such as engine power output, wheel alignment or brake deceleration rates. Some devices use data-processing systems for test evaluation with a digital display. Most devices display the condition tested in analog form. Significant also is the variety of test equipment necessary for a comprehensive vehicle test. Most of the units work under differing physical principles, and are manufactured by different companies. As an illustration: Measurement of the electrical circuits is accomplished through a combination of instruments, generally installed in a console. This connection between test instruments and vehicle components is done with individual cables, clamps or plugs.

On-Board Diagnosis: The on-board technique is based on

1. a continuous connection between sensing devices and a display unit, and
2. signals from sensors installed in vehicle components. These are amplified, stored and evaluated by an “on-board” central processing unit. Digital data are displayed to the driver and indicate the actual condition of the vehicle. An example of a simple on-board device is the brake warning light, required by safety standards.

There are two alternatives to any diagnostic and maintenance system. 1. Pre-Determined Parts Replacement which requires the exchange of parts subject to wear and tear, at a specified mileage and time, regardless of their condition. This is the way aircraft are maintained. (Determination of component
life expectancy should be based on the manufacturer's statistics."

2. As diagnosis devices and parts replacements at pre-determined intervals are expensive, improvement of component durability should be considered. All parts or subcomponents could be of such quality that they would last for the expected life of a total assembly, or for the life of an entire vehicle. Value analysis very often shows that certain parts built for a given component are over-designed and last 3 to 5 times longer than the component itself. From an engineering point of view, this is a very promising source for recovering additional costs incurred in extending parts durability.

**Alternative Aspects To Be Considered**

Uniform Design of Components: Computerized diagnosis in vehicle maintenance requires a total integration of test item and test instrument. Any vehicle components evaluated by a given diagnosis instrument must be so-equipped with condition sensors as to be compatible with the test instrument.

Performance and Quality Standards: Such standards would be necessary to manufacture test equipment-compatible parts or subassemblies. Parameters for performance and function of such components are basic requirements.

Determination of Test Principles: Any proposed program should be evaluated in light of two different diagnosis principles:

1) function test,
2) failure test.

This is important, due to the differences between methods regarding instruments, systems, standards, cost/benefit ratio, accuracy, and extensiveness of information required. The failure test checks individual parts and compares the actual test values with the specifications, thereby indicating defects, e.g., voltage output, generator). The function test provides information about the performance of a subassembly group under operating conditions (state of health).

**A United Approach**

The interdependency of the various groups involved in automotive maintenance and the complexity of organizational systems affected has previously been outlined by us (Ref. 8). The evaluation of alternatives to testing systems and methods applied, as well as the responsibilities for the various test categories is a large endeavor. It will require the conscientious involvement of all participants, in order to weigh all aspects and to avoid unrealistic decisions. Let me, therefore, briefly comment on their major aspects and give you an idea of what this entails. This might prompt an in-depth discussion at some later time, or even within the existing SAE committees.

**Evaluation of Alternative Systems**

On-Board/Off-Board Computerized Diagnosis requires a total vehicle/test equipment integration. This integration provides for detailed troubleshooting and incipient failure warning. Since the expensive part of the system permits multiple uses, the information return, per dollar of installed hardware, is relatively high. That is, however, only if the required integration is limited to vehicles of one make. A multipurpose automated diagnosis system would require much higher investments, both in-vehicle and for external hardware, thus decreasing the cost/benefit ratio considerably. The on-board/off-board method appears adequate, where increasing the durability of a part is too expensive, or technically not feasible. This type of system increases repair reliability and, as a consequence, the safety of vehicle components, as would any of the other suggested automated systems.

Off-Board Test Equipment in its present state cannot meet the requirements for automation of the diagnosis process. Connection of such a system is both difficult and time-consuming. Skilled and reliable manpower is a prerequisite for evaluation of test data. Further, a combination of various test units in
a shop is a tremendous investment which often may be economically unfeasible.

However, test results are relatively accurate and failures can be pinpointed. An additional benefit is near-total compatibility with various vehicle makes. This is, of course, less important to franchised dealers. If we hold the theory that government tests should only be function tests, then our breakdown of repair categories indicates that all safety- and emission-related components could be checked with off-board test equipment.

Equipment required for performance tests should be developed in response to the expanding needs of the industry. Not only should this equipment be easier to handle, from the mechanic’s point of view, but it should also work much faster and have provisions for changes in automotive technology. Additional technology and methods should be explored to meet these requirements.

Further, maintenance of the test equipment has to be outlined, minimized and calibration facilitated.

On-Board Diagnosis seems to be the most convenient and most immediate method of providing defect information. At the same time, it is the most expensive and technologically most complex method. Its application can be recommended only in those cases which present high risk factors, or in which considerable investments are jeopardized. Such systems are economically feasible, especially in areas where electronics supplement systems, for example, ignition or fuel metering or automatic transmission shift initiation.

Predetermined Parts Replacement might be considered, where durability studies indicate regular wear-and-tear patterns for a given vehicle model (spark plugs, breaker-points, brake pads). Basically, this is the most logical method of vehicle maintenance. Admittedly, it still leaves a small element of risk, in such cases where a vehicle is operated under extreme conditions.

Additionally, this method offers sorely-needed advantages, both to customers and the service industry:

1. A clearer picture of total service costs, and
2. More efficient utilization of shop capacity.

Extended Parts durability compared with standardized components and their relatively low cost/benefit ratio might well be explored as an alternative. It might also be in the consumer’s interest to spend a little more at the time of initial purchase, than to try to keep up with rising wages and parts prices.

Evaluation of Alternative Aspects

Uniform Design of Components based on standardized test equipment should not be applied under circumstances in which the particular advantages offered by a given make would be severely limited. This would hinder the industry’s ability for timely response to the continuously-changing requirements of the market.

Performance and Quality Standards if necessary, should be established only on the basis of sufficient empirical data. A suspension designed for a sports car would obviously manifest different characteristics than one for a stationwagon. As a consequence, a variety of standards must be established. As vehicle technology changes rapidly, the research and administrative work involved in keeping track of new techniques and new standards would be extremely great. The question remains as to whether or not existing test equipment would require updating as well.

CATEGORIES OF COMPONENTS TO TEST

Since we’ve discussed the systems and the various alternative approaches, let’s turn now to a determination of components affected. In a second part, we will try to separate each component into its individual repair elements. Furthermore, we have indicated items which, in our opinion, should be viewed as safety or emission checkpoints. This being so, a list of such checks was developed, requiring the
service industry's attention. Each list indicates the appropriate test method. Three main categories can be postulated:

1. **Safety and emissions**
   - Brakes, antiskid system
   - Steering
   - Suspension components
   - Tires
   - Emissions
   - Lights, visibility
   - Signals (horn, warning signals for safety devices)
   - Restraint systems
   - Vehicle body (door locks)

2. **Maintenance (wear-and-tear items)**
   - Engine
   - Transmission and clutch
   - Propeller shaft
   - Rear axle
   - Body and chassis parts
   - Door locks
   - Electrical system

3. **Convenience items**
   - Radio
   - Power windows
   - Air conditioners
   - Convenience lights

### 4. TEST CATEGORIES FOR SPECIAL INTEREST GROUPS

<table>
<thead>
<tr>
<th>Assembly Groups</th>
<th>Function Test</th>
<th>Dimension</th>
<th>Test Method</th>
<th>Evaluation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheels and Suspensions,</td>
<td>—brake effect, anti-skid</td>
<td>ft, rad, lb, in, psi</td>
<td>*</td>
<td>DCE</td>
</tr>
<tr>
<td>Steering, Springs, Brakes</td>
<td>—tire condition</td>
<td>1/sec</td>
<td>*</td>
<td>DCE</td>
</tr>
<tr>
<td></td>
<td>—spring suspension and shock absorbers</td>
<td></td>
<td>*</td>
<td>DCE</td>
</tr>
<tr>
<td></td>
<td>—steering condition</td>
<td></td>
<td>*</td>
<td>DCE</td>
</tr>
<tr>
<td></td>
<td>—operating forces (steering, pedals)</td>
<td>lb</td>
<td>*</td>
<td>DCE</td>
</tr>
<tr>
<td>Body and Body Equipment</td>
<td>—corrosion and deformation of body</td>
<td></td>
<td>*</td>
<td>+/-</td>
</tr>
<tr>
<td></td>
<td>—windshield wiper system</td>
<td></td>
<td>*</td>
<td>+/-</td>
</tr>
<tr>
<td></td>
<td>—locking mechanism of doors and lids</td>
<td></td>
<td>*</td>
<td>+/-</td>
</tr>
<tr>
<td></td>
<td>—seat belt system</td>
<td></td>
<td>*</td>
<td>+/-</td>
</tr>
<tr>
<td></td>
<td>—defrosting system</td>
<td></td>
<td>*</td>
<td>+/-</td>
</tr>
<tr>
<td></td>
<td>—trailer hitch</td>
<td></td>
<td>*</td>
<td>+/-</td>
</tr>
<tr>
<td></td>
<td>—interior noise level</td>
<td>dB</td>
<td>*</td>
<td>DCE</td>
</tr>
<tr>
<td>Electrical and VisibilityEquipment</td>
<td>—warning systems</td>
<td>*</td>
<td>*</td>
<td>+/-</td>
</tr>
<tr>
<td></td>
<td>—anti-theft devices</td>
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Vehicle Function Test by Government

VC = Visual check  BS = On-board system
TE = Test equipment  DCE = Data comparison with evaluation
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Vehicle Function Test by Service Industry
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Vehicle Failure Test by Service Industry
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Vehicle Failure Test by Service Industry (cont.)
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Vehicle Failure Test by Service Industry (cont.)
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Vehicle Function Test by Vehicle Owner

OTHER SUBJECT-RELATED FACTORS AND CONCLUSION

The Public's Opinion on Diagnosis (Ref. 9)

Based on our experience with the installation of computer diagnosis equipment, we asked customers in the Grand Rapids, Mich., distributor area for their opinion. The results are significant. Almost every person interviewed had a decidedly positive attitude toward the system and its benefits. Seventy percent of the respondents gave such positive comments as: "high reliability," "works faster," "finds little things." Only 20% of those persons interviewed could ascertain no benefits. Seventy out of every one hundred people contacted believe that VW Computer Diagnosis improves service and/or reduces costs.

Another benefit felt to be important was the printout. We were told that it inspired more customer confidence in us.

People do appreciate a detailed failure analysis and defect indication. However, if this results in increased repair costs, due to the higher accuracy of the computer diagnosis, they are reluctant to order the necessary repair.

The Public's Opinion on Safety

The uninitiated person is usually surprised to find that the average driver is not very safety-oriented. Out of many sources, we want to cite one comment which we found in the book, How To Reduce Road Accidents,
by T. S. Skillman: "Motorists won't cooperate, in the first place, because they don't want to. This is sometimes because the accident situation has failed to catch their sympathy. Because of the lack of realism on this subject, everybody has plenty of alibis. Pedestrians are the trouble, or fast drivers, or bad roads, or the lack of speed control. Somebody, somebody else should do something." It is always "the other guy" who makes the mistake.

Manufacturer's statistics show that the incidence of overdue maintenance checks increases in older vehicles.

As we have seen, the public generally favors diagnosis. And, as we have also seen, the public generally disregards the idea of safety. If the installation of diagnosis systems was generally required by law, either in vehicles, at inspection stations, or in dealerships, would the public be willing to accept this additional expenditure on top of the already high (and growing) costs of operating a vehicle?

There is no question that there is lack of awareness of driving risk factors in general, and specifically, of the hazards presented by unsafe components. Therefore, we feel that the public must be better-informed regarding this subject. Hopefully, this would result in more positive attitudes and a better understanding of the problem.

References

1. Virginia 26%, Washington, D.C. 41%, Louisiana 29%, Idaho 64% failures of vehicles examined.


ABSTRACT

The pneumatic tire functions as an important component of the suspension in the total vehicle system. The tire supports the vehicle mass and transfers all of the propulsion, braking and directive forces.

The contribution of the tire toward the safety of the integrated system is examined with respect to these major functions. Research is focused on establishing appropriate measurement techniques to monitor or predict tire behavior.

The primary methods of measurement are reviewed and discussed. These are classified as functional (quantitative-tire operation) and physical (qualitative-tire construction). Additional refinement of these techniques is needed and progress is demonstrated.

Product development is the ultimate beneficiary for applied research. However, the results cannot be applied in a vacuum. All the elements of satisfactory tire performance (friction, treadwear, handling, load carrying capacity, noise, strength, uniformity, high speed, etc.) must be balanced and carefully integrated with the vehicle suspension system and the highway environment. Some new developments are reviewed with respect to vehicle safety.

INTRODUCTION

The pneumatic tire performs as an important component of the suspension in the total vehicle system. Therefore, the contribution of the tire toward the safety of the entire system must be viewed with respect to its function in the operational environment.

The function of a tire is to carry/cushion vehicle load and to transmit directive forces in the plane of the road surface. Specifically, the tire supports static and dynamic loading and directs propulsional, braking and cornering forces (Fig. 1).

However, actual implementation of this task becomes exceedingly complex in practice with many subtleties and trade-offs in quest of optimum overall performance. For the purpose of our discussion today, we shall deal with the very basic role of the tire and the direction of current research in the field.

The major area in tire research is parameter measurement. The primary categories we will survey in this regard are: Structural Integrity and Dynamic Response. We will close our discussion with a brief look at some interesting new Product Development features directed toward system safety (Fig. 2).

Figure 1
STRUCTURAL INTEGRITY

The first area of interest, then, deals with the requirement that the tire support the load for the duration of the service period. This general category treats the Structural Integrity of the tire.

Because any tire is a complex composite of similar and dissimilar materials, it presents a challenge to analyze structurally and predict performance. Therefore, it is desirable to have the capability of determining the integrity of the tire structure before, during, or after application (or test).

Non-Destructive Tire Testing

Non-Destructive Tire Testing is receiving attention by the industry, equipment fabricators and DOT, in particular The Transportation Systems Center (TSC). Of the Non-Destructive Testing (NDT) techniques currently available, it is accurate to say that no single test is capable of evaluating all the important categories of tire structural integrity with precision. Thus, we are interested in a number of different methods.

X-RAY

X-ray is an established technique with considerable application in manufacturing plants. It is particularly valuable for producing a visible image of the internal tire structure and for locating foreign material and voids. In view of the increased complexity and required precision of current passenger tires, X-ray analysis is an effective in-plant quality control tool. The manufacturer is interested in the production tolerances of a
number of specific components within the composite. X-ray enables detailed inspection of uncured tires after assembly and cured tires after molding (Fig. 3).

The major drawback of X-ray is the inability to detect areas of weak bonding or delamination.

HOLOGRAPHY

Laser Holography is gaining acceptance in some specialized applications. As a research-tool, Holography shows some advantage for locating porosity, weak bonds, and separations in experimental tires. Identification of anomalies is interpretive however, and some operator expertise is necessary for accuracy and consistency (Figs. 4 & 5).

It is doubtful this method will see widespread application in manufacturing plants or as an inspection tool because of high cost, time consuming cycle and interpretative results.

ULTRASONICS

Ultrasonics is currently an area of considerable development effort. Two forms of ultrasonic inspection exist: Through Transmission and Pulse Echo.

The Through Transmission method operates in 25-35 KHz range. While able to sense some common types of anomalies, this system surveys the specimen on a gross basis and is unable to discriminate internal components and depths (Fig. 6).

While ultrasonics inspection normally requires a medium to act as an impedance
match between the signal source and the test specimen, a recent development enables signal transmission without a liquid couplant. This technique is under investigation for tire applications, especially in the retread field (Fig. 7).

The liquid coupled Pulse Echo (reflection) technique shows significant promise. Operating in the 1 to 5 MHz range, Pulse Echo has inherent potential because it can discern depth, material interfaces and perhaps bond strength. Any characteristic which alters the acoustic response of a sample under investigation may potentially be detected (Fig. 8).

Pulse Echo ultrasonic inspection is quite commonly used in the metals industry and the equipment has been refined for that application. To date there has been limited success with ultrasonic tire inspection, but several current developments indicate that the Pulse Echo method may see considerable future use in tire inspection.

George Halsey of the Scientific Testing Laboratory, Indiana, Pa.; The Transportation Systems Center, Cambridge, Mass.; and the Naval Air Development Center, Warminster, Pa., are all active in perfecting this method.

INFRARED

Infrared sensing apparatus has some specialized application for in-progress tests, particularly laboratory wheel testing. Areas of potential failure can be identified and monitored without disturbing the progress of the test.

One type of infrared instrument measures the temperature gradient (ΔT) on a tire as it operates on a test wheel under load. Variation in the temperature profile around the tire is indicative of subsurface changes within (Figs. 9 & 10).

Another type of infrared instrument is used to traverse the tire surface at a given scan rate and measure the absolute temperature.
OTHER TECHNIQUES

Some other techniques such as liquid crystals, resonance, photoelastic coatings, miniature cord tensile gauges, thermistors, and microwave have laboratory status with only very limited research applications.

The appropriateness of any indirect NDT method can only be gauged through comparison with actual tire performance. Accordingly, several current correlation studies are designed to relate testing results to vehicle and wheel performance. It must be emphasized that so many types and combinations of tire service are encountered that this becomes a formidable but necessary undertaking.

Destructive Tire Testing

Destructive tire testing is, of course, a major departure from those types of tests we've just described. In a manner of speaking, a destructive test seeks to assault a specific area of the tire under accelerated and often abusive conditions. Many of these tests are "sure fail" tests and are intentionally designed to determine the destructive limits of the component. As in other fields a controlled measurement of failure can be a significant quotient of performance.

Again, the extreme nature of the testing environment is often far removed from normal service circumstances so interpretation and correlation factors are necessary.

While individual tire manufacturers have specific in-house specimen and QC tests, a common denominator for passenger tires today is the series of MVSS 109 laboratory tests; wheel high speed, wheel endurance, static plunger energy and static bead unseat force. The significance of these tests is that they provide a common basis for tire performance in accordance with repeatable test conditions. It is important, however, to consider the validity of the laboratory schedule with field service.

