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Piscataqua River Bridge on I-95 between Kittery, Maine, and Portsmouth, N.H. (Photo courtesy of the Maine Department of Transportation and the New Hampshire Department of Public Works and Highways.)

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A New System for Inspecting Steel Bridges for Fatigue Cracks

by[1] Anthony Leone, Charles H. McGogney, and J. Robert Barton

The nondestructive detection and characterization of fatigue cracks in steel bridge structures is a major engineering problem. Recently one solution to this critical inspection problem was developed by a joint industry-Government team using technology transfer. The inspection system developed consists of two independent, complementary, lightweight, battery-powered electronic instruments: (1) An acoustic crack detector (ACD) for rapid survey, which uses ultrasonic principles, automatic signal analysis, and a simple digital data display, and (2) a magnetic crack definer (MCD), which uses magnetic principles and a simple ON-OFF light data display for defining the precise crack location and length. A brief review of the program, including inspection techniques, assessment and selection, results obtained with *breadboard* models during laboratory and preliminary field evaluations, and laboratory and field evaluations of the prototype instrumentation system, is presented in this article.

Since this article was prepared, the Federal Highway Administration, Office of Development, has contracted for 10 additional prototype instruments. These units are being purchased by nine States and the Office of Development for extensive field tests and evaluation purposes as reported in "Status of New Inspection Instrumentation for Steel Structures," *Public Roads,* vol. 37, No. 5, June 1973. As of December 1973, bridge inspectors from the States of Arkansas, Connecticut, Idaho, Montana, Ohio, and Pennsylvania have received units and initiated field testing. Georgia, Texas, and Virginia will test the remaining units as soon as fabrication and deliveries are complete. This major effort is expected to provide an objective evaluation of the overall instruments' utility in the shortest time possible and results will be reported in *Public Roads* at a later date.

Introduction

The problem

Many bridges on our highways and rural road systems were designed and constructed 30 to 40 years ago. At that time, traffic volume on most bridges not only was low, but heavy or excess loadings were a rarity. Accordingly, fatigue problems and allowances for such occurrences in steel design were normally not considered. These same bridges today are carrying traffic volume and loadings completely unforeseen by the design or specifications originally applicable to the structures. With fatigue-prone regions such as eyebars, ends of cover plates, and tension area welds, the possibility of fatigue failures in many of our existing older steel structures and even in some relatively recent structures is a matter of concern.

The significance of small, hidden cracks was made prominent by the collapse of the Silver Bridge over the Ohio River at Point Pleasant, W. Va., on December 15, 1967. In that bridge, cracks grew to a critical size by a combination of stress-corrosion and corrosion-fatigue. However, fatigue alone can cause such cracks to grow to critical size. One of the conclusions reached by the National Transportation Safety Board, in their review of this collapse, was that there was need to "develop a new generation of inspection equipment for use under field conditions to detect critical or near critical flaws in heavy structures."

The Silver Bridge episode also focused attention on the need for all the highway departments to very substantially increase their bridge inspection activities. Although the highway departments did immediately initiate needed supplemental programs for inspections of all their structures, and on a frequent and systematic basis, they still lacked easy-to-use devices for detecting fatigue cracks in fatigue-prone areas which could lead to sudden collapse of a structure. This need for inspection devices was further emphasized by the fact that the highway departments found they had many bridges where the collapse of one member, or of a key connection, could lead to collapse of the entire structure.

Approach to solution

Each highway department is generally unable to enter into the research and development of such needed inspection devices completely on its own. Fortunately,

[1]Presented at the 9th Nondestructive Evaluation (NDE) Symposium, San Antonio, Tex., April 25-27, 1973.

the Federal Highway Administration (FHWA), which is the Federal agency that works very closely with all of the highway departments on highway matters, was in a good position to initiate development of such needed inspection equipment and would also be in the best position to later implement the use of this instrumentation with all of the highway departments. Accordingly, in the spring of 1971 the Office of Research, FHWA, solicited bids from 103 prospective contractors. The prospective contractors were a cross section of public and private research institutions, manufacturers of nondestructive test instrumentation, and private laboratories of various industries.