Similar compliance testing is proposed for all other tires including truck and bus. MVSS-119, presently a proposed rulemaking,
specifies laboratory performance requirements for tires applied to over-the-road highway vehicles other than passenger cars. The requirements currently include a laboratory wheel speed/endurance test and tire plunger strength test.

In the course of product development, a wide variety of specialized destructive tests are employed. This varies with the company but the following are some of the more common.

Road Treadwear represents a significant time and man-power commitment. The recent Tire Quality Grading proposal portends even more extensive expenditures. Unfortunately, despite the extent of experience, this remains a highly sensitive and variable test on the road. Attempts at laboratory simulation have proven to be totally unsatisfactory to date (Fig. 13).

Track High Speed has always been an important indicator. However, the changing complexion of the transportation picture appears to deemphasize the significance of this test and some reassessment may be in order. The reduced high speed capability of the newer cars resulting from increased weight and lower net horsepower is an influencing factor (Fig. 14).

Various types of hazard and fatigue schedules are commonly applied throughout the industry. The dynamic bead durability trailer and the cobblestone course are just a few examples (Figs. 15 & 16).

Service remains the best "test." The need to expose the complex structure of the tire to the conditions of so-called "common" service can not be over-emphasized. At its best, any test can only attempt to simulate this.

Figure 13. Treadwear measurement

Figure 14. Track high speed test

Figure 15. Dynamic bead durability trailer

Figure 16. Cobblestone course
DYNAMIC RESPONSE

We also are concerned with the physical behavior of the tire in the dynamic environment. The "mission profile" is complex and while boundary limit performance may be of interest to the researcher, the functional spectrum is most important to the tire designer, the test engineer and the ultimate tire user.

Recently, a great deal of effort has been directed toward researching the broad field of tire dynamics. Today, we will survey the progress of the work in Braking Traction, Hydroplaning and Force and Moment measurements. Again, we will see that the thrust of the research is directed toward parameter measurement.

Braking Traction Measurement

In the area of tire braking traction, Goodyear recently completed a NHTSA contract. The objective of this program was to establish a comprehensive data bank for passenger tires and to evaluate state-of-the-art apparatus and test procedures (Fig. 17).

The two-wheel traction trailer was used to generate peak and slide coefficient values for a variety of test conditions. Test parameters included three surface skid numbers, two water depths, three speeds, three inflations and three loads. All runs were conducted on a representative Original Equipment type tire with a corresponding proposed bias/belted ASTM control tire (Fig. 18).

The results of the program emphasized the importance of equipment design and rigid test condition control, particularly water depth. Some future research has been proposed, including possible equipment refinement and a tire traction population study.

Future braking traction research in the industry includes other classes of tires. This is a new traction trailer under completion at Goodyear. It is designed to generate braking coefficient data for truck tires. The test tire is positioned in the open center bay of the trailer and is loaded with a pneumatic cylinder. A servo system monitors and controls the tire load throughout the test. The unit will accommodate appropriate truck and bus tire sizes (Figs. 19, 20 & 21).

The test cycle is directed from the mobile test "room" behind the cab. Data is monitored and recorded on a strip chart recorder and magnetic tape.
Hydroplaning Measurement

The field of Hydroplaning or "Aquaplaning" research is an area promising considerable benefit.

We generally define Hydroplaning as a hydrodynamic displacement or support of all or part of the tire tread by a fluid. This is distinguished from so-called "pure" tire traction which describes the mechanism and behavior of the tire tread under complete intimate tire-to-surface contact. Normally, however, a given wet traction measurement can contain components of both effects. As techniques are developed to diagnose and study the effects of this phenomenon, some means of implementing this knowledge can be envisioned. The applications include operator education, road construction, tire maintenance procedures and tire design.

The operator has a considerable effect on the incidence of hydroplaning. The effects of speed and water depth are well documented but not well known among the public, and even less applied or practiced. You may have observed this yourself if you have driven on a freeway during a heavy rainstorm. Driving techniques and sensitivity are major variables (Fig. 23).

Road construction is a factor. The type of surface texture and provision of drainage are important. Some states or municipalities have had considerable success with road grooving or treatment. In some instances, even a tire
worn smooth will not fully hydroplane up to 70 MPH on a grooved surface (free-rolling).

Tire maintenance and inspection is a major area for improvement. No amount of tire design can improve the hydroplaning performance of a tire worn smooth. Treadwear indicators presently require tire removal at 2/32nds groove depth. Obviously, if improvement at some cost is deemed necessary, earlier tire replacement would have immediate beneficial results.

The study of the effects of tire design on hydroplaning is an active area. A number of design guidelines have been developed using research techniques including unit tread pressure measurement and the glass plate.

The glass plate is the primary tool for hydroplaning research. It consists of a special laminated glass plate through which high speed motion and still images of hydroplaning behavior can be photographed. Carefully controlled water depths are maintained on the plate and a fluorescent dye is added to the water to aid visual analysis. Eighty thousandths water depth is commonly used (Fig. 24).

Because free-rolling hydroplaning can develop in less than 18 inches of forward travel at a given speed, a glass plate 48 inches long is ample to stabilize the condition. Tire hydroplaning is most likely to occur on smooth surfaces so glass is a realistic surface to represent the worst case.

At the present time, free-rolling tire hydroplaning is tested on the front position of a vehicle. The vehicle is traversed across the glass plate at speed intervals of 5 MPH from 30 MPH up to 140 MPH. High speed 16 mm movies capable of 10,000 frames/sec can be used (Fig. 25).

A new technique has been devised to take a single color photo illuminated by a strobe light source operating at 1/30,000 of a second.

Free-rolling hydroplaning cannot be determined by measuring any forces on the tire because it would influence the free-rolling condition. Therefore, hydroplaning is rated by percent of the footprint area displaced by the water. This can be done precisely by using a special analyzer with the scaled photographic images. This photo shows 70 percent hydroplaning at 80 miles per hour. In comparison, this photo shows 15 percent hydroplan-
ing at 80 MPH. A tire is considered fully hydroplaned when more than 80% of the footprint is displaced (Figs. 26 & 27).

Locked wheel tire hydroplaning depends not only on the water depth standing on the surface but also on the wedge depth which accumulates with increased puddle length. The glass plate is at the end of a long trough, designed to maintain and hold a controlled water puddle. This test is conducted using a standard SAE traction trailer and locking the tire at the beginning of the puddle. The test tire is locked automatically and test speeds are conducted in 5 MPH increments from 30 to 70 MPH (Fig. 28).

These locked wheel tests have shown that a sliding tire will hydroplane from 10 to 30 MPH earlier than most free-rolling tires. It also degenerates faster and is less variable with respect to water depth.

The results of this work indicate the dominant factor of water depth in hydroplaning and probably, in wet traction measurement in general. Special water depth controlled surfaces were designed and built to prove out this single factor. The results indicated that water depth is the dominant variable to wet traction testing and any decrease in the measured coefficient of friction with increased speed on a wet surface is due to partial tire hydroplaning.

The glass plate has provided many answers to the tire hydroplaning phenomenon. These findings also apply in varying degree to wet traction. The glass plate is not intended to replace a single traction test, but can be used to verify high speed design parameters and to supplement critical, difficult to obtain, data needed to evaluate tires (Fig. 29).
CORNERING FORCE AND MOMENT MEASUREMENT

The study of the dynamic complexities and the inter-action of the tire with the vehicle suspension has received attention from many participants.

Some of the measuring equipment developed and used by the industry is shown here.

This is a shot of the B. F. Goodrich cornering trailer operating on a wetted surface. Slip angle is generated by "towing in" the tires toward the centerline of the apparatus. The resulting force and torque are measured and recorded. Ford and General Motors also have operational trailers which operate on somewhat the same principle (Fig. 30).

Laboratory machines are also used. Many types exist including drum surfaces. This photo shows a flat surface tire dynamics machine used by B. F. Goodrich at the Brecksville Research Center (Fig. 31).

Potentially, the most significant accomplishment in the past year has been the completion and start-up of the new CALSPAN TIRF-(Tire Industry Research Facility) (Fig. 32).

This elaborate laboratory device utilizes a stainless steel belt road surface supported by a frictionless air bearing. Force and moment measurements are made through the tire/wheel carriage assembly which is loaded onto the moving belt. Slip angle, camber angle, and load are controlled. When fully operational, the machine's capabilities will include: 200 MPH top speed, ±30° slip angle, ±15° inclination angle, 12,000 lbs. vertical load max. and provision for watering. A preliminary passenger tire validation test program has been run recently and is currently being evaluated (Figs. 33 & 34).

In a related field, vehicle handling programs have examined the relationship of tire factors to vehicle performance. A recent report observed the effects of prolonged boundary limit performance on side force.
study the effects of service variables (wear, inflation, tire mixing, etc.) while the other would examine the influence of construction factors.

**PRODUCT DEVELOPMENT**

We have discussed some of the advanced work being done toward development of various tire measurements. The beneficiary for any type of *applied* research is ultimately the product itself.

Today, there are many different inputs to the tire engineer and manufacturer. Some are receiving new emphasis but most have been around for some time now. To name a few of these "inputs"; traction, treadwear, handling, load carrying capacity, noise, strength, endurance, uniformity, handling, consumer needs, high speed, and so on. The point is, that in some cases, these parameters interact inversely. For example, increasing traction generally reduces treadwear. In the end product, a balance must be attained and it must also be responsive to the application and the highway environment.

Let us now look at some new developments and ideas that can contribute to safety.

In a very rudimentary sense, this diagram characterizes the "ultimate" failure mode of a pneumatic load supporting member. This cycle is inherent to the nature of the component (Fig. 35).

The cycle can be initiated at any of the three major points depending upon circumstance. These are shown in the larger red circles and are: *Depressurization*, *Delamination* and *Material Degradation*. These in turn, relate functionally to Load Support, Composite Bonding and Material Physical Properties.

For example, if a tire were operating under load at a low pressure, the excessive hysteresis could cause thermal stresses in excess of operating levels of the materials and result in ultimate degradation and failure. The alternative path is also a possibility. The sheer stresses could assault the bond between laminates and result in failure.

The smaller blue satellite circles are only a few examples of possible causation for these
classes. Basic tire design principles have been directed toward providing warning and fail safe subsystems as backup safeguards. It should be noted that statistical data indicates an extremely low incidence of such occurrences in service. However, if backup support with cost and operational trade-offs is a criterion, we can examine some system possibilities.

WARNING SYSTEM

With respect to depressurization, this slide represents a design progression. The first is a current, single chamber pressure vessel. To prevent destructive depressurization, a warning system may be integrated (Fig. 36).

Several approaches to a low pressure warning device have been tried but time does not allow a complete review.

Low pressure warning systems designed by Avco, Goodyear, and Winther Corp. have been evaluated recently by DOT in Goldstone, California. As an example, this is the Goodyear System. It consists of an electronic device which monitors detecting units at all wheel positions; a dashboard signal light is activated. Experimental units have been applied successfully to off-the-road vehicles, trucks, and passenger cars (Figs. 37 & 38).

RUN FLAT

Assuming an air loss may be unavoidable under some circumstances, work has been directed toward limited run-flat capability and vehicle control. This concept is particularly appropriate today as vehicle space and weight are at a premium and vehicle manufacturers desire to eliminate the spare tire.
One approach to this problem is exemplified by this special Dunlop "Total Mobility" tire and wheel assembly. The design of the assembly is such that the deflated configuration will support load for "limp-to-aid" capability (Fig. 39).

FAIL SAFE

Another solution is to have redundant capability, in other words, an auxiliary air chamber. This could be called "fail safe" because the secondary inner tire is capable of all the basic tire functions; spring rate, load capacity, slip angle, etc., (Fig. 40).

This is a photograph of such a dual chamber tire. This particular configuration was supplied for evaluation on the AMF and Fairchild Hiller Experimental Safety Vehicles tested last year by DOT. Similar devices have been successfully used for years in NASCAR stock car racing (Figs. 41 & 42).

FOAM INFLATION

The third step in the progression is Foam Inflation. In a sense, this is simply a means of forming millions of tiny pressure compartments. Therefore, the tire continues normal operation as a structural member but no longer is required to perform as an integral pressure container or envelope (Fig. 43).

This is a truck tire inflated with Permafoam.* Different composition foams are used according to the application (Fig. 44).

*TM The Goodyear Tire and Rubber Company.
Foam inflation has been used successfully on mining and logging vehicles, military vehicles and fork lift trucks as shown here, to name a few (Fig. 45).

Figure 40. Goodyear LifeGuard (TM)

Figure 43. Tire inflated with Goodyear Permafoam (TM)

Figure 41. Fairchild and AMF ESV's

Figure 42. Goodyear racing LifeGuard (TM) – NASCAR

Figure 44. Foam inflated truck tire
The limitations to date are primarily weight and speed. Passenger car applications are conceivable with improvements in the foam substances.

NON-PNEUMATIC

The last stage in the progression would be a non-pneumatic tire. A solid rubber tire as used by some slow speed industrial vehicles is one example. This has obvious drawbacks (Fig. 46).

A wire tire of the type used by the Apollo Lunar Rover is another example. Here again, the service criteria of fatigue, wear and traction are critical factors (Fig. 47).

CONCLUSIONS

In conclusion, considerable effort is being directed at the function of the tire in the vehicle system. Active areas include traction, force and moment studies, handling programs, hydroplaning and destructive and non-destructive testing.

The outputs of these ambitious programs can have a long-range beneficial influence on the tire and its operation. However, this can only be attained through a better understanding of the integration and interaction of the tire in the vehicle system and operational environment.

Regardless of how precisely we can measure specific tire parameters in the laboratory or under controlled conditions, these are but disproportionate fragments of the whole. This technology is of little practical value without a gauge to relate to application. The inclination to simply “maximize everything” is not the productive engineering approach.

The emphasis must be directed toward defining the “mission profile” and assigning relative priorities. Operational requirements, boundary conditions and cost trade-offs must be considered for the specific “mission."

We are not implying that this would be either simple or completely objective in the scientific sense. But, it is essential for constructive, applied research in this area.
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References


Questions & Answers

SUMNER MEISELMAN, AAA:
I have two or three questions, I'll try to keep them brief. In your tests were they bonded shoes or riveted?

Then there's no work that's been done, apparently, in the case of riveted shoes?

And so, my next question is: Can you account for the anomaly, I guess, of the no degradation on lining thickness relationships?

In this case, if I remember correctly, they were all bonded.

This is planned in the future— that's correct.

Well, I guess, we really wouldn't expect too much with lining thickness except when you got to the case where it completely wore out. I mean, I guess we really don't see any rationale for saying it should degrade with decrease in thickness.
Development of Brake Inspection Criteria and Equipment

Maurice H. Cardon
Bendix Research Laboratories

ABSTRACT

Presented is a summary of past, current, and future research and development efforts directed to development of a passenger car-light truck brake inspection system for use in the implementation of state inspection programs. In initial efforts, literature searches and studies established the state-of-the-art of state inspection programs, standards, and inspection equipment and the current knowledge of brake system degradation. Vehicle tests were used to evaluate the effects of various modes of degradation. In subsequent efforts, an approach of establishing the performance of degraded components and relating that performance to vehicle performance using computational methods was developed and verified through comparisons with actual vehicle tests. Also, methods of effectively simulating degraded components were developed. Modes of degradation investigated using this approach included worn friction materials (linings, pads, discs and drums), and contaminated linings. Results indicate that some modes of degradation result in catastrophic failure and thus brake system inspection must include measurement of more than just performance. Current efforts are directed to the development of a cost-effective brake inspection system. The effort includes the evaluation of available equipment, development of inspection techniques, generation of inspection system specifications, and building and demonstrating the brake inspection system.

Future R&D efforts will be directed to generation of data for establishing objective limits of degradation, establishing the degradation characteristics of the general population of friction materials, and expanding our knowledge of the effects of other modes of degradation.

INTRODUCTION

Congress, in the 1966 National Traffic and Motor Vehicle Safety Act, set forth its policy with regard to the inspection of in-use vehicles to encourage and strengthen the enforcement of state inspection of used vehicles. It directed the Secretary of Transportation to conduct studies, recommend necessary legislation, and establish uniform motor vehicle safety standards applicable to all used motor vehicles, expressed in terms of motor vehicle safety performance. The research and development effort being presented was conducted in response to the indicated policy and direction.

Early studies indicated that there are three problems associated with used-vehicle safety programs and their method of enforcement, periodic motor vehicle inspection. These three problems are 1) the need for an objective link between vehicle defects and crash causation, 2) the need for a sound technical basis for the vehicle in-use safety standards, and 3) the importance of providing a vehicle inspection program which is economically acceptable to the consumer.

The first element in any research program addressing these problems is the in-depth investigation of accidents to determine the extent to which defects cause or contribute to accidents. This effort is supported by the other elements of a rational research program which are the determination of the safety status of the vehicle-in-use population (i.e., what is the nature and level of vehicle defects?) and the determination of the effects on vehicle performance, either present or
potential, of vehicle system and component degradation.

Accident studies conducted thus far strongly suggest that motor vehicle inspection tends to reduce accidents or deaths, while not necessarily implying the cause. In accident studies directed particularly to the investigation of causes of accidents, those accidents in which vehicle defects were a contributing factor contained brake system defects as one of the higher ranking classes of defects.


The discussed efforts concern brake inspection and are directed to the solution of three indicated problems. The initial discussion concerns itself with a recently completed research effort entitled “Component Degradation: Braking Systems Performance.” The next concerns itself with a current effort entitled “Passenger Vehicle and Light-Truck Braking Systems Inspection Equipment,” and the final area is a discussion of future planned “Component Degradation: Braking Systems Performance” efforts.

The initial “Component Degradation: Braking Systems Performance” effort was conducted under two separate contracts and was completed in mid-1972. This program was directed to determining experimentally the effects of various modes of brake component degradation on vehicle braking performance. The “Passenger Vehicle and Light-Truck Braking Systems Inspection Equipment” program is a two-phase effort and was initiated in mid-1972. In the first phase, the specification for a brake inspection system is to be generated and, in the second phase, the system is to be built and demonstrated. Future plans concern themselves with continued research to determine the effects of brake component degradation on vehicle braking performance and the establishment of limits of degradation.

COMPONENT DEGRADATION: BRAKING SYSTEMS PERFORMANCE

The purpose of the research to be discussed here was to seek to determine the relationship between selected braking system degradation modes and vehicle braking system performance. The primary objectives of the effort were 1) to determine experimentally how selective types, degrees, and combinations of brake system component degradation effect objective and quantitative measures of vehicle braking system performance; 2) to recommend limits of braking performance degradation and the corresponding limits of component degradation; and 3) to determine and recommend the most cost-effective means of inspecting the braking system for wear, deterioration and failure.

The first part of this effort was a literature and industry survey conducted to identify modes of degradation, establish the state of the art in vehicle brake inspection standards and form a technical base in the area of motor vehicle braking. The survey was followed by an experimental program in which the effects of select modes of degradation were investigated.

Literature and Industry Survey

In addition to an extensive literature survey, automotive and brake component manufacturers, and states having vehicle inspection programs, were contacted and surveyed. Brake system design factors and operational characteristics were evaluated in detail to identify and establish an analytical baseline. System and component standards used for both qualification and inspection of brake systems were investigated. Data on vehicle brake performance, vehicle and component test and inspection systems, criteria, and statistical data representing the effectiveness of these systems were collected and analyzed to provide information on the types and relative frequency of degradation modes occurring in the population of vehicles.

At the time of the survey, there were thirty-one states which had some type of
inspection. Eight of these employed a random or spot type of inspection. Brake inspection standards used by many of these states were developed from a standard that was originally published in 1941 with revisions in 1956 and 1963. The standard specifies stopping distance from 20 MPH which will not necessarily reveal defects in brake systems that become apparent in high-energy stops from higher velocities. The standard requires the removal of the wheel and examination of the linings and pads. Much of the defined inspection is dependent upon a subjective opinion of the inspector.

The survey revealed that uniform, safety-related criteria for brake system performance does not exist in any state inspection program, and safety criteria do not exist in any form within any nationally recognized and accepted standards. Test levels, speed, input force, etc., commonly used are not always sufficient to detect degraded performance. The results of the survey indicated the need for research directed to the development of safety-related inspection criteria.

More than 57 basic degradation modes were identified and wear-out degradation modes were found to predominate. The literature was found to contain virtually no data on the effects of established modes of brake system degradation except in terms of symptoms noted. The only frequency-of-occurrence data found was from motor vehicle inspection sources. The review of a nationwide survey indicated that more than 32 percent of the vehicles on the road contain one or more types of brake system degradation and at least 11 percent of the vehicles tested dynamically in a nationwide survey were found to have deficiencies in braking balance or braking force. Brake linings, drums or discs and wheel cylinders are most frequently reported in degraded condition, but accident data seem to indicate that the hydraulic system degradation is responsible for more accidents caused by brake degradation.

Experimental Program

In the initial experimental program, vehicle tests were used to determine the effects of selected modes of degradation on vehicle braking performance. Performance measures were made on a test track and a chassis-type brake dynamometer. In the tests where actual vehicle performance was measured on the test track, the measures of vehicle performance were deceleration, stopping distance and vehicle directional stability.

Stopping distance was measured directly, using a tape measure, with the beginning of the stop marked by an explosive event marker triggered by the vehicle’s brake system. In the test a driver applied and controlled brake inputs. Stopping distance tests were conducted from initial vehicle velocities of 20, 60 and 80 MPH. Tests conducted using the chassis-type brake dynamometer followed procedures defined by its manufacturer and procedures developed under the program. Modes of degradation investigated included lining and pad wear, drum and disc wear, combination of pad and disc wear, and drum and disc defects. While much data was derived from this program, the desired resolution was not obtained, indicating the need for a new or refined experimental approach.

In establishing a new experimental approach to meet the objectives of this effort, a number of requirements which the selected approach should meet were established. These requirements were:

1. That conditions of the experimental approach be sufficiently controllable to allow the quantitative resolution of the effect of various levels of degradation being investigated and/or that when wide variances in data are obtained, they be primarily the results of the performance of components being investigated.

2. That performance data of the degraded component, as well as vehicle performance, be obtained for the purpose of
providing data for possible inspection at component or subsystem levels.

3. Because of the number of modes of degradation that must eventually be investigated, the number of levels of each mode of degradation prescribed for evaluation, and number of test repeats required to establish the validity of data, it is necessary, from an economic standpoint, that the effort and equipment involved in deriving the desired data be cost effective.

It is possible that the first two requirements could be achieved with an experimental approach utilizing direct but improved vehicle testing techniques. It would be difficult and it is very doubtful that it could be achieved with a minimum of cost. Thus, an approach involving the use of an inertial dynamometer to derive component performance data, vehicle computer simulation to relate component performance to vehicle performance, a limited amount of vehicle testing for checking and verification purposes, and the simulation of degraded components was adopted for this effort.

The inertial dynamometer is used to determine output torque characteristics of brakes, as a function of time, under load and operating conditions simulating those of maneuvers prescribed to measure vehicle braking performance. These results are then used with a vehicle computer simulation to calculate the vehicle performance in the prescribed maneuvers. Selected modes of degradation are investigated in vehicle tests and the results are compared to the simulation results to insure that the simulation techniques are performing as intended.

An inertial brake dynamometer simulates vehicle inertia load and measures the output torque characteristics of the brakes being evaluated. Modern dynamometers are equipped with automatic control which allows test conditions, from test to test, to be accurately controlled and repeated. Tests such as fade and recovery may be programmed and conducted automatically, keeping manpower requirements to a minimum. When compared to vehicle testing, dynamometer instrumentation is fixed and, therefore, does not require the attention that vehicle instrumentation does to achieve accurate and repeatable results. It also does not have to be set up for each vehicle tested. The dynamometer provides detailed performance data of the brake itself, which is felt to be essential in achieving the ultimate objectives of this effort.

The use of vehicle computer simulation has many of the same advantages as the dynamometer in that test conditions are accurate, controlled and not subject to change from test sample to test sample; instrumentation is fixed, and other difficult-to-control variables associated with vehicle testing may be precisely controlled.

Also, common to both of these tools is that they are not subject to weather conditions, as is a test track, and evaluation may easily be scheduled at any time of the year, day or night.

Components with simulated modes of degradation are used in both dynamometer and vehicle tests. Degradation is simulated in physical proportions, surface finish, surface microstructures, and surface material compositions.

TEST PROCEDURES

The measures of vehicle braking performance were effectiveness, fade and recovery, efficiency, and combined braking and steering characteristics while braking in a turn.

The dynamometers used in the test program were two-wheel, full-scale inertial dynamometers that are automatically programmed, allowing test runs to be repeated accurately, and are capable of conducting either constant brake pressure or constant brake torque tests (see Figure 1).

The inertia loads of the dynamometers were adjusted to simulate one-half the vehicle's inertia and one front and one rear brake were used, except in the case where a mode of degradation affected one wheel only. In this case the inertia load was adjusted to simulate load on the front axle and two front brakes were used.
computer vehicle program. The program utilized a mathematical model of the automobile which is an extension of the basic BPR-CAL ten-degree-of-freedom model developed by the Cornell Aeronautical Laboratories for the Bureau of Public Roads. The model incorporated in the program contains 16 degrees of freedom encompassing body motion, wheel rotation and front wheel steering.

During the dynamometer tests for each given speed and pressure, three trials for each of three materials were made. Thus a total of nine trials were made available for determining an average response for the given tests.

In addition to calculating stopping distance, the program provided such information as steering input displacement and torque, longitudinal and lateral acceleration, and vehicle speed and yaw rate as a function of time.

In the vehicle tests, the test sequence and conditions, such as vehicle speed, brake pressure, brake application rates, etc., were the same as in the dynamometer tests. A brake applicator was used with the capability of applying the brake repeatedly at a desired rate and maintaining constant brake pressure or vehicle deceleration. The vehicle was instrumented to measure the following parameters and to record them as functions of time:

- Brake Pressure
- Pedal Force
- Pedal Travel
- Steering Wheel Torque
- Steering Wheel Displacement
- Vehicle Speed
- Longitudinal Acceleration (Deceleration)
- Lateral Acceleration
- Yaw Rate
- Stopping Distance

In the experimental studies, the initial tests for both vehicles were run with three samples of brake components in original OEM condition.

Test repeatability and experimental correlation with actual vehicle tests provided the basis for determining the acceptability of the experimental procedure.
VERIFICATION

The verification of the experimental method was accomplished by establishing vehicle brake performance from data derived from dynamometer tests and comparing it to that obtained from vehicle tests. Both stopping distance and fade performance were compared for brakes in OEM condition and for brakes with one contaminated brake. The performance of two vehicles, one with four-wheel drum brakes and the other with drum/disc brakes was measured.

The repeatability of the 10- and 15-stop fade and recovery sequence, conducted on the inertial dynamometer, is shown in Figures 2 and 3. As shown, the repeatability of the brake friction material temperatures, encountered during the fade and recovery tests, was very close for the three samples tested.

During the effectiveness tests run on the dynamometer, the main output was brake torque as a function of test time for each brake. The brake torque data were converted into vehicle braking performance with the vehicle computer simulation. The results of the baseline effectiveness tests for Vehicle A (with disc front brakes) are shown in Figure 4. The repeatability of the dynamometer tests was within ±2 to 3 percent at the 30 and 60 MPH test speeds and within ±12 percent at 80 MPH. The correlation between dynamometer tests and vehicle tests, that are also shown, was within 7 to 8 percent.

The wide spread in dynamometer test data at 80 MPH was the result of one set of rear friction materials having a low effectiveness level. This condition was evident only at 80 MPH. This finding was made through an examination.

Figure 5 shows the baseline test results of the effectiveness test, performed on the dynamometer, for Vehicle B (drum front brakes).

![Graph showing vehicle A's baseline results](image-url)
The results are presented as a plot of simulated vehicle stopping distance versus brake pressure for each of the three test speeds. The band of test results represents the range of results for three sets of baseline sample materials and two repeats of each stop for a total of nine stops for each test condition. The repeatability of the test results is of the same magnitude as that reported for Vehicle A.

Also shown in this figure is the correlation between vehicle and dynamometer-computer test results. The two sets of results fall within 17 to 18 percent of each other.

In order to obtain realistic results from the experimental studies using sample components with simulated degradation, it is essential that the simulation be reasonably accurate. The approach followed in simulating worn linings/pad and disc/drum was to obtain actual degraded components and characterize friction materials using optical microscopy, thermogravimetric analyses, and surface finish measurements. The optical microscopy is used to define the microstructure of the sample material and from the thermogravimetric analyses, chemical composition is inferred.

In the case of lining and pads, from the data obtained, a service temperature history is postulated and a brake dynamometer test sequence is prescribed to duplicate this history on an accelerated basis. New linings which are ground to a size to represent the desired wear are subjected to the dynamometer test sequence. These linings are then examined using the same microscopy and thermogravimetry techniques and compared to the used linings. A similar procedure is followed in the case of the drums, except that only the microstructure is examined. When
comparable data are obtained, a condition procedure is said to have been established and is used to prepare test samples.

In the thermogravimetric analysis, three to four layers of a sample of the lining or pad being analyzed are removed for analysis (see Figure 6). The characteristics of these layers are then determined and a chemical composition estimated. An example of data derived, comparing a simulated worn-in-service lining with actual in-use linings, is shown in Figure 7. It is known that microstructure of the cast iron friction surface varies with usage and to insure that proper simulation was being obtained, microstructures of the surfaces of both used and simulated drums were evaluated, using an electron microscope.

After a particular lining has been run with a drum for awhile, it will produce a steady-state surface roughness on the drum or rotor. Thus, drums for brakes simulating worn conditions were finished as close to the finish found on used drums as possible. The drums or rotors were then subjected to the same conditioning sequence on the dynamometer as the linings they were to mate with.

Figure 6. Schematic showing friction material layers analyzed
COMPONENT DEGRADATION STUDY

The braking performance of two vehicles with their brake systems in as-new condition and with three modes of degradation were evaluated following the described procedure. The vehicles were Vehicle A, a 1970 luxury-sized passenger car with disc front and drum rear brakes and Vehicle B, a 1971 intermediate-sized passenger car with front and rear drum brakes.

The modes of degradation investigated were contaminated brakes, worn friction material and worn discs and drums. The brake contaminants were brake fluid and wheel bearing grease.

The measures of vehicle braking performance were effectiveness, fade and recovery, efficiency, and combined braking and steering characteristics while braking in a turn. The discussion in this paper will be limited to the first three.

The test sequence followed in establishing braking performance was:
1. Burnish
2. Ten-Stop Fade and Recovery
3. Reburnish
4. Fifteen-Stop Fade and Recovery
5. Reburnish
6. Effectiveness
7. Braking Efficiency

The results of the study of Vehicle A are summarized in Figure 8. During the fade tests (Figure 8(a)), the worn friction materials showed a marked decrease in fade properties at thicknesses below 0.100 inch. These results accompanied an increase in friction material wear as shown in Figure 8(d). The thin discs also exhibited a decrease in fade properties during the 15-stop fade tests. This is signified by the increase in brake pressure required during the test. During the effectiveness tests, none of the degradation modes produced significantly large deteriorations in performance relative to baseline.
During the contaminated friction material tests, one problem arose that must be considered when reviewing the test results. The problem was that the effect of the contaminant, which was added prior to the fade sequence and the effectiveness sequence, varied during the tests. The varying effect was the result of erosion and evaporation of the contaminant during the tests. An alternative to the procedure used would be to add contaminant continually during the testing. The main difficulty with this solution is that the test samples would not be any more repeatable because not all the contaminant would be removed after each stop and the addition of more contaminant would produce a total additive effect which would vary throughout the test sequence.

An important aspect of the one-front-brake contamination tests is that although overall vehicle brake effectiveness is not greatly altered, side-to-side brake imbalance is altered. The side-to-side brake imbalance obviously will produce undesirable vehicle steering inputs during braking that must be compensated for by the driver.

The efficiency tests, one level of worn friction materials and one level of thin discs run on a wet surface, produced results lower than baseline. The decreases in braking efficiency can be the result of an increase or decrease in the gain of one or more brakes in a system. A decrease in a brake gain will produce a decrease in efficiency proportional to the decrease in the brake output. During this condition, the operating pressure to achieve minimum stopping distance without wheel lock-up remains unchanged. With an increase in brake gain of one or more brakes, the operating pressure to avoid wheel lock-up must be reduced, thereby decreasing the stopping forces from the unaffected brake and decreasing braking efficiency. For the two cases cited above, the decreases in efficiency were the result of rear brake gain increases.
Figure 8. Vehicle A disc brake experimental results summary
A summary of the Vehicle B results is shown in Figure 9. During the fade tests (Figure 9(a)), only the contaminated friction materials produced any marked reduction in fade properties relative to baseline results. The contaminated friction materials also produced brake imbalance as reported for the disc brake results and an increased wear in the mating uncontaminated front brake (Figure 9(d)).

In the effectiveness tests and the efficiency tests, none of the degradation modes produced any marked performance decrease from baseline levels. The drum brake results were similar to the disc brake results. During the effectiveness test, the drum brake exhibited higher gain for thin-drum modes of degradation. This increase was attributed to a decrease in drum rigidity. The decrease in drum rigidity also has an effect on the lining-to-drum contact characteristics.

Discussion

In the "Component Degradation: Braking Systems Performance" effort just described, an experimental approach was developed for relating component degradation to vehicle braking performance that yields both vehicle and component performance data, the results of which are sufficiently repeatable to allow objective conclusions to be drawn. The effects of three modes of degradation of disc and drum brakes were investigated. The modes of degradation involved worn and contaminated friction materials.

In the investigation of the effects of contaminated front brake friction materials it was found that a vehicle's braking effectiveness was not affected appreciably but that an undesirable imbalance was created that required a driver's input to correct for it and which could result in vehicle stability and control problems. No objective data could be found with regard to acceptable limits of brake imbalance with regard to either driver capabilities or vehicle control and stability. Also, in this area, the friction materials themselves did not appear to suffer from the contaminants investigated, indicating that it probably is not necessary to replace linings or pads which have been contaminated, if the contaminant is removed. The question that is raised is whether all lining and pad materials behave in a similar manner.

Brake performance was found to be little affected by thin linings or pads and that, if replaced when recommended by the manufacturer, they should not be a problem. When trying to establish limits for inspection purposes, several questions arise. If vehicle inspection is a yearly affair, it is quite possible that a thin lining or pad just above the manufacturer's recommended limit may wear to the point of failure before the following inspection. Thus, it may be desirable to establish a limit above that recommended by the manufacturer. This is particularly true in the case of a pad material similar to that investigated whose wear rate accelerates when it becomes thin. But what should this limit be? There is little information and data available from which to draw an objective conclusion. Also, again, only one pad and one combination of lining materials were investigated; will other material behave in the same manner as that studied?

These questions are being addressed and research planned to provide data necessary for establishing objective recommendations to the limits of degradation. These planned research efforts are discussed in a following section.

VEHICLE INSPECTION

A companion program to the brake degradation effort is the "Passenger Vehicle and Light-Truck Inspection Equipment" program now under way. This program is a two-year, two-phase effort. The objectives of the first phase are: 1) to determine the most cost-effective method of inspecting, detecting and measuring brake system defects and degradation; 2) physically evaluate existing brake inspection equipment capable of inspecting, detecting and measuring any or all brake system outages; and 3) recommend and/or develop the specifications for a brake inspection technique and associated inspection equipment based on the objectives 1 and 2.
Figure 9. Vehicle B drum brake experimental results summary
The primary objectives of Phase II of the research project are 1) to design and build the recommended brake inspection system resulting from Phase I, and 2) evaluate the performance of the recommended brake inspection system.

Fundamental to the successful development of any inspection program is a clear definition of the criteria by which items will be inspected and the rationale by which these criteria are developed.

The brake systems of in-use passenger vehicles and light trucks are the items to be inspected by the inspection program to be developed. The basic intent of the inspection program is to determine if a brake system has the ability to perform in a safe manner for a reasonable length of time. The developed program must be able to establish immediate brake system performance capabilities and if there are any defects or degradation that will lead to near-future catastrophic failures or sublevel performance. Characteristics defining brake performance are outlined in NHTSA's Docket 70-27, Hydraulic Brake Systems, Proposed Motor Vehicle Safety Standards. The characteristics defined in this document can form the basis from which performance inspection criteria are developed. While NHTSA may choose different levels of acceptance for vehicles in use, the performance characteristics measured in an inspection program should be related to the performance criteria outlined. The definition of defects and degradation that lead to substandard performance and catastrophic failure must be derived from histories, established from previous and current research efforts of NHTSA, and objective data published by, or available from, other responsible organizations.