General technical guidelines for bids

It was clearly stated that off-the-shelf equipment and existing nondestructive test methods for detecting defects in metal members of inservice highway bridges were far from satisfactory. Furthermore, at the incipient stage, fine cracks, such as are associated with stress corrosion or fatigue, are of a size (length and depth) that are not detectable by present state-of-the-art techniques. Also, such cracks may be hidden by fasteners, splice plates, or gusset plates. A suitable method for the detection of such hidden flaws in structural metal members of inservice bridges must incorporate the following requirements:

- The associated equipment must be portable to the extent that the inspection process is not rendered costly and time consuming or hazardous to personnel.
- The cost of the equipment and materials required for a complete and thorough bridge inspection must not be excessive.
- The associated equipment must be suitable for use without extensive shelter or protection in a range of ambient temperature from 0° to 120° F.
- The associated equipment should be rugged and durable and not susceptible to damage or malfunction from rough handling.
- The method and equipment should not require unusual operator skill or experience.
- There should be no residual deposits or effects from the inspection process which of themselves could accelerate or catalyze the natural processes of metal deterioration.
- Any necessary power for operating the detection equipment should be obtained from self-contained power supplies in the portable equipment if possible.
- Noncontact methods utilizing a single piece of equipment are preferred.
- The need for preliminary surface treatment of metal surfaces should be avoided if possible.

It was further stated that all structural metal that had been in service for a considerable length of time would have a markedly altered surface condition due to corrosion and oxidation. Many layers of paint and scale could be expected on the surface. These conditions would not only limit, but could eliminate from consideration certain inspection methods. The size, configuration, and orientation of structural members or assemblies might also limit the utilization of defect-detection equipment. Any proposed defect-detection method should require neither specific positioning of the members nor accessibility to all sides. The method or methods proposed must be adaptable to the field inspection of all types of joints and assemblies commonly found in structural steel bridges, and the inspection system should be consistently repeatable in performance.

Selection of Nondestructive Inspection Methods

To establish an overall perspective for the rational selection of nondestructive methods for detecting fatigue cracks in highway steel bridges, the following factors should be considered: (1) An understanding of fatigue phenomena, (2) the magnitude and difficult nature of the bridge inspection problem, (3) present inspection procedures, and (4) an American Society of Civil Engineers (ASCE) subcommittee report.

Although a comprehensive understanding of fatigue is desirable, and many comprehensive treatments exist, for conciseness here only a limited review is presented. According to Grosskreutz (*1*)[2] "Metals fatigue because of local concentrations of plastic strain." He also states:

> To the naked eye, the progress of fatigue is mysteriously devoid of feature until the catastrophic growth of a macrocrack in the final few cycles. This observation early led to the concept of accumulation of fatigue 'damage' during the featureless portion of the life which finally culminated in the rapid fracture of the material. Despite early microscopic observations that damage consisted mainly of growing microcracks, the concept of widespread degradation of the material during fatigue has persisted. Although isolated examples of fatigue-induced material weakness do exist, by far the most common mode of fatigue failure consists simply of initiation and growth of cracks to the point of static failure. The uncracked material is still good as new in most cases.

[2]Italic numbers in parentheses identify the references on page 293.