As goals, the inspection system developed should have the following capabilities:

- Ascertaining a brake system's performance capabilities in severe, safety-related maneuvers and duty cycles.
- Detecting defects and states of deterioration that will lead to eventual sublevel performance or catastrophic failure.
- Identifying components or areas of the brake system which are defective when brake system outages occur.
- Displaying inspection results in a manner commensurate with capabilities of personnel manning the system.
- Sufficient flexibility to allow for changes in vehicle design and the incorporation of new techniques of inspection as they occur.

Presented in the following is a description of the technical approach being followed in Phase I, a summary of brake defects and inspection methods, a description of the basic inspection system concept being followed, and a discussion of currently available brake dynamometers.

Technical Approach

The technical approach being followed in Phase I of the program is outlined in Figure 10. The first item of the outlined approach is identification of brake system defects, effects of the defects, and brake inspection methods. The first item is accomplished through a thorough brake system failure analysis, review

![Figure 10. Diagram of technical approach of passenger vehicle and light-truck inspection equipment program-phase I](image-url)
of current and previous NHTSA research efforts, and an industry and literature survey. The results of this first effort are then used to develop a preliminary inspection system concept and specification. The preliminary specification will indicate functions to be performed, equipment required, and performance capabilities desired. Also generated is a test plan for evaluating equipment, developing inspection techniques and procedures, and establishing equipment performance requirements. The generation of the preliminary specification is followed by an equipment screening study and the procurement of inspection equipment. This study involves evaluating the capability of inspection equipment with the potential of meeting the requirements defined in the specification. Equipment of primary interest in this study are devices capable of loading and measuring the retarding force developed by a vehicle’s brakes.

Information is derived from contacts with manufacturers of such equipment and published literature. Where possible, for each piece of equipment, the fundamental operating principle, sensing method, readout instrument, and recommended use procedures are evaluated. Equipment considered to have potential is selected for either further analytical and/or physical evaluation.

The next step in the approach is to evaluate the procured equipment and refined evaluation procedures. The refined evaluation procedures are then used to evaluate existing equipment at on-site installations.

For this purpose a passenger vehicle is equipped with a brake application machine for introducing known pedal forces at given rates, sensors for measuring brake torque being developed, and a hydraulic proportioning device in the brake system for simulating side-to-side imbalance and line restrictions.

Other equipment being evaluated, but not necessarily physically, include electronic readout, signal processing, memory and test scheduling devices for automating and reducing requirements for operator skill in the inspection system.

In the specification evaluation and development test activities, inspection methods are evaluated and refined data for quantifying equipment specifications are generated. This activity includes physical tests, involving vehicles and procured equipment, and analysis.

Upon completion of the equipment and specification evaluation and development test efforts, a cost tradeoff study is conducted before preparing the final specification.

In the second phase of the program, the specified system will be designed, built, and tested as to its capability for detecting safety-critical degradation modes and in its operation by inspecting randomly selected vehicles.

Summary of Brake System Defects and Inspection Methods

A summary of brake system defects and inspection methods is presented in the chart in Figure 11. The defects or modes of degradation have been subdivided into the following categories:

1. Degradation with effects on current performance.
2. Degradation with effects on future performance.
3. Degradation without experimentally verified effects on brake system performance.

Those modes of degradation which affect performance have been subdivided further into those which can be identified in dynamic performance tests and those which can be identified from static performance tests. Degradation modes which will affect future performance will have to be inspected visually or by some measure other than performance. In the chart, the defects, or modes of degradation, are identified with the particular area of the brake system they are associated with.

Basic Concept

A functional block diagram, illustrating the concept of a brake inspection being developed, is shown in Figure 12. The basic elements of the system are:

- brake dynamometer
- input control actuator
<table>
<thead>
<tr>
<th>Brake Subsystem</th>
<th>Dynamic Performance Tests</th>
<th>Static Performance Tests</th>
<th>Nonperformance or Visual Inspection</th>
<th>Degradation Without Verified Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>System Gain</td>
<td>System Response (Application and Release)</td>
<td>Fade</td>
<td>-Front-to-Rear Balance</td>
</tr>
<tr>
<td>Brake Pedal Linkage</td>
<td>Sticky Linkage</td>
<td>Sticky Linkage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Booster</td>
<td>Booster Failures Low Engine Vacuum Vacuum Leaks</td>
<td>Sticky Booster Vacuum Leaks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic System</td>
<td>Large Master Cylinder Leak Line Leakage Frozen Wheel Cylinder Faulty Valving Line or Hose Restriction Wrong Wheel Cylinder Size</td>
<td>Large Master Cylinder Leak Sticky Wheel Cylinder Line or Hose Obstructions Frozen Wheel Cylinder Faulty Valving</td>
<td>One Sticky Wheel Cylinder Frozen Wheel Cylinder Faulty Valving Line or Hose Obstruction</td>
<td>Large Master Cylinder Leak Line Leakage Bad Proportioning Valve Incorrect Wheel Cylinder Size Line or Hose Obstruction</td>
</tr>
<tr>
<td>Anti-Skid Brake Control</td>
<td>Modulator, Sensor, or Logic Unit Failure</td>
<td></td>
<td></td>
<td>Modulator, Sensor, or Logic Unit Failure</td>
</tr>
<tr>
<td>Brakes</td>
<td>Poor Friction Material Incorrect Parts or Assembly Maladjustment Bent, Broken or Missing Parts</td>
<td>Bad Return Spring Shoe Hang Up Bent, Broken, or Missing Parts</td>
<td>Poor Friction Material</td>
<td>Oversized Drums Friction Materials Which Are Unmatched or Have Degraded Incorrect Parts or Assembly Maladjustment Bent, Broken, or Missing Parts</td>
</tr>
</tbody>
</table>

Figure 11. Brake system inspection chart
• sensors
• data processing, readout and test control computer

For performance measures, the basic concepts call for a well-controlled and measured input to the brake system and both dynamic and steady-state measures of the brake system output. The number of parameters sensed and final configuration of the system is dependent on the results of the analyses and studies of this effort.

Survey of Chassis Brake Dynamos

Presented in the following are the results of a survey of chassis-type brake dynamometers that can be utilized for vehicle brake inspection and are available in various configurations. The basic function of any type of brake dynamometer is to provide a load to a vehicle brake system such that brake system performance characteristics can be measured. The techniques used to supply the brake loads fall into two categories, electric motors and inertia weights. Electric motors are used in conducting constant-speed types of brake load tests and inertia weights are used for variable-speed or stopping-type of brake tests.

Currently available chassis brake dynamometers use rollers to transmit the dynamometer loads to the vehicle brakes through the vehicle tires and wheels. The most popular roller configuration is two rollers per wheel sized and arranged such that the vehicle wheel is guided between the two rolls. For the various available dynamometers, the roll sizes range from 8 inches to 21 inches in diameter. Also, the most common dynamometer configuration is such that two brakes, or one axle set, are tested at a time. Some special machines have been made to test all four brakes per test but these machines are costly and need a mechanism to allow for machine adjustments to compensate for variations in vehicle wheelbases.

For discussion purposes, the available types of dynamometers have been grouped into four basic operating modes: low con-
constant speed, high constant speed, variable speed, and a combination of high constant speed and variable speed. A description of these types of machines follows.

LOW CONSTANT-SPEED DYNAMOMETERS

Low constant-speed dynamometers are currently manufactured in Europe and only recently have been imported for sale in this country. These machines utilize electric motors and gear boxes to conduct constant-speed brake tests at three miles per hour. At this speed they are capable of generating loads of up to 1000 pounds of retarding force per wheel or brake. These machines utilize textured or cement-coated rolls to obtain roller coefficients of friction of approximately 0.7.

HIGH CONSTANT-SPEED DYNAMOMETER

There are three domestic manufacturers of this type of machine. These machines also use electric motors to conduct constant-speed brake tests. The test speed utilized depends on the manufacturer, but ranges from 35 MPH to 80 MPH. Because of the high test speed and electric motor size limitation, these machines generate loads up to 400 or 500 pounds of retarding force per wheel.

VARIABLE SPEED DYNAMOMETER

There is one domestic manufacturer that has built several special machines of this type. This type of dynamometer uses inertia weights to supply the brake loads.

This dynamometer is a four-wheel unit that utilizes the test vehicle drive train to power the dynamometer rolls up to the desired test speed. Upon reaching the desired test speed, the vehicles brakes then stop the rolls and inertia weight. The amount of brake retarding forces generated with this type of machine will depend mainly on the tire-roller interface characteristics.

COMBINATION HIGH CONSTANT-SPEED AND VARIABLE-SPEED DYNAMOMETER

There are two domestic manufacturers of this type of machine. These dynamometers are similar to the high constant-speed dynamometers, inasmuch as they use electric motors to generate brake loads in a constant-speed operating mode. One of the dynamometers operates at 46 MPH and the other at 77 MPH. During the variable-speed mode, the brake loads are generated by the inertia weights. In this mode, high brake retarding forces can be generated and mainly are limited by the tire-roller interface characteristics.

FUTURE EFFORTS

Planned future efforts will be directed to the continuation of research to determine the effects of brake system component degradation on vehicle brake system performance and the generation of data to assist in the defining of limits of braking performance degradation and corresponding limits of component degradation. There are four areas of research planned; they are

1. relationship between friction material degradation and brake system performance,
2. relationship between friction material or rotor degradation and driver control/vehicle stability, and
3. brake pedal reserve limits.

The results of these efforts will then be analyzed and studied to establish limits of degradation for application modes.

Relationship Between Function Material Degradation and Brake System Performance

In the relationship between friction material degradation and brake system performance, three tasks are to be performed. These tasks are 1) to determine the effect of thin friction material on vehicle braking performance, 2) establish limits of brake proportioning front-to-rear, and 3) determine the wear characteristics of friction material. In previous work in thin friction material, only one drum-lining combination and one disc pad material were evaluated. Both of the friction materials were bonded to the shoe or pad. It is planned in future efforts to expand the investigation to cover a major portion of
the pad and lining types on the market. To be evaluated are two more OEM disc pad materials, three aftermarket pad materials and three aftermarket lining materials. One of OEM pad materials will be evaluated in the riveted and bonded configuration.

The objective of the second task is to determine allowable limits of front-to-rear brake balance for defined classes of vehicles. The data for establishing the limits will be generated from an analytical study, using balance criteria established in another NHTSA research effort, and available vehicle parametric data.

The objectives of the third task are to determine experimentally the wear-rate characteristics of selected materials for moderate- and heavy-duty to abusive operation, at various levels of material life; and to recommend minimum thickness requirements for friction materials to provide safe brake system operation between motor vehicle inspections. The experimental studies will be conducted using an inertial brake dynamometer in a manner similar to that used in a burnishing procedure. One OEM and two aftermarket pad and lining materials will be investigated. Also in this task, a data base will be established for disc and drum brake relining frequency as a function of miles driven, time of use in months, terrain or locale effects, and other significant factors.

Relationship Between Friction Material
or Rotor Degradation and Driver
Control/Vehicle Stability

There are four tasks involved in determining the relationship between friction materials or rotor degradation and driver control/vehicle stability. The tasks are: 1) determine the effects of contaminated brake shoes and pads on vehicle braking performance; 2) determine the effects of various modes of degradation on vehicle braking performance; 3) physically evaluate the effects of various degrees of side-to-side, front wheel brake imbalance on drive performance capabilities; and 4) determine the effect of differences in the side-to-side brake torque on the stability and control of a vehicle.

Previously, the effect of contaminants was studied on one pad material and one combination of drum-lining material. Also, in these tests the method of applying or introducing the contaminant was not entirely satisfactory. Thus, in the first task, a new method of introducing a contaminant to the brake friction material will be developed and a study of the effect of contaminants on additional OEM and aftermarket pad and lining materials will be conducted. Contaminants to be investigated will include brake fluid, wheel bearing grease and axle lubricants.

The second task of this effort is an expansion of the modes of degradation currently being investigated. Modes of degradation to be studied include scored drums and discs and sticking wheel cylinders and caliper pistons. The modes of degradation, with the possible exception of the sticking wheel cylinder and caliper piston, will be investigated using the inertial dynamometer technique developed in the previous brake degradation effort.

In the task involving the effects of side-to-side imbalance on driver-vehicle control, vehicle road tests will be conducted with vehicles equipped to produce controlled and repeatable side-to-side brake imbalance on both front and rear wheels. The vehicles will be instrumented to monitor pertinent driver inputs and vehicle output parameters. Tests to determine the effects of brake imbalance on vehicle free-control trajectory and the ability of test drivers and a selected sample of the general driving public to cope with the imbalance will be conducted.

The objective of the fourth task is to establish the effect of differences in the side-to-side brake torque on the stability and control of a vehicle in straight-line and combined steering and braking maneuvers. The results will aid in determining a performance envelope, as a function of side-to-side brake imbalance limits, for safe vehicle operation. The study will be conducted utilizing a vehicle simulation. In the straight-line braking
test, the vehicle will be directed to maintain a straight-line path while braking. A number of stops will be made in which the side-to-side brake torque balance of the front and rear wheels will be varied to determine the effects of brake pull on the directional orientation of the vehicle and its ability to remain in a twelve-foot lane. The same procedure will be followed for a combined braking and steering maneuver.

Brake Pedal Reserve Limits

Effort in the area of brake pedal reserve limits is directed to establishing brake pedal travel limits for passenger cars and light trucks. The effort will involve an analysis of the brake system to define variables that affect brake pedal travel and pedal reserve and the identification of the critical variables; the obtaining of brake system parametric data associated with the critical variables; physical evaluation of selected vehicles to establish working clearances, deflections and maximum pedal-travel capabilities; defining fade travel requirements; and the defining of a rationale for establishing pedal reserve limits.

The results of the previously described efforts will be studied and analyzed to establish acceptable limits of brake system component and performance degradation for the modes of degradation studied.

Presented has been a summary of past, current, and future research and development efforts directed to the development of brake inspection criteria and equipment. The early efforts indicated areas of needed research, established effective experimental techniques and provided a limited amount of data as to the effects of brake system component degradation. Current efforts are directed to the development of inspection equipment and future efforts will be directed to broadening our knowledge as to the effects of component degradation and providing data to establish objective limits of component degradation.
BOB MELOSH, VIRGINIA TECH:
Some of your data showed that as the brakes wore down, they got better. How do you explain that—in the thinning of the lining, in particular?

Well, actually, I guess there is in that, as the shoe becomes a little bit thinner, it conforms a little bit better—the drum—and therefore its effectiveness increases a little.
Anticipatory Sensors for Collision Avoidance and Crash Protection as Applied to Vehicle Safety Research

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ABSTRACT

Considerable effort has been expended in recent years to develop anticipatory crash sensors—effective means of detecting motor vehicle collisions immediately prior to occurrence. If the potential crash is sensed early enough, evasive action may be instituted to avoid the accident. If technical or dynamic considerations limit the warning time to a very short interval, benefits can still be obtained through initiation of passive restraint deployment significantly earlier than would otherwise be the case, extending the effectiveness of such systems to higher impact speeds than are now tolerable.

The latter case—restraint system deployment—is more readily defined, and is discussed here in terms of research directed toward delineation of operational requirements, optimal means of realization, and performance characteristics. Research which has been reported by a number of investigators will be described.

Collision avoidance is a more complex topic, in that no consensus yet exists as to explicit performance objectives. Research into possible operating modes and technical realizations will be discussed, with emphasis on inherent sensor requirements in each case. Topics appropriate to future research will be indicated.

INTRODUCTION

The safety of motor vehicle operation requires continual decisions based upon surveillance of highway and surroundings. The general task of discriminating between hazardous and nonhazardous conditions, and taking appropriate action, is one which—like pattern and speech recognition—human beings can accomplish with considerable success. However, incapacitation, inattention, or inadequate skill can lead to accidents, and it is natural to seek to develop automatic systems to augment or replace, insofar as possible, certain of the safety-related tasks facing an automobile driver. Crucial to this goal is realization of effective means of surveillance of vehicle surroundings and identification of hazards. This must be achieved in such a manner as to permit effective countermeasures. Detection of potential collision objects prior to actual impact is often referred to as “anticipatory sensing,” and is the subject of this paper.

Research on anticipatory sensors has been directed primarily at two potential applications. The first is collision avoidance, which can merely refer to alerting the driver, or could (conceptually) include automatic steering, braking, and accelerating of the vehicle along a safe trajectory. The second topic to which pre-sensing is relevant is actuation of deployable passive restraint systems, for which a small advance warning can extend system effectiveness to relatively high impact speeds. These two application classes are quite distinct, in that one requires sensing at tens to
hundreds of meters distance, whereas the other needs an effective range of only one to three meters. However, the potential collision objects are the same in each case, and basically similar technologies have been investigated by various researchers. Thus it is appropriate that research in both areas be described here. This paper draws heavily upon the research of other groups and individuals, both published and unreported, and is intended to provide a meaningful survey of the current state-of-the-art. However, the proprietary nature of the field limits the flow of information, and this presentation does not purport to be all-inclusive.

For the purposes of this discussion, a broad definition of “anticipatory sensor” will be assumed. That term is used here to include both the means of obtaining the necessary information—the surveillance function—and such signal processing as is required to provide necessary output actuation signals. For example, if automatic braking is envisioned, the anticipatory sensor output would directly control both the timing and degree of brake application, operating through an electromechanical interface. Separation of surveillance and information processing is an artificial distinction here, in that the nature of the processing depends upon the information gathered. This intimate relationship between basic sensing, data processing, and ultimate function implies that required overall system characteristics be sharply defined in the initial phase of investigative efforts. Since that function which is desired may not, in fact, be feasible, an iterative process is often needed to determine a research goal which is both attainable and of real value. A major aspect of anticipatory sensor research has been determination of reasonable overall objectives and selection of the technology by which they can be achieved. Thus, a significant part of this paper will deal with such topics.