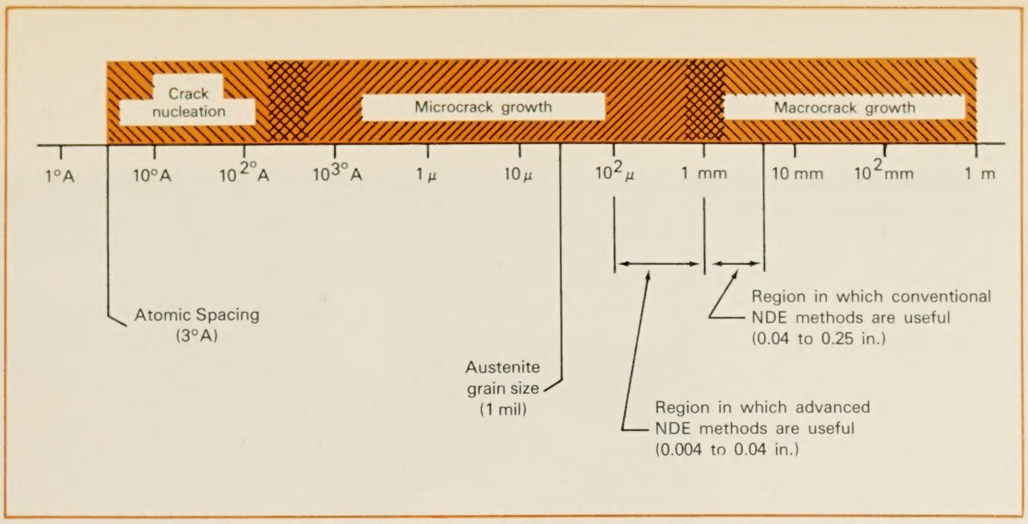

Figure 1.—Schijve's scale of crack dimension.

The phrases "...devoid of feature" and "...growth of cracks to the point of static failure" should be remembered.

From an engineering viewpoint, fatigue damage consists essentially of growing cracks, and Schijve's scale (2) of crack dimension, figure 1, illustrates the entire spectrum of fatigue cracks. The regions in which nondestructive methods are useful have been indicated. It is apparent that fatigue cracks can be infinitely small, and in general the minimum size observed is limited only by the preparation and examination procedures. Since the necessary preparation and overall costs of searching for fatigue cracks increase rapidly with decreasing size, the minimum size fatigue crack specified to be detected is a controlling cost factor.

Magnitude of bridge inspection problem

According to Hassett (3), there are more than 700,000 highway and railroad bridges in the United States. A major fraction of these are steel bridges. In addition to the number of structures, two significant problems in accomplishing even a visual inspection are (1) obtaining the required number of qualified inspectors who can both climb and work at great heights and make the proper observations, and (2) in many instances obtaining access to the regions to be inspected.

Figure 2 illustrates the complexities and hazardous environments under which many inservice inspections will have to be accomplished. Access often requires special equipment (Cherry Picker and Snooper from $35,000 to $75,000; Sky Climber from $12,000 to $15,000, plus tug and barge at $150 to $200 per day). Usually four to six persons are required in the field to support one inspector, and it may be necessary to restrict traffic. Obviously, it is mandatory that inspections be accomplished rapidly and reliably.

Although periodic inspection of inservice steel bridges for fatigue cracks is a formidable problem, it is by no means insurmountable. As indicated previously, fatigue crack development in structures is confined to regions with localized plastic flow from stress concentrations (e.g., termination of a welded cover plate, end of a welded stiffener, a rivet hole) with crack initiation and propagation being strongly dependent on the magnitude and duration of the applied alternating loads. Accordingly, a practical way to inspect for fatigue would be one in which examinations are localized to preselected critical regions. With such an approach the impossible requirement to periodically examine the entire volume of steel in every bridge is eliminated, and an adequate inspection program becomes feasible.

Figure 2.—Typical bridge inspection.

ASCE subcommittee report

An ASCE subcommittee report (4) outlines a rationale for the comprehensive inspection of bridges for fatigue damage. Important features of the approach are as follows:

- Characterize those bridges most fatigue prone on the basis of the bridge design and traffic statistics (number and weight of vehicles).
- Determine the locations most likely to develop fatigue damage on the basis of stress analyses and existing knowledge about the fatigue proneness of various types of bridge structures. The determination of the criticality of regions for inspection might also include consideration as to whether failure of a joint would result in catastrophic failure of the entire structure.
- Conduct a visual inspection supplemented by nondestructive testing on those regions of those bridges suspected of having fatigue problems.