GENERAL CONSTRAINTS ON ANTICIPATORY SENSORS

There are a number of constraints which must be satisfied by any anticipatory sensor if it is to be viable in general automotive use. Major requirements are listed below.

HIGH RELIABILITY

Automobiles often have a long useful life, even with relatively little special care. At the same time, a viable sensor must achieve a very low failure rate, with respect to both failure to operate when needed, and to inadvertent operation when not appropriate. Design must be fail-safe, in that the least hazardous condition occurs in the event of failure. In both categories, the reliability requirements for anticipatory sensors far exceed those normally imposed on automotive systems. Also, failure of the sensor to actuate subsystems because of inherent inability to detect the potential collision object must be uncommon, and actuation of avoidance procedures or restraint deployment must virtually never occur as a result of inadequacies of the object detection process. That is, target discrimination must be good.

OPERATING ENVIRONMENT

The automotive environment includes a wide temperature range, exposure to high levels of moisture, and much foreign matter. Vibration can be severe, and the electrical environment includes high noise levels and large voltage variations.

VANDALISM

It is possible that triggering of anticipatory sensors could be seen by vandals as an enjoyable sport. Thus, it is important that false triggering not be readily accomplished by those so inclined. Similarly, the sensor must not be easily damaged by direct malicious acts.

LOW COST

There are two basic limitations on cost. The first is that of the marketplace. The second consideration is a more rigorous overall cost/benefit evaluation in terms of true societal costs. Both approaches have generally been found to imply a restriction in the range of $50 to $250 per vehicle as sold to the
consumer. OEM price must, of course, be much lower.

RESEARCH INTO POSSIBLE TECHNIQUES FOR ANTICIPATORY SENSING

There are many known or conceivable means of sensing the presence, closing rate, and nature of nearby physical objects, but most methods can be discarded immediately as far as this application is concerned. Indeed, the real burden is to demonstrate that any truly promising methods can be found. The basic classifications of sensors which have been considered are mechanical, proximity, and ranging. Mechanical methods include the use of probes, extendable bumpers, etc. Proximity techniques are basically static, such as capacitive, inductive, magnetic, etc. In ranging sensors, energy is radiated ahead of the automobile and the reflection (if any) is analyzed to provide information as to the range, movement, and nature of the reflecting object. The consensus of research findings with respect to these classes will now be discussed briefly, with the understanding that system details inevitably depend upon required operational characteristics.

MECHANICAL SENSORS

Mechanical sensors are inherently relevant only to short-range crash prediction. One must, in essence, advance the physical position of the sensor relative to the vehicle. An indication of the mass or immobility of such a target is necessary in order to predict the seriousness of the collision. While a mechanical sensor offers this capability, its sensitivity depends upon the capacity of the sensing system to absorb energy. A physically small sensor extended in front of the car might undergo severe decelerations even for relatively minor impacts. Alternatively, a massive structure which could better judge the seriousness of the crash would be a complex and expensive device, since substantial extension would be necessary, and it would presumably have to be retractable. Thus, this approach has not found favor.

PROXIMITY SENSORS

Inductive, capacitive, and magnetic vehicle detection systems are well-known. However, for this application it would be difficult—often impossible—to distinguish between effects of range, velocity, size, and target characteristics. Capacitive or inductive sensors would also require inconveniently large structures. Infra-red radiometric sensing is vulnerable to environment, and temperature-discrimination would be a poor means of determining the relative hazard of obstacles. Proximity techniques have generally been found insufficiently promising to warrant detailed investigation for this task.

RANGING SYSTEMS—OPTICAL

Good discrimination of target position is possible, and sharply-focused optical systems can provide determination of obstacle dimensions. The closing rate can readily be measured. However, optical sensors are vulnerable to dirty apertures and dust, fog, or snow in the air. Finally, attaining satisfactory target discrimination does not appear possible.

RANGING SYSTEMS—SONIC

For an air-medium, high-resolution system, relatively short wavelengths are required. Avoidance of creation of audible noise, as well as reduced susceptibility to environmental noise, imply frequencies above the audible range, but frequency is limited by atmospheric attenuation which can be quite large at higher frequencies. Thus, 30 to 100 kHz has been found to be the optimum for an acoustic sensor. The basic requirement for very wide bandwidth, combined with the need for a transducer “window” operable under severe weather conditions, raises both technical and economic problems. Attenuation and susceptibility to wind and noise are serious problems. Finally, target discrimination is quite poor. Thus, this approach has not been widely explored.

RANGING SYSTEMS—RADAR

Radar has been used extensively for object detection, particularly in aviation and
marine applications. The frequency, transit time, amplitude, phase, direction, and polarization of a reflected radio signal all can provide information about the reflecting object and its motion relative to the radar system. For significant directivity, the antennas used must have dimensions large compared to the radio wavelength; this consideration alone dictates use of frequencies of 10 GHz and above. (Component prices tend to be a minimum at 10 GHz, rising sharply with frequency.) Range and rate can be determined accurately, but the size of the target must be inferred primarily from the magnitude of the returned signal. One can expect only limited correlation between target lethality and radar cross-section. However, motor vehicles, which are the major obstacle category, generally provide a strong reflection. In summary, microwave radar suffers less from poor target discrimination than do other methods, and has in its favor a wealth of known techniques and available components. On balance, this approach has been selected for detailed investigation by a number of investigators, and almost all reported experimental anticipatory sensors have been based upon radar technology. A discussion of such research follows.

RESEARCH INTO ANTICIPATORY SENSORS FOR CRASH PREDICTION

The relevance of presensing to crash prediction arises from the development in recent years of deployable passive restraint systems, such as airbags. The maximum impact speed at which such devices can be effective is crucially dependent upon the means by which the collision is sensed. Conventional electro-mechanical sensors typically do not actuate until 17 to 30 msec after the collision has begun. When one adds 20 to 30 msec additional for restraint system deployment, the total time budget required is so large as to limit overall system effectiveness severely in crashes occurring at barrier-equivalent impact speeds greater than approximately 30 MPH. However, improved vehicle structures and airbags offer the potential of survivability for velocities of 50 to 60 MPH. The key to this performance is initiation of restraint deployment sufficiently early in the crash sequence. In view of the large percentage of casualties which occur in the impact speed range from 30 to 60 MPH, such capability is highly desirable, and it is this goal which provides the motivation for development of crash prediction sensors.

Basic Requirements

Analysis has shown that crash prediction sensors need acquire and process only limited information. Since overall system operation requires only 25 to 35 msec anticipation, a sensing distance as short as one meter is adequate. For collision speeds of interest, no meaningful changes in velocity or trajectory will occur prior to impact, so it is only necessary to detect the presence of a potentially hazardous object within a small region ahead of the car, with a relative closing rate greater than the threshold velocity for which deployment is deemed necessary. The basic sensing needs, therefore, are threefold: 1) Position (occupation of a critical volume); 2) Velocity (closing rate above a specified threshold); and 3) Nature of obstacle. Each of these elements will now be considered.

POSITION DISCRIMINATION

Simple detection of the presence or absence of an obstacle immediately in front of a vehicle is relatively simple, and rather similar approaches have been reported by Toyota, GM, and TSC. In essence, a bistatic arrangement is used (physically separated receiving and transmitting antennas), with position discrimination arising from overlap of the antenna patterns. Only objects simultaneously in both beams will reflect energy from the transmitter to the receiver (see Figure 1). Both Toyota and TSC have described use of four-antenna systems to obtain a more-nearly optimum region of coverage; Figures 2a and 2b show calculated regions of sensitivity for particular 2-antenna and 4-antenna systems, respectively.
VELOCITY DISCRIMINATION

This is similarly straightforward, and reported radar sensors have generally been CW doppler systems. Mixing of the received signal with a sample of the transmitted energy—a very simple process—generates an output at the difference frequency, which is proportional to the closing rate. This doppler output is at a readily utilized frequency: 31 Hz per MPH for a 10 GHz system. Thus, simple audio-frequency discrimination circuits can be used. A more sophisticated approach is possible if desired, in which actuation criteria and time, and inflation rate, are functions of closing rate.

TARGET DISCRIMINATION

This task has generally been found to be the most challenging aspect of anticipatory sensing. In principle one can derive considerable information from the amplitude, phase, frequency, transit time, direction, and polarization of a reflected microwave signal, particularly when examined over a significant time interval. However, it is not clear that even a relatively elaborate system will distinguish with sufficient precision between targets of varying lethality, and such techniques can be expensive. The most common approach has been to use reflected signal amplitude. This is a reasonable—though far from perfect—first approximation, since motor vehicles are usually good reflectors. Figure 3 shows (in conceptual form) the basic predictive crash sensor configuration typically considered.

Experimental Realizations

Laboratory prototype sensors have been constructed by a number of researchers (see Figure 4). Those systems which have been formally reported have been single-frequency radars, although promising work has been done by Sperry Rand and others utilizing sophisticated short-pulse systems, which, in effect, carry out simultaneous observation over a wide range of frequencies. Experimental radar sensors typically have utilized existing microwave technology. Both conventional horn antennas and newer, far more compact planar array antennas have been used. This latter type offers both cost benefits ($1 to $3 per antenna) and greater compatibility with automotive use. An example of such an antenna is shown in Figure 5. Solid state microwave oscillators, requiring only a 10 to 15 V DC power source, have in recent years become sufficiently developed and economical to be considered for consumer markets, and are highly suited to the crash sensing application. Most reported research has been based on these devices. Conventional mixer diodes ordinarily comprise the receiver, with all further circuit functions involving only low (audio) frequency elements.

Signal processing is commonly carried out either with analog/digital or purely digital circuits. Our studies indicate that the basic function can be achieved utilizing a single LSI (Large Scale Integration) chip, at a cost of several dollars (in automotive volume) and with extremely high circuit reliability.

Performance Considerations

TARGET DISCRIMINATION

As indicated previously, this is the most critical and weakest aspect of radar sensors. Researchers in the field have found (not surprisingly) that radar reflections from
(a) Single antenna pair

Two identical, but mirror imaged, systems antenna spacing 1800 meters

(b) Dual antenna pair

Figure 2. Detection sensitivity patterns (calculated)
Figure 3. Basic overall crash prediction radar anticipatory sensor

hazardous objects, such as trees, may be substantially lower than returns from relatively innocuous obstacles such as roadside signposts, etc. Automobiles, which represent approximately one-half of collision objects, provide a strong reflection from most angles, and concrete walls are also “good” targets. Telephone poles are difficult to sense at a high level. Typical doppler reflections are shown in Figures 6 and 7. There appears to be no easy solution to this difficulty; radar sensors are inherently imperfect, and—if placed in service for restraint actuation—could fail to operate in some circumstances when needed. Attempts to alleviate this by easing the triggering criteria would lead to an unacceptable “false-alarm” rate. On the other hand, it should be noted that even partial success in this area can provide an effective and desirable safety system, particularly in view of the large number of fatalities occurring in the higher speed ranges for which presensing is relevant.

ENVIRONMENTAL EFFECTS

Potential difficulties associated with false activations, due to rain, splashing water, etc., have been investigated and reported by Toyota. They find some problem when low triggering thresholds are set. However, the difficulty does not seem to be severe, particularly when proper signal processing and shaping of antenna patterns are included in basic designs.

INTERVEHICLE INTERFERENCE

In general use, each radar receiver will often be exposed to signals transmitted by other vehicles, with the possibility of false actuation by misinterpretation of the intruding signal as a reflection. Fortunately, the antenna configuration, short required range, and high triggering threshold used in this application tend to operate strongly against this problem. Simple distribution of crash sensor radars over a wide band would be adequate, but it is desirable that only a narrow band be needed, and that such interference be made a truly negligible factor. The benefits of applying frequency modulation to the carrier have been investigated at TSC. Simple sweeping over a 25 MHz range can provide virtually complete protection if the sweep rates vary from car to car (see Figure 8). No two systems can then stay sufficiently close in frequency for a long enough time to generate a sufficient number of simulated doppler cycles to trigger the system. Alternatively, noise modulation of the carrier frequency has been shown—both analytically and experimentally—to achieve statistically complete immunity with a very narrow crash sensor frequency band (Figure 9).

RADIATION HAZARD

The possibility of harm to those people who are, by virtue of occupation or habit, constantly exposed to radiation from vehicles must be considered. Once again, the short-range nature of the system is helpful. Successful operation requires no more than 10 mW output, and this implies a power density at the antenna of approximately .25 mW/cm², one-quarter the generally allowed level. At a range of one meter the level is down to .002 mW/cm², one-fifth of the intensity permitted
(a) Three-frequency test set: 10, 22, and 35 GHz (TSC)

(b) Laboratory model, 10 GHz (TSC)

(c) Mounted in vehicle (GM)  (d) Mounted in vehicle (Toyota)

(e) Mounted in vehicle (TSC)

Figure 4. Prototype anticipatory sensors
for continuous exposure under the conservative standards of the USSR. If desired, power could be reduced still further and effectiveness would be unaffected.

**COST**

Cost has always been seen as a major challenge to crash sensor viability and has received considerable attention. Although the components involved are typically hundreds of dollars in unit purchases, automotive volume offers very dramatic reduction. TSC has undertaken specific studies concerning both the antennas and signal processing circuitry and finds a cost of approximately $3 per antenna (two required) and $4 for the basic circuit. The microwave components (oscillator and mixer diodes), in a properly integrated form, should add approximately $5. Thus, given the presence of a deployable passive restraint system in a vehicle, the OEM cost of adding anticipatory crash prediction should be approximately $15. Adding the
search if anticipatory sensors are to achieve viable performance in crash prediction applications.

TARGET DISCRIMINATION

As indicated above, considerably more information can be acquired with radar than is utilized by crash sensors constructed to date. General Motors researchers have drawn attention to the potential benefits of comprehensive radar signature studies, aimed at successful discrimination between hazardous and non-hazardous obstacles. A small computer would presumably be necessary for implementation of this approach, but advances in solid state technology permit this possibility. This applies equally to single-frequency and short-pulse techniques.

HYBRID SYSTEMS

Utilization of sensing means additional to radar also can significantly mitigate discrimination problems. TSC has proposed addition of bumper-mounted impact switches for intermediate speeds, and GM has pointed out potential benefits of lasers for determination of target size. However, there has been no large-scale effort to explore such concepts.

OPERATION IN A REALISTIC ENVIRONMENT

Although a number of research groups have tested anticipatory sensors under normal
(and abnormal) conditions, implementation of such devices would require a lengthy and full-scale test involving fleet installation with appropriate recording devices.

**RESEARCH ON ANTICIPATORY SENSORS FOR COLLISION AVOIDANCE**

**Possible Modes of Operation**

Examination of accident statistics suggests that very large costs are associated with collisions which might have been averted or moderated by timely brake application or evasive maneuvers. Development of technology which offers the possibility of electronic assistance in this task has led to increasing interest in recent years in the subject of automatic motor vehicle collision avoidance systems. However, what at first glance may seem a relatively straightforward problem is, in fact, very complex in terms of both definition and technical realization of optimal operating characteristics. Although experimental tests of various operational concepts and specific hardware are of importance, the variety of modes and characteristics possible requires careful attention to proper analysis and definition of requirements. Most of the systems which have been investigated or proposed in recent years fall somewhere within the following categories, listed in order of increasing technical complexity:

1. Driver advisory/alarm, warning of possible hazards;
2. Headway control under constrained conditions;
3. Maximum braking, in emergency situations only;
4. Completely general, full-time use, applying moderate braking whenever needed for obstacle avoidance; and
5. General collision avoidance, including steering, braking, and acceleration.

**Basic System Requirements**

In addition to the general constraints delineated earlier, it is particularly important that fully automatic systems be such that occasions on which a correctly operating device causes an accident must be extremely rare. Such events could occur, for example, through unwarranted brake applications in heavy traffic, or through prevention of evasive maneuvers. Also, the driver who is discomforted, placed in jeopardy, or merely annoyed once a week or even once a month is very likely to disable the device permanently, and a significant incidence of this could destroy overall value.

Further, it must be remembered that the typical driver compiles an impressive record. It has been estimated that the human failure rate in brake applications is less than one in 100,000. Construction of an economically feasible system which can surpass the human capability for sensing, interpreting, and acting upon information about one's surroundings is a challenging task.

**Technical Requirements**

As outlined above, there are many possible operating modes, each implying somewhat different technical needs. However, certain requirements are virtually inherent in accident statistics. For example, the vast number of rear-end collisions make clear the crucial importance of this class of obstacle. Therefore, any system must respond effectively in virtually all cases involving this target. Further, a very large number of urban accidents involve striking a stopped vehicle, so sensing of fixed (stationary) objects is important in most potential applications.

The general target discrimination considerations relating to crash prediction apply here, also. Basic operation of avoidance systems invariably implies some measurement of range and closing rate. Some indication of position—whether the target is actually in a vehicle's path—is necessary. More sophisticated systems or operating modes require more information concerning the trajectory of the obstacle as seen by the vehicle. A range of 100 to 200 meters is necessary if moderate braking is to be utilized and protection is required at high speeds. Even emergency use only, assuming .75 g braking, requires a range
of approximately 50 meters. It is assumed that anti-skid braking systems would be in use on any vehicle equipped with a collision avoidance system.

**Trajectory Considerations**

Some useful insights into inherent limitations of a simple narrow-beam system, aimed directly ahead of the vehicle, can be obtained by examination of certain vehicle/obstacle trajectories. In this brief analysis a much simplified model is used: uniform accelerations, frictional forces with constant coefficient, and all motion assumed to occur on a planar surface with no rotational vehicular movement.

**STRAIGHT-LINE BRAKING**

The stopping distance $s$ is given by $s = \frac{v^2}{2 \alpha}$, where $v$ is the initial vehicle velocity, and $\alpha$ is the deceleration. For a maximum available deceleration $\alpha_m$, the minimum stopping distance is then $s_m = \frac{v^2}{2 \alpha_m}$. This is plotted in Figure 10 for various $\alpha_m$. The maximum deceleration normally attainable is .8 to .9 g. $s_m$ is also the required anticipatory sensing distance, assuming braking is automatically initiated at a deceleration of $\alpha_m$. (An alternative view is to calculate the maximum velocity for which complete stopping is possible, as a function of sensing distance, for various $\alpha_m$; this, too, may be read from Figure 10.)