This comprehensive procedure for bridge inspection, along with the use of highly effective nondestructive inspection equipment, holds great promise because it logically and advantageously incorporates the use of existing knowledge about the fatigue phenomenon, traffic statistics, and the characterization of each bridge for inspection—a one-time effort based on its design. It also permits a rational basis for establishing a priority rating in a bridge inspection schedule so that those bridges most likely to be fatigue prone can be given the highest priority for inspection and maintenance. Furthermore, with this approach the development of well designed, nondestructive inspection equipment makes it feasible to reduce the required inspection time and to minimize the level of training required for inspectors.

The following nondestructive inspection techniques were considered to appraise their relative applicability for inspecting inservice steel highway bridges for fatigue cracks:

- Acoustic emission
- Acoustic birefringence
- Barkhausen noise
- Eddy current
- Holography
- Infrared
- Magnetic field disturbance
- Magnetic particle
- Magnetoabsorption
- Mossbauer effect
- Penetrants
- Ultrasonics
- X-Radiography
- X-ray diffraction

Each technique was assessed according to 15 factors which included:

- Minimum size crack detectable—in welds, in mechanical joints, beneath the surface—and the degree of discrimination of the technique.

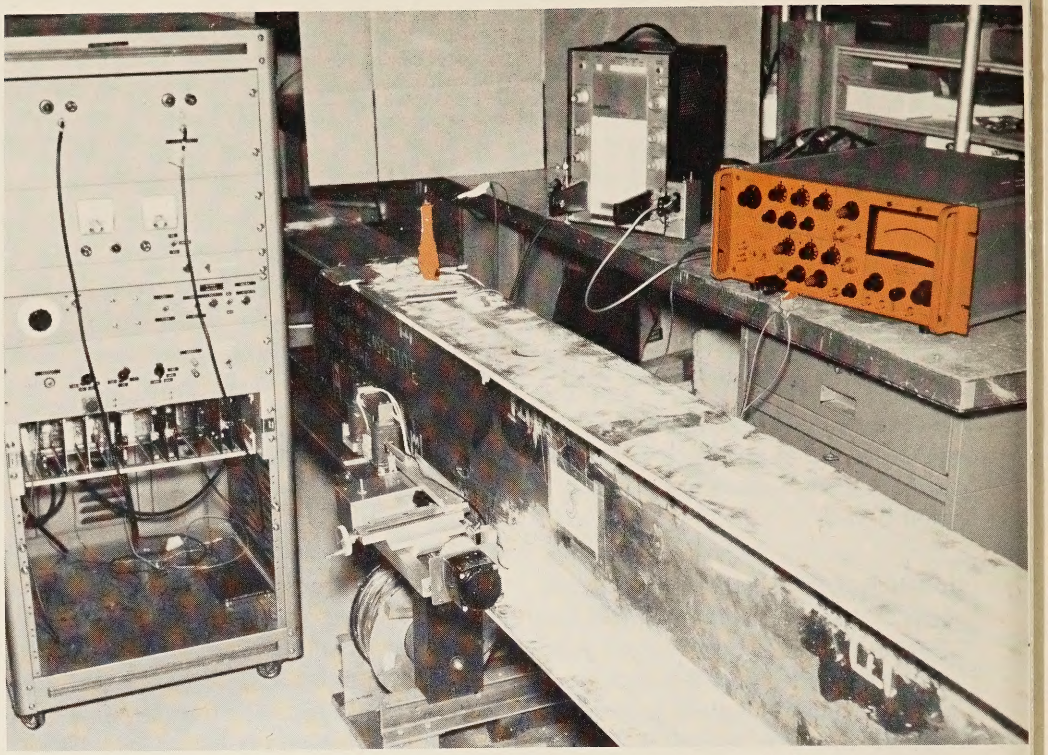

Figure 3.—View of I-beam (specimen 3) with fatigue cracks