**BEAMWIDTH**

Given a particular maximum required sensing distance (determined by the maximum speed for which the system is intended to provide protection), it is desirable that the radar observe approximately a full lane-width.
at that distance, and no more, lest roadside objects and vehicles in adjacent lanes be misperceived as hazards. The required beamwidth $\theta$ is then given by $\tan(\theta/2) = (w/2)/s_s \approx \theta/2$, or $\theta = w/s_s$, where $w$ is the lane width, e.g., for $s_s = 75$ meters and $w = 4$ meters, $\theta = 0.053$ rad $= 3.0^\circ$. (It is assumed that there is no attempt to use a scanning antenna or a trajectory-mapping signal processor; it is unlikely that such systems could meet the basic cost constraints.)

CURVED ROADS

One aspect of the narrow-beam requirement is the problem of curving roads: the radar, looking straight ahead, may fail to observe a roadway obstacle, while being alerted by objects not hazardous. It is necessary to consider under what circumstances the required sensing distance, $s_s$, becomes greater than $s_r$, the distance at which misalignment by one-half lane-width (the criterion chosen here) occurs, for under such conditions the system cannot operate correctly (see Figure 11a). $s_r$ depends upon the lane width and the road curvature $R$: $s_r = \sqrt{Rw}$. However, it's useful to express $R$ in terms of the lateral (centripetal) acceleration $a_q$, necessary to cause an object with velocity $v$ to follow a path of radius of curvature $R$: $R = v^2/a_q$. Thus, $s_r = \sqrt{w/a_q}$. The average motorist is quite sensitive to non-zero lateral accelerations, and normally prefers to limit $a_q$ to low values. On curved roads, he does this by limiting his velocity to a value appropriate to the existing $R(a_q = v^2/R)$. In essence, sharply curved roads limit the effective radar range to $s_r$, but also (by enforcing reduced vehicle velocity) reduce substantially the required sensing distance, $s_s$. At lower speeds, there is thus no problem, but since $s_s$ is proportional to $v^2$, while $s_r$ varies only as $v$, the moderately curved roads (permitting higher velocities) present potential difficulties. The condition for satisfactory operation is $s_r \geq s_s$ (permissible sensing distance greater than required sensing distance), or $v\sqrt{w/a_q} \geq v^2/2\alpha_m \cdot v_b$, the maximum (boundary) velocity for which the system can operate as intended, is then

$\nu_b = 2\alpha_m\sqrt{w/a_q}$. As an example, consider $\alpha_m = 0.75$ g, $a_q = 0.2$ g, and $w = 4$ meters. Then $\nu_b = 21$ m/sec $= 47$ MPH. $\alpha_m$ is quite important here; a system designed to apply only moderate braking encounters this limit at much lower speeds. Highway banking can also significantly increase the tolerable $a_q$, similarly lowering the boundary velocity for viable operation, i.e., banking can permit speeds sufficiently high—even on sharp curves—that the radar can not "see" far enough ahead to provide protection.

EVASIVE MANEUVERS

A similar problem arises in situations which require abrupt maneuvers, as when avoiding potential collisions by swerving around them. This is indicated in Figure 11b, with two possible approximations to the required lateral accelerations shown in Figures 11c and 11d. In this case, $\nu_b = 2k\alpha_m\sqrt{w/a_q}$,

![Figure 11. Trajectories](image-url)
with \( 2 \leq k \leq \pi \), depending on the lateral acceleration assumed. This appears to indicate that the uniform curve constraint is the more severe. However, a substantially larger \( \alpha \) might be tolerable in an emergency situation, and \( w \) could be somewhat smaller. (The important consideration here is that the radar must not induce severe braking for an obstacle which might more safely be circumvented.)

**Experimental Realizations**

Most research in this area has been carried out by companies with a proprietary interest, and little of a technical nature has been published. However, a number of comments can be made. There is, of course, a significant similarity between radar crash sensors and collision avoidance hardware, but there are also differences. The bistatic (two-antenna) configuration is not mandatory here, and both monostatic systems (Bendix, Rashid Corp.) and bistatic sensors (AutoStop) have been demonstrated. Range can be estimated from reflected amplitude, but explicit ranging is more often used, typically achieved by use of a frequency modulated or two-frequency (diplex) doppler radar. Direction discrimination—whether the target is approaching or receding—is a necessity. (This is unlike the crash sensor case, in which the receding situation can never involve high enough velocity to cause a problem at the short range in question.) Systems designed only for headway control may choose to disregard fixed objects by comparing closing rate to ground speed, generally available through road back scatter.

A major option in realization is the choice of an independent or cooperative technique. In the latter case, potential obstacles are in some fashion equipped with a transponder which the radar can identify. RCA has demonstrated such a system, in which a special harmonic antenna is mounted on target vehicles and reflects a signal at exactly twice the frequency transmitted. The radar receiver similarly operates at twice the radiated frequency, and is thus insensitive to reflections from all other objects which are at the fundamental frequency. It is thus immune to many of the problems inherent to independent systems—target discrimination, “blinding” by other systems, clutter, etc. However, these benefits are achieved through sharply limiting the number and variety of targets to which the radar is responsive. Thus, the distinction between cooperative and independent radars is not merely technical; quite different functional characteristics result.

Consideration of optimal frequency is a question both technical and economic. Lowest prices are generally found for X-band (10 GHz) components, but antennas of adequate directivity (narrow beamwidth) will be 30 to 60 cm (12 to 24 in.) in diameter, which raises serious installation questions. Thus, both GM and Bendix have constructed automotive radars operating at 35 GHz, for which suitable antennas are approximately the size of headlights. At present, components such as oscillator diodes are far more expensive at this frequency, but this may change with time. The shorter wavelengths also must be examined for performance aspects, such as ground return (apparently reduced), sensitivity to rain, target discrimination, etc.

**Performance Considerations**

Collision avoidance systems have been demonstrated in recent years which show reasonable basic characteristics. However, analysis of implementation for general usage indicates performance aspects which require comment.

**TARGET DISCRIMINATION**

The basic target discrimination problem here is quite similar to that for the crash prediction case, and little elaboration is needed. Requirements depend critically upon the operating mode selected. Note that even a cooperative (transponder) system may exhibit such directional characteristics that discrimination becomes highly dependent upon target orientation.
INDETERMINACY

There are many collisions preceded by only the briefest hazardous trajectory, just as many “collision courses” exist only transiently. Substantial and accurate tracking is required, and even this may prove insufficient to deal with occurrences such as cars crossing in front of other vehicles, making turns, yielding (or not yielding) right-of-way, etc. It will not be easy to match the perceptual capabilities and predictive skills of even a sick, inebriated, or inexperienced driver.

RADIATION HAZARD

The greater system range and informational requirements needed for collision avoidance, as compared to crash prediction, make this a more significant question here. For the range capability required 100 mW has been found to provide sufficient signal, and even at 35 GHz, power density at the antenna should be less than 1 mW/cm². However, a lowering of allowed levels is possible, and could put such systems into a marginally safe category, particularly for those whose occupations involve continual exposure to automobiles.

PROPAGATION EFFECTS

A signal transmitted to a target and reflected back can travel in other paths than a direct line. Reflected energy arriving from the target via both direct and indirect paths can interfere to produce periodic fading of the signal as the range changes. A similar phenomenon which could generate “false” targets is reflection off other vehicles so that a target appeared to be in a different location than the one occupied (a mirror effect).

BLINDING

At night, a motorist may have difficulty seeing due to the intense high-beam lighting of approaching cars. A radar receiver faces a similar problem when exposed to direct radiation from nearby on-coming vehicles. Detection of true reflections and derivation from them of sufficient information for proper operation can be greatly hindered or even prevented completely.

INTERFERENCE

A given system must be able to distinguish between a reflected return and a signal from another system. Misinterpretation of the received signal could cause an unnecessary emergency brake application. For the crash prediction case, effective countermeasures were found to be relatively simple. However, the greater range and informational requirements of collision avoidance radar make the problem considerably more difficult.

COST

The present ambiguity as to optimal form and function makes difficult accurate estimation of costs. However, the TSC crash sensor studies provide a basis for a rough approximation. The probable need for higher-frequency components, higher power, substantially more elaborate modulation and signal processing, and probable connection to the braking system all make likely a cost increase by at least a factor of 2, and probably 4 or 5—an OEM price in the range of $25 to $75. (Anti-skid braking is assumed already present.) The same multipliers as were invoked previously lead to an estimated life-cycle cost to the consumer of at least $150, quite possibly over $500.

The preceding discussion has hopefully made clear the many distinctions between crash prediction and collision avoidance; it seems unlikely that any significant cost savings are possible through commonality if both were to be installed.

Topics for Further Research

Past research on collision avoidance sensors and systems has tended to concentrate upon specialized units which meet a particular perceived need, often influenced by what is technically feasible for the developer. However, adequate determination of the optimal system—and hence of optimal sensor characteristics—requires a comprehensive and analytical investigation. Topics worthy of inclusion
are indicated below, categorized in terms of analysis and engineering tasks.

SYSTEM ANALYSIS

1. Definition of Operating Modes. As a first step toward a comprehensive analysis, it is necessary to define explicitly a reasonable number of operational modes: advisory only, headway control, short-range emergency braking, etc.

2. Development of a Data Base. All available sources of accident data must be examined and utilized to permit an estimate of the potential effectiveness of the various operating modes. Additional data may have to be generated by special studies.

3. Examination of Trajectories. A computer model for examination of normal and abnormal driving trajectories and collision patterns is needed to predict the actual performance associated with various modes.

4. Study of Driver Response. It is necessary to determine the response of a wide spectrum of drivers exposed to automatic systems, under various conditions. Advisory systems are included.

5. Effects on Other Vehicles. Consideration must be given to the effect on other vehicles under all road and traffic conditions. At best, introduction of such systems would entail a long period of partial implementation. A mix of automobile characteristics offers a potentially hazardous situation and must be studied.

6. Effect on Highway Capacity. Presumably, at some level of system implementation, safe headway on high speed roads could be less than is currently the case. A general examination of road capacity as a function of implementation, for various road and traffic conditions, would be of value.

SYSTEM ENGINEERING

1. Specific Problems. Specialists in radar technology should examine the many relevant technical problem areas, including multipath effects, blinding, interference, target discrimination, etc.

2. Optimal Specifications. Optimal range, beamwidth, frequency, and type of radar should be determined for those operating modes which appear to have potential viability.

3. Cooperative vs. Independent Radar. It is not possible at present to reach a conclusion concerning the relative merits of cooperative and independent systems. Certain technical problems are dramatically reduced for the former case, but many targets are then ignored. There is additional cost associated with the transponder, and effectiveness becomes dependent upon both elements not only being installed but adjusted and operating correctly. This question, which is of fundamental importance, will require significant efforts in both system analysis and engineering to resolve.

4. Technology Assessment. It is appropriate to analyze and test samples of all currently available collision avoidance systems to gain insight into technology problems and operational characteristics.

5. Cost/Benefit Studies. Approximate estimates of system cost and potential safety benefits, as well as overall reliability predictions, should be carried out for candidate systems and system concepts. Analysis of benefits should include consideration of the impact of other safety improvements recently introduced or mandated for the near future. For example, improved bumper and head-restraints reduce the toll of rear-end collisions, and thus limit the value of preventing such accidents.
CONCLUSIONS

Crash Prediction

Radar crash prediction with good—though far from perfect—accuracy appears to be technically feasible, at a moderate cost. However, ultimate viability depends upon other factors. Basic, of course, is realization of the expected benefits and public acceptability of deployable passive restraints. Further, since the primary value of anticipatory sensing is associated with higher velocity accidents, improved vehicle structures of sufficient basic crashworthiness must be available. Finally, the relevance of true anticipatory sensing is dependent upon developments in bumper-mounted sensors and more rapid deployment of restraint systems. Sufficient progress in these areas could substantially lessen the need for the more expensive and less discriminating radar approach. On the other hand, the advantages of less rapid deployment may give special value to predictive sensing, and the steady trend toward higher speeds may require a faster overall system than can be obtained in any other way.

Collision Avoidance

It is hoped that the preceding discussion has provided some feeling for the complexity of automatic collision avoidance systems. Virtually none of the questions which can be raised as yet have satisfactory answers. Thus, aside from the realization that the subject is not a simple one, no final conclusions can be stated. However, some preliminary observations can be made.

It is particularly clear that technical difficulties increase sharply with the desired range of the system. This includes factors such as target discrimination, out-of-lane targets, curves, evasive maneuvers, intervehicle interference, dynamic range, and blinding. Further, a system which—through long-range sensing—provides low-g braking frequently in normal driving is likely to annoy a motorist to the point of system disablement, or lull him into a false sense of security and—ultimately—an accident. Thus, a system designed only for emergency operation, intended only to apply full braking at the last possible time, and thereby with the shortest possible sensing distance, appears to be optimal in terms of both accident reduction and driver acceptability. For example, a deceleration of .75 g permits a complete stop from 60 MPH in 50 meters (160 feet); in only 30 meters (100 feet) speed can be reduced from 60 MPH to 30 MPH or to a full stop from 47 MPH—a speed which includes a very large percentage of actual accidents.

Given the difficulties associated with the simplest form of radar braking, it appears to be very questionable whether a higher degree of automation—obstacle avoidance through “radar steering,” for example—has any hope of practical viability. Determination of the value and desirability of incorporation of a warning device—an alarm—into such a system will require substantial testing of driver response. It would require substantially greater sensing distances to allow several seconds for necessary perception, decision, and action. A high percentage of false alarms could damage credibility. It is unlikely that a system which merely alerts the driver, with no brake actuation, can reduce accidents sufficiently to warrant the cost, since even this limited function will be relatively expensive to provide.

It remains to be demonstrated that a truly effective system is technically feasible within realistic constraints. Many problems pose a severe challenge to the system designer, magnified by the requirements for very high reliability and low cost, with operation in a most challenging environment. Thus, future research in this area should first focus upon questions of feasibility and potential benefits, with the clear understanding that a negative conclusion may result.
Acknowledgement

All TSC research referred to has been part of a program in Crash Sensor Development sponsored since 1970 by the Office of Vehicle Structures Research, NHTSA. TSC staff members who have contributed significantly to these studies include F. R. Holmstrom, M. Hazel, R. Abbott, T. Newfell, and E. White.

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Automotive Recorder Research and Its Effects on Future Vehicle Safety

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ABSTRACT

It is of utmost importance for NHTSA to understand real-world accident phenomena more completely. This can only be achieved by increasing the amount of quantitative information resulting from these accidents. Up until this time, accident reports have been written, safety systems designed, and safety standards set using subjective and qualitative accident information to a large extent. The Automotive Recorder Research Program presents the opportunity for NHTSA and the entire automotive safety community to obtain a significant increase in quantitative real-world accident data. The data is absolutely essential for continued progress and effective rulemaking in auto safety.

This paper has been prepared to present the basic objectives of NHTSA's Automotive Recorder Research Program and the uses to which the program results will be applied. Also, the paper describes the progress NHTSA has made in developing, producing, and installing automotive recorders which record operational (pre-crash) and crash data. Finally, the possibility of developing a vehicle crash severity index for classifying automobile collisions is discussed.

INTRODUCTION

There is presently a significant difference in results from various studies which compare motor vehicle accident severity with occupant injuries and fatalities. This difference can be attributed to several factors including the lack of quantitative pre-crash and crash data. Other factors which affect study conclusions are the 1) number of accidents or samples analyzed, 2) location of the accidents—e.g., urban vs. rural—which in effect determines the range of vehicle speeds and types of crash modes, 3) variety of vehicle structural configurations, energy absorbing characteristics, and occupant restraint systems in the sample, 4) measure of accident severity used as a common denominator, and 5) systematic errors (bias) and random errors in estimating.

As seen in Figure 1, the curves of fatalities vs. estimated barrier equivalent speed diverge significantly above 30 MPH depending on the source of data. This divergence is illustrated also by Figure 2 in which the results from two studies are expressed as the cumulative frequency of fatalities vs. estimated traveling speed. It is expected that a similar range of results exists between various studies of vehicle and driver pre-crash factors. The accuracy of the results from accident studies has a direct effect on future progress and effectiveness of rulemaking in automobile safety.

In 1969, NHTSA took a step to increase the accuracy and amount of quantitative accident data by awarding a contract for development of a recorder to measure crash acceleration/time histories during vehicle collisions. In 1970, a contract was awarded for development of an automotive recorder which could measure pre-crash data (vehicle traveling speed, brakeline pressure, steering wheel angle of rotation, and accelerations) as well as crash data. By mid 1971, the results
from these contracts had shown that reliable and relatively inexpensive recorders could be produced for installation in vehicles to obtain the required information. To date, the development and production engineering phases of both recorder systems have been completed, recorder units which were fabricated and tested have met NHTSA specifications, and over 900 production recorders have been installed in vehicles.

During July 1971, NHTSA organized a study team to take a first cut at outlining the guidelines and recommend plans for its Automotive Recorder Research Program. The objectives of the program, as currently stated, are to:

- Assess effectiveness of present motor vehicle safety standards
- Establish and confirm the needs and criteria for future motor vehicle safety standards in the areas of accident avoidance and crash survivability
- Correlate accident severity with occupant injuries and fatalities
- Assess driver performance under real-world conditions to improve preventative and remedial driver education curricula
- Determine the relative importance of contributory factors in accident causation and severity to indicate areas for greatest countermeasures emphasis.

Basically, the recorders will provide measurements of operational (pre-crash) and crash data which will be used to:

- Determine vehicle and driver performance quantitatively
- Relate controlled laboratory crash tests to real-world accidents
- Estimate the distribution of various crash modes and vehicle acceleration/time histories for serious injuries and fatalities
- Validate other methods of estimating crash severity such as vehicle traveling speed, and estimated barrier equivalent impact velocity, by comparison with barrier/pole test data
- Validate theory/models of accident dynamics

![Figure 1. Percentage distribution of barrier-equivalent speeds for single collision frontal fatality vehicles by source of data (Ref. 1)](image1)

![Figure 2. Cumulative frequency distribution of speed of faster vehicle in fatal multivehicle crashes (Refs. 2 & 3)](image2)
• Assist accident investigators to reconstruct pre-crash events
• Assist in the preparation of meaningful motor vehicle standards.

Now that automotive recorders are developed for installation in large numbers of vehicles, it is time to give serious thought to defining a more meaningful representation or measure of vehicle crash severity. In the past, there has been a relatively inconsistent use of terms to define the severity of vehicle collisions as related to occupant injuries and fatalities. When referring to Figures 1 and 2, we should note that the ordinates are labeled “barrier equivalent speed” and “estimated traveling speed,” respectively. Other terms used to categorize accidents or express a measure of comparison between vehicle collisions include: vehicle deformation index, estimated impact velocity, and impact velocity change. Both recorders will provide crash acceleration/time histories which will be processed via conventional computer techniques in digital form. In addition, one of the recorders will provide pre-crash vehicle speed and other data up until the time of impact. Automotive recorders will thus provide a wealth of dynamic data from real-world accidents to complement the data which is obtained from controlled laboratory crash tests. With this data it should be possible for the automotive safety community to define a meaningful vehicle crash severity index.

RECODER DEVELOPMENT AND PRODUCTION ENGINEERING

Disc Recorder

A variety of inexpensive peak g sensors are commercially available. However, peak g’s alone do not provide sufficient information to describe accident severity. Therefore, in September 1969, the NHTSA awarded a contract to Teledyne-Geotech for the development and demonstration of an inexpensive device capable of measuring the acceleration/time histories encountered in vehicle collisions.

DEVELOPMENT

As originally conceived, the disc recorder was designed to record vehicle acceleration/time histories in two orthogonal horizontal axes. During development, a major portion of the effort was aimed at designing a sufficiently accurate and inexpensive accelerometer. Because of expensive signal conditioning and recording equipment associated with electrical output devices the decision was made to design a mechanical recording system. Ten prototype biaxial units were fabricated, featuring magnetically damped accelerometers which induce flux lines onto a sensitive film attached to a metal disc driven at a constant 60 rpm. The units were then subjected to a series of crash tests after which data from expensive and highly accurate baseline accelerometers were compared with recorder data to evaluate the performance of the recorder. To assure proper comparison, the recorder and baseline accelerometers were mounted on a common baseplate, and both types of data were processed at approximately the same filtering levels. Results of these evaluations demonstrated that the recorder did have the potential to serve its intended purpose. With minor improvements to the accelerometer and the recording disc, an acceptable design was obtained.

PRODUCTION ENGINEERING

During a follow-on production engineering contract, the recorder was redesigned to improve overall accuracy and performance of the system, add a vertical axis recording capability, and develop the system to facilitate large quantity production. The production design of the triaxial disc recorder is described below.

DISC RECORDER DESCRIPTION

The disc recorder (Figure 3) consists of six primary elements: three accelerometers, a motor drive assembly, the recording disc and a capacitor for auxiliary power. The accelerometer (depicted in Figure 4) is a magnetically damped device designed and fabricated
specifically for this application. It consists of a highly conductive copper coil suspended in cantilever fashion by a flexure and immersed in a magnetic field produced by two opposing magnets, all of which are housed in a two piece cylindrical steel cup. A tapered aluminum stylus arm attached to the coil supports the stylus ‘‘writing’’ tip and provides mechanical amplification of the mass (coil and stylus) movement (production accelerometer shown in Figure 5). The movement of the mass through the magnetic field is proportional to acceleration forces applied perpendicular to the flexure. Increased sensitivity, optimum damping and improved frequency response (Figure 6) were obtained by increasing the strength of the magnets, reducing the weight

![Figure 3. Automotive disc recorder](image)

![Figure 5. Production accelerometer (Ref. 5)](image)

![Figure 4. Accelerometer schematic (Ref. 4)](image)

![Figure 6. Typical accelerometer frequency response curve (Ref. 5)](image)
of the accelerometer mass, and altering the dimensions of the steel cup. The permanent magnet stylus tip induces flux lines on a specially molded recorder disc.

The molded disc is constructed of an iron oxide/polypropylene material with integral gear teeth molded on the outer rim. It is designed to provide a uniform and undistorted recording surface for all three axes. A significant amount of effort was spent in finding a material mixture which could be molded and machined and still provide a uniform iron oxide distribution to “receive” a clear trace. In addition, molding the support bearings integrally with the disc eliminated “play” or radial movement of the recording surface during an acceleration pulse. A temperature compensation element was added to the disc after results of environmental tests indicated variable disc/stylus clearance during operating temperature extremes. Subsequent test results were successful.

The disc is driven at a constant speed of 120 rpm through a single reduction gear by a Siemens brushless DC motor, controlled by a germanium switch Hall device. The speed of the disc was doubled (prototype speed was 60 rpm) to produce an inherently superior resolution of the record and to yield an accurate impact velocity change measurement.

The recorder is equipped with a capacitor to supply auxiliary power in the event that vehicle power is lost during a collision.

TEST AND EVALUATION

After completion of the triaxial recorder design, production drawings were prepared and 200 preproduction recorder units were fabricated. The production drawings were revised to reflect the knowledge gained through fabrication of the preproduction units. Twenty-three of the units were subjected to a variety of tests to assure that recorder performance met NHTSA specifications (Appendix A). Some of the preproduction units were sled tested and crash tested to evaluate their performance under environments representative of those encountered in real-world collisions. As with the prototype units, the recorder response was compared with baseline accelerometer data. Figure 7 shows the comparative traces from a typical crash test.

Several of the recorder units were then subjected to a series of road tests to evaluate recorder reliability and maintainability under actual operating conditions. A total of approximately 80,000 miles (2,000 hours) of operation were completed with no failures. In addition to the road tests, some of the recorder units were subjected to a series of preliminary environmental tests to ensure that they met the NHTSA specifications. Satisfactory performance was recorded under the test conditions.

DATA ENCODER

One of the important aspects of the disc recorder design effort was the development of a data reduction technique. Records from the prototype and preproduction units were developed by photographic techniques and

![Graph](image1)

**Figure 7.** Comparison of acceleration and velocity data from a crash test (Ref. 6)
then digitized by hand. Obviously, this data reduction system left much to be desired with respect to speed and accuracy. Therefore, a special semi-automatic optical encoder was designed and fabricated to provide for accurate and quick digitizing of raw disc data. The encoder (Figure 8), which eliminates the gross errors introduced by manual digitizing, is integrated with conventional card punch equipment to allow data analysis through computer techniques. Several disc records from early evaluation tests, which were reduced manually, were analyzed again with the encoder. As a result, discrepancies between recorder data and baseline accelerometer data were reduced to a minimum.

Tape Recorder

DEVELOPMENT

Even before work began on the disc recorder concept the NHTSA was aware of the desirability of developing an automotive recorder system which could record operational (pre-crash) data as well as crash acceleration/time histories. The data which would result from a large automotive recorder research program using both recorders could be useful not only in the areas of occupant protection and crash survivability but also to research efforts in accident avoidance (e.g., vehicle handling and braking, and driver performance). Thus, on June 30, 1970, after a review of a number of proposed designs, a contract was awarded to AVCO Corporation to develop a device capable of recording crash data (impact acceleration/time histories) and dynamic pre-crash data (traveling speed, brakeline pressure, steering wheel angle of rotation, and longitudinal and lateral accelerations). The original specification required the system to record 250 milliseconds of crash data and 4 seconds of pre-crash data. Although this recorder would perhaps be more expensive and complex than the disc recorder, the prime objectives of the project were to design a system of high accuracy and reliability, and relatively low cost.

Core Memory

It was known from the outset of this development project that the major emphasis would have to be placed on developing the memory or recording mechanism and the associated signal conditioning electronics. The first approach was a non-volatile core memory design which was selected on the basis of its inherent system reliability and long life and its capability to withstand severe shock environments. However, it was soon apparent that high production cost estimates of the core memory alone were incompatible with the desired total cost of the recorder system. Thus, this concept was eliminated from consideration and the investigation of magnetic tape designs as likely candidates followed.

Magnetic Tape

Magnetic tape has long been used for processing analog and digital signals, and providing large storage capacity over a wide frequency range in a number of readable formats. In addition, a wide selection of recording equipment is available. After an initial investigation it was determined that the standard cartridge tape mechanism was well suited for our requirements. Further analysis revealed that the ¼-inch tape was the most suitable from the standpoint of cost and ruggedness. Therefore, the research efforts were directed toward integrating a compatible signal conditioning and transducer system with a ¼-inch tape cartridge recorder.

Figure 8. Data encoder for automotive disc recorder (Ref. 7)
During the development phase of this project the primary emphasis was placed on developing the signal conditioning electronics. In addition, a trade-off study of commercially available transducers was conducted to establish a baseline system from which to build six engineering models for test and evaluation.

Modulation

Modulation (method of converting transducer data for magnetic tape storage) was studied for a technique compatible with system accuracy requirements and low cost transducers. Analog techniques such as direct record of signal strength, were assessed as unsuitable for this application. In order to meet the environmental and accuracy requirements, analog systems would require costly and sophisticated electronics to compensate for bias effects. The virtual independence of digital techniques from tape characteristics, and the capability to produce extremely accurate records over the frequency range from d-c to 10,000 cps, resulted in selection of a digital modulation concept. The choice was narrowed to two modulation techniques, pulse amplitude modulation/frequency modulation (PAM/FM) and pulse code modulation (PCM).

PAM/FM

For PAM/FM the transducer signals are separated into several distinct samples, each sample having an associated distinct frequency. A low frequency indicates a low amplitude level while a high frequency indicates a high amplitude level. The signal modulated with these frequency pulses is then recorded on tape through conventional magnetic heads.

PCM

For PCM each sampled analog signal is converted to a binary value in an analog to digital converter (typical PCM encoder system shown in Figure 9). The analog to digital conversion is accomplished through successive approximation electronics where the signal is tested to determine whether it is greater than a reference voltage. The number of bit conversion stages determines the accuracy of the system. (Table 1 and Figure 10 illustrate the digital values and the serialized words derived from a typical three stage converter, respectively.) After the conversion has been accomplished, the bits are then dumped into a shift register where the data is formatted and a synchronization or identifier word is inserted into each frame. Coded data is then recorded on the magnetic tape.

Trade-Off Analysis

In order to select the optimum modulation technique a trade-off or error budget analysis (Table 2) was performed on the PAM/FM and the PCM techniques. All other factors being common to each system, the analog-to-digital conversion of PCM and the voltage controlled oscillator of a PAM/FM system were compared. PCM was assessed as superior on the basis of performance because it requires 20 db less recorded signal strength than PAM/FM, and requires only one record-

<table>
<thead>
<tr>
<th>INPUT SIGNAL</th>
<th>STAGE 1 OUTPUT</th>
<th>STAGE 2 OUTPUT</th>
<th>STAGE 3 REF. LEVEL</th>
<th>STAGE 3 OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1.0</td>
<td>0</td>
<td>0</td>
<td>0.625 V</td>
<td>1</td>
</tr>
<tr>
<td>+2.0</td>
<td>0</td>
<td>1</td>
<td>1.875 V</td>
<td>1</td>
</tr>
<tr>
<td>+4.0</td>
<td>1</td>
<td>1</td>
<td>4.375 V</td>
<td>0</td>
</tr>
<tr>
<td>+4.5</td>
<td>1</td>
<td>1</td>
<td>4.375 V</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1. Typical Bit Conversion of a Three Stage Converter (Ref. 8)
second, which is adequate for PCM but not FM.

4. Should non-volatile solid state memory designs become competitive with tape recorders for this application PCM would be directly compatible with such devices.

**PCM Encoding Formats**

The various PCM encoding formats considered for application in the automotive tape recorder design are illustrated in Figure 11 for a typical analog pulse. PCM quantizes signals into intervals and uses a binary word to describe the regions within which the sample lies. With the non-return-to-zero (NRZ) code, an energy pulse is generated each time there is a binary level change at the time of measurement. Therefore, the energy pulse remains the same for a series of binary zeros. As a result, a long series of all zeros will not provide time correlation and will appear as lost information when data are decoded through a bit synchronizer. To prevent this from occurring the bi-phase code was used which provides transitions for each bit period, i.e., a pulse is generated during the first half of a bit interval to mean a one, while a pulse in the second half means a zero. Therefore each bit is identified by the presence of energy rather than with the absence of energy. The bi-phase code was used in the prototype design. Another format which was considered but not incorporated because of its added complexity

**Table 2. Error Budget Analysis (Ref. 9)**

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>PCM</th>
<th>FM</th>
</tr>
</thead>
<tbody>
<tr>
<td>SENSOR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONDITIONING</td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>COMMUTATION</td>
<td></td>
<td>1%</td>
</tr>
<tr>
<td>NOISE</td>
<td>IMMUNE</td>
<td>SNR</td>
</tr>
<tr>
<td>WAVE AND FLUTTER</td>
<td>IMMUNE</td>
<td>DIRECT ERROR</td>
</tr>
<tr>
<td>MODULATION</td>
<td>1.5% [6 BIT ADC]</td>
<td>1% [≤ 40% VCD]</td>
</tr>
<tr>
<td>RSS TOTAL</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>REMARKS</td>
<td>ACCEPTABLE</td>
<td>ACCURACY</td>
</tr>
<tr>
<td>SNR: SIGNAL TO NOISE RATIO</td>
<td>DIGITAL ERROR</td>
<td>FORCES</td>
</tr>
<tr>
<td>ADC: ANALOG TO DIGITAL CONVERTER</td>
<td>RATE DETERMINES SNR</td>
<td>SNR</td>
</tr>
<tr>
<td>VCD: VOLTAGE CONTROLLED OSCILLATOR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 11. PCM formats (Ref. 9)**
to the recorder electronics is the Miller code in which the boundary of a pulse is formed with the bi-phase leading edge.

**PCM Parameters**

After selection of the appropriate coding format, design of the total recorder system was continued. It was determined that six bits per word were required to meet the accuracy requirements (specifications in Appendix B) for the impact data recorded at 200 samples per second and the pre-crash data recorded at 20 samples per second. Therefore, the PCM electronics contains 63 quantization intervals (PCM parameters shown in Table 3) to produce those accuracies described in Table 4.

**Transducer Selection**

Concurrently with the PCM design effort, a trade-off study was performed on commercially available hardware which resulted in the selection of transducers for the recorder design. A variety of off-the-shelf transducers were available which could be adapted to the recorder to meet NHTSA requirements. Thus, the transducer selection narrowed down to a cost versus performance trade-off.

The acceleration transducer (Figure 12) is a triaxial piezo-resistive device of a Wheatstone bridge configuration with a d-c output. This design gives excellent linearity to enable measurement of both crash and pre-crash g's and minimize thermal zero shift. To measure triaxial crash accelerations, an amplifier configuration adjusts the bridge for mid-scale output at zero stimulus and provides gain so that maximum output is consistent with the PCM encoding range. Pre-crash accelerations (longitudinal and lateral) are accommodated by adding another amplifier to the high range output with an a-c coupled output.

A planar impact sensor is housed with the accelerometer in a small package (Figure 13) designed for installation under the front seats of passenger vehicles. The impact sensor, which defines a crash event (5-7 g's for 15 msec), consists of a seismic mass held between a conical plate and a flat plate by a permanent magnet (Figure 14). A sufficient shock pulse causes the mass to short the plates and initiate a delay switching circuit to shut the recorder off ten seconds after crash detection.

During the shock event the impact sensor activates a relay, and auxiliary power is applied to the system. The vehicle and auxiliary power sources supply energy unless the impact disrupts the prime supply. In that case the auxiliary power, supplied by a parallel arrangement of alkaline “transistor radio”

### Table 3. PCM Parameters (Ref. 9)

<table>
<thead>
<tr>
<th>WAVE LENGTH</th>
<th>6 BITs PER WORD</th>
</tr>
</thead>
<tbody>
<tr>
<td>WORD RATE</td>
<td>800 WORDS/SECOND</td>
</tr>
<tr>
<td>BIT RATE</td>
<td>4800 BITs/SECOND</td>
</tr>
<tr>
<td>SYNCHRONIZATION</td>
<td>12 BITS</td>
</tr>
<tr>
<td>CODE</td>
<td>1110101100100</td>
</tr>
<tr>
<td>DATA CHANNELS</td>
<td>3 AT 200 SAMPLES PER SECOND</td>
</tr>
<tr>
<td>ENCODING RANGE</td>
<td>ZERO TO 5.04 VOLTS</td>
</tr>
<tr>
<td>QUANTIZATION INTERVAL</td>
<td>80 MILLIVOLTS</td>
</tr>
<tr>
<td>FORMAT</td>
<td>4 WORD/SUB-FRAME</td>
</tr>
<tr>
<td>BIT RATE STABILITY</td>
<td>± 2%</td>
</tr>
</tbody>
</table>

### Table 4. Quantization Intervals (Ref. 9)

<table>
<thead>
<tr>
<th>MEASUREMENT</th>
<th>RANGE</th>
<th>QUANTIZATION INTERVAL</th>
<th>ACCURACY REQUIREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMPACT ACCELEROMETER</td>
<td>± 50 g's</td>
<td>1.58 g's</td>
<td>3.0 g</td>
</tr>
<tr>
<td>PRE-CRASH ACCELEROMETER</td>
<td>± 1 g</td>
<td>0.632 g</td>
<td>0.05 g</td>
</tr>
<tr>
<td>STEERING MOTION (COARSE)</td>
<td>± 60°</td>
<td>20.0°</td>
<td></td>
</tr>
<tr>
<td>STEERING MOTION (FINER)</td>
<td>± 30°</td>
<td>2°</td>
<td></td>
</tr>
<tr>
<td>BRAKE PRESSURE</td>
<td>200–2000 psi</td>
<td>31 psi</td>
<td>80 psi OR 7% GREATEST</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>–35°F to +160°F</td>
<td>3.1°F</td>
<td>5°F</td>
</tr>
<tr>
<td>POWER SUPPLY</td>
<td>0–18 VOLTS</td>
<td>0.3 VOLTS</td>
<td>0.5 VOLTS</td>
</tr>
</tbody>
</table>

**Figure 12. Accelerometer (Ref. 9)**
batteries, provides sufficient energy to operate the system for 10 seconds after impact.

The steering wheel transducer (Figure 15) is a dual potentiometer device which is mounted on the firewall and connected to the steering shaft by a constant force coil spring to measure lock-to-lock rotation of the shaft.

The brakeline pressure transducer (Figure 16) is a piezo-resistive device which is placed on one side of the proportioning valve to measure hydraulic brakeline pressure.

The tape recorder system also has a speed sensor (Figure 17) consisting of a magnet rotor attached to the speedometer cable. The permanent magnet turns through a stationary field winding inducing pulses which are proportional to the vehicle speed.

From the appropriate locations in the vehicle the transducers transmit their signals to the recorder and signal conditioning electronics located in the trunk (Figures 18 and 19).

Environmental Tests

After completion of the system design, six engineering models (two each of three tape deck configurations) were fabricated and then subjected to a series of environmental tests. Results from preliminary development shock tests showed that tape/head separation during severe shock environments was sometimes sufficient to prevent data retrieval. To solve this problem the PCM electronics was modified to incorporate two tracks of tape data. The second channel receives data which has been delayed approximately 0.4 seconds by two non-volatile bit storage elements, more than sufficient time to allow recorder stabilization after a crash pulse. The engineering models, modified to incorporate the delay channel, retrieved data successfully during the environmental shock tests.

During preliminary development vibration tests excessive tape speed variations and signal
amplitude variations (caused by perturbations induced to the tape or drive mechanism) made data reduction, using a conventional bit synchronizer, difficult. Further tests and analyses showed that signal amplification factors related to construction of the tape deck frames were the major cause of these variations. Therefore, a new tape deck with an improved frame was purchased and tested at the same vibration levels with successful data.
retrieval (Figure 20). Related to this, a special data decoding technique (discussed later) was developed to improve the reduction of data recorded during extreme vibration environments.

In addition to the environmental tests, some tape units were subjected to life tests. Over 1,500 operating hours of successful data retrieval were achieved with conventional tapes. All recorder components, other than the tape, exceeded the life specification of 3,000 hours. Although a 1,500 hour tape life will be sufficient for the research program with a periodic replacement policy, a search for longer life tapes is being conducted.

PRODUCTION ENGINEERING

In light of the successful recorder performance during development testing a follow-on contract was awarded to complete the recorder design, prepare production drawings and instruction manuals, fabricate 10 prototype units, and provide improved data decoding procedures. The production engineering for the tape recorder has been completed, successfully.

Data Decoding

The recorded data is a series of “ones” and “zeros.” In order to decode their appropriate value, a true time synchronization (clock) must be derived from the data in

![Graph showing vibration spectrum and data recovery rate.](image)

**Figure 20. Vibration test results at ambient temperature for ATR 2, ATR 3, and ATR 4 (Ref. 10)**

VIBRATION SPECTRUM:
- 2g 5-30 Hz
- 0.044 30-47 Hz
- 5g 47-100 Hz
order to strobe the values of “ones” and “zeros” into synchronization and decommutation equipment (Figure 21). Because of rapid bit rate changes, due to tape speed variations as large as 20 percent during extreme operating environments, the capabilities of conventional phase-lock loop synchronizers were exceeded. Therefore, a unique method for deriving the clock time from bi-phase data, “strobe transfer electronics,” was developed.

Bi-phase data has a transition in the middle of each bit period (refer to Figure 11). These transitions may be used directly to derive the clock since they are where they belong, independent of speed variations. Depending on the bit pattern, there also may be a transition at the leading edge of each bit period. In the event that transitions are “missing” during a bit period, a transition is dubbed or inserted by a clock synthesizer. Each leading and trailing edge triggers a 0.5 microsecond one-shot whose output is delayed by ¾ bit so that a decision can be made that a pulse was missing in the previous bit period. If it was, a dub is generated and the data is transferred at the instantaneous bit rate. The dub can only be in error if the preceding ½ bit is too long by ¼ bit or the following ½ bit is too short by ¼ bit. Therefore, this method, illustrated in Figure 22, is successful for tape speed variations up to 50 percent peak-to-peak.

Having performed clock derivation, frame synchronization is then started by acquiring a 100 percent correlation with the unique synchronization word. Channel selection is accomplished by counting of 6-bit word groups in accordance with the PCM format.

Figure 22. Strobe transfer electronics timing (Ref. 12)

The data is then passed through a digital-to-analog converter to conventional display and computer equipments.

Prototype Fabrication

Assured that recorder data retrieval under a range of environments was feasible, ten prototype units were fabricated to drawings and specifications. These units were subjected to a variety of tests to evaluate recorder performance under real-world environments.

The recorder prototypes operated with no failures during sled tests, and excellent comparisons with sled accelerometer data were obtained (Figure 23). However, the unit did not record vehicle accelerations properly during crash testing. Post test analyses revealed that the recorder electronics performed satisfactorily (the switching relay shut off the recorder ten seconds after impact). Further investigation of the crash test data and recorder equipment indicated that the undamped accelerometer sensing elements had been excited at their natural frequency causing excessive overtravel and element breakage. As a result a new fluid damped accelerometer was chosen and included with several modified prototypes for additional crash testing in June 1973.
Other evaluations being performed include road tests (over 40,000 miles have been recorded so far on one of the tape systems with no failures), handling maneuvers and further environmental tests. The completion of these evaluations is scheduled for the end of July, 1973. Assuming that recorder performance during these tests is successful, the NHTSA will be in a position to purchase production quantities of tape recorders during fiscal year 1974.

**RECODER PRODUCTION AND FLEET INSTALLATION**

After completion of the disc recorder production engineering phase, 1,000 production recorders were built to the revised production drawings and the NHTSA specifications. This was in addition to the 200 units which were fabricated during production engineering. Over 900 of these units have been installed in vehicles as part of the pilot fleet project.

During the development and production engineering efforts, the NHTSA initiated the experimental design of the Automotive Recorder Research Program. Such items as fleet criteria, a recorder production plan, and data system requirements were defined.

The selection of fleets to participate in the program is based on the considerations listed below to enhance the success of the program and the statistical significance of results and conclusions:

- Control of maintenance, inspections, and data retrieval
- Vehicle, driver, and environmental representation
- Vehicle speed and accident rate/severity
- Cooperation of fleet owners and drivers
- Proximity to NHTSA Multidisciplinary Accident Investigation (MDAI) teams
- Fleet size
- Mileage for which vehicles are retained in fleet
- Legal aspects of 1) retrieving recorders from non-Government vehicles, and 2) restricting recorder data for research purposes or having data subpoenaed in criminal or civil actions.

The Recorder Program will include Government and privately-owned fleets.

The pilot fleet project was initiated in August 1972 to identify procedures and techniques essential to successful recorder fleet operations. Agreements have been signed with various fleet owners to cover procedures for recorder installation, inspection, and maintenance; notification in the event of accidents involving recorder-equipped vehicles; and recorder retrieval. This pilot project represents a small part of the recorder research program during which the NHTSA plans to install large numbers of recorders in fleet vehicles. Full-scale production of recorders is scheduled to begin in FY 1974 and continue through FY 1976.

In preparation for this program, various government and private fleet officials have been contacted to solicit support and cooperation. In addition, the data system to process and analyze recorder data and accident report data will be developed by Transportation Systems Center during FY 1974-1975.

**DISCUSSION OF A VEHICLE CRASH SEVERITY INDEX**

Several terms are presently used to categorize accidents, express a measure of comparison between vehicle collisions, or classify accidents in a manner which implies crash severity. An important indicator of vehicle crash severity is the barrier equivalent impact
velocity (BEIV). This is often estimated in accident analyses for comparison with impact velocities specified in the motor vehicle safety standards. BEIV's can be computed by estimating the vehicle velocity at the time of impact, the change in velocity during impact, and the amount of energy absorbed by the object struck. Currently, these estimates are rough approximations because motor vehicle accidents are complex events from which reliable quantitative data is difficult to obtain.

Impact velocities are specified in the standards because they provide a simple and repeatable means for testing and evaluating the crashworthiness and crash survivability potential of vehicle safety systems. Repeatability and reliability of test methods are of prime importance in determining whether safety systems comply with the motor vehicle standards. However, present methods of relating real-world accidents to motor vehicle safety standards are not simple and repeatable. Also, static measurements taken after the accident are not necessarily representative of the dynamic interactions which occur during vehicle collisions.

The task of determining BEIV's will be greatly simplified when recorder-equipped vehicles are involved because accurate dynamic data will be available from the accident. The velocity change during impact will be computed directly by integrating under the acceleration/time curve which is obtained by both types of recorders. Also, vehicle traveling speed up to the time of impact will be obtained if the vehicle is equipped with a tape recorder.

However, the problem is that most vehicle collisions cannot be equated directly to a barrier impact. The many crash modes that are possible on the streets and highways can hardly be duplicated in relatively simple laboratory barrier crash tests. As a result, we must ask the questions: Is the severity of a real-world accident represented best by a BEIV? Can a more representative measure of vehicle crash severity be developed? Now that accurate records of vehicle acceleration vs. time from real-world accidents may be made available, can we develop a meaningful vehicle crash severity index?

Those in the field of biomechanics have already taken a step in defining a more meaningful measure of crash injury severity. Let us focus for a moment on the evolution of the head injury criterion (HIC) for indicating human head injury as measured in a barrier crash with instrumented dummies. As published on November 3, 1970, Motor Vehicle Safety Standard 208 specified a head acceleration level of 70 g's that could not be exceeded for a cumulative duration of more than 3 milliseconds, and a maximum peak acceleration of 90 g's. On March 10, 1971, the "208" criterion for head injury was changed to the SAE Severity Index system originally developed by C. W. Gadd and published as SAE Information Report J885a. As amended on June 23, 1972, Standard 208 incorporated the HIC which was based on average acceleration and is expressed as:

$$HIC = \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt \right]^{2.5} (t_2 - t_1)$$

$a =$ resultant acceleration expressed as a multiple of $g$
$t_1$ and $t_2 =$ any two points in time which maximize the function of the crash event.

Through an iterative process, people working on the biomechanics of humans in crash environments improved the definition of head injury severity as a function of acceleration and time.

The fact that an injury severity index can be defined for human heads is no guarantee that a crash severity index can be developed for motor vehicles. In developing a vehicle crash severity index, there are several complicating factors which should be considered. A vehicle crash severity index may have to incorporate measures of vehicle internal geometry; structural size, mass, and crush characteristics; occupant restraint system characteristics; and the impact situation.
addition, the aggressiveness of one car against another, which depends upon the relative structural characteristics of the two vehicles, may have to be considered. However, as a first attempt at defining such a severity index, a weighted average of acceleration vs. time somewhat similar to the HIC may prove to be appropriate.

Development of a crash severity index for vehicles will not have an effect on using impact velocities as performance requirements, at least in the near future. One reason for this is that current NHTSA plans call for only a few types of vehicles to be equipped with automotive recorders. The selective nature of these results from the Automotive Recorder Research Program will thus preclude early development of a crash severity index for all vehicles. However, future motor vehicle research will be guided through the application of automotive recorders and similar technology that serve to improve the quantification and reliability of data.

References


2. Oakland County, Michigan, 1968-1970 accident file maintained by the University of Michigan, Highway Safety Research Institute. NHTSA queries this file from a terminal in the Nassif Building.

3. NHTSA's copy of the Cornell Aeronautical Laboratory file, Automotive Crash Injury Reduction (ACIR), which consists of 75,000 injury-producing crashes recorded between 1953 and 1969. Only the 1960 and subsequent data were used for Figure 2.


Questions & Answers

HERB SACHS, WAYNE STATE UNIVERSITY:
Steve, I was very much interested in your presentation. I have one essential question. In determining the precrash history of a vehicle I think it would be very important to know the direction properties of the resultant acceleration vector. It appears to me that since you are using a system which operates in three mutually vertical directions—X, Y and Z—that the data could be easily composed and you could obtain your resultant acceleration vector and thereby determine the directional properties.

DICK WILSON, GENERAL MOTORS:
I have a comment and a question. The comment: On using the speed cable drive as a speed indication, I think you're going to have a lot of wrecks at zero speed with locked wheels that happen very often. I don't know how to get around that exactly, but that seems to me to be a big problem.

Second, a question. Is there any way to give a research group or somebody a set of information that you are likely to get and then see if they can do anything with it, prior to actually going through the expense of obtaining it?

I am interested in more on the actual use of the information in the rulemaking rather than the technicalities in the design.

That is, in fact, true. Of course, for precrash data we only measure the planar surface (longitudinal and lateral) accelerations from which we can obtain directional properties. When the recorder design was formulated we looked at parameters that we felt could give us the most useful information. Precrash acceleration data in conjunction with the steering wheel angle of rotation were chosen partially because they will give us directional information.

Yes, that is a slight problem. However, we hope that by knowing the initial vehicle traveling speed, time of brake/wheel lockup, and precrash decelerations as measured by the recorder, we'll be able to derive some of that information.

We had planned to contract for development of a data system and experimental design for the Automotive Recorder Research Program during FY-73, but funding for the Program was not appropriated by Congress. As a result, we are not in a position to perform in-depth comparative analyses of recorder data. Although we are set up to reduce and display disc and tape recorder data by computer techniques, we have not yet integrated these outputs with accident investigation data. We have resubmitted our plans to develop the full-scale data system during FY-74 and will do so as soon as Program funding is appropriated.

This is an important aspect of data system development; to determine in what form the Program results should be presented for incorporation into rulemaking. We feel strongly that such a tie-in is necessary, and we reflect this in the Program objectives and uses.
Appendix A

AUTOMOTIVE DISC RECORDER SPECIFICATIONS

Operating Environments
Temperature
-35°F to 160°F

Shock (3 axes)
±50g, 100 millisecond, sq. wave
±30g, 200 millisecond, sq. wave
±100g, 10 millisecond, half sine wave

Vibration
2.0g, 5-30Hz
0.044 inch double amplitude, 30-47Hz
5.0g, 47-100Hz

Altitude
-1000 feet to +10,000 feet

Humidity
95% at temperatures up to +149°F and down to 72°F

Non-Operating Environments
Temperature
-50°F to 180°F

Shock
±100g, 6 millisecond sawtooth

Electro-Magnetic Interference (EMI)
These environments shall not affect the operation and functioning of the disc recorder

14KHz – 35MHz 10 volts/meter
35MHz – 150MHz 5 volts/meter

Physical Characteristics
Size (max.)
5-1/2 in. x 6-3/16 in. x 3-1/16 in. (not including mount)
4 lb. (not including mount)

Operating Characteristics
Accelerometers
Range
±50g

Natural frequency at 25°C
85 Hz min

Damping
0.5 critical, min

Sensitivity at 25°C
.004 in/g ±5%

Accuracy (including linearity, resolution, readability, and hysteresis)
±8% full scale

Cross axis sensitivity
Less than 3% of input
Recorder
Disc speed 120 rpm ±5%
Record length for .5 sec Vertical — 10.2 in. nominal
Fore-aft — 8.3 in. nominal
Lateral — 5.5 in. nominal
Record time .5 sec (one revolution)
Design life 3,000 hrs. or 3 years, whichever occurs first
Operation Continuous, .1 sec. after ignition switch is turned on
plus .5 sec. min. beyond loss of power

Power Requirements
Input Volts 11-15 Vdc
Input Current 0.1 Amp, nominal, fused 2 amp

Appendix B
AUTOMOTIVE TAPE RECORDER SPECIFICATIONS

Operating Environments
Shock ±50g, 100 millisecond, sq. wave
±30g, 200 millisecond, sq. wave
±100, 10 millisecond, half sine wave

Vibration 2.0g, 5-30Hz
0.044 inch double amplitude, 30-47 Hz
5.0g, 47-100Hz

EMI 14KHz-35KHz, 10 volts/meter
35KHz-150MHz, 5 volts/meter

Altitude -1000 feet to +10,000 feet

Humidity 95% at temperatures up to 149°F and down to
72°F

Temperature -35°F to +160°F

Non-Operating Environments
Shock ±100g, 6 millisecond sawtooth

Temperature -50°F to 180°F

Accuracies
Measurement Impact Acceleration ±50g's ±3% F.S.
Pre-crash Acceleration ±1g ±5% F.S.
Steering Motion (Course) ±630° ±20°
Steering Motion (Fine) ±360° ±3°
<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brake Pressure</td>
<td>200-2000 psi</td>
<td>±60 psi or ±7%, whichever is greater</td>
</tr>
<tr>
<td>Vehicle Speed</td>
<td>0-120 mph</td>
<td>Speedometer Accuracy</td>
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<tr>
<td><strong>Operating Characteristics</strong></td>
<td></td>
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</tr>
<tr>
<td>Tape Speed</td>
<td>3-3/4 i.p.s.</td>
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<tr>
<td>Design Life</td>
<td>3,000 hrs. or 3 years, whichever occurs first</td>
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<tr>
<td>Record Length</td>
<td>6 min. operational (pre-crash) data, 10 sec. crash data</td>
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<td><strong>Power Requirements</strong></td>
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</tr>
<tr>
<td>Input</td>
<td>Volts 12-17 VDC, Current 850 ma</td>
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</tr>
</tbody>
</table>
Closing Remarks

U.S. Department of Transportation
National Highway Traffic Safety Administration

First, let me thank each speaker for taking the time to prepare and deliver the fine papers we have heard the last two days.

Second, I'd like to thank you in the audience for your attendance and participation. It far exceeded my expectations.

At this point I was going to indicate some budget trends, but events preclude that from taking place. However, there are a few items which warrant some comment.

It is my hope that we will become more of an "action" group than reaction. For too long we in research have been reacting in a firefighting role, and it appears we have reached the point where we can begin to initiate the action. This will manifest itself in two ways. We will be starting more basic research at one end of the spectrum and more integrated research at the other. Examples of these are illustrated by recent contracts on materials research and some proposed effort matching structure response with occupant protection systems or the systems approach.

I would like to see develop more interchange of data between the industry and my staff. We really need to work on this. Too often industry comes to NHTSA to challenge the standards writer but does not communicate with the NHTSA researcher. I expect that, with this symposium, you became familiar with some of our accomplishments and our future needs. With this beginning, let us have a flourishing cross-fertilization of ideas and mutual sharing of knowledge for the solution of the vehicle safety problem.

Thank you for coming, and have a nice trip back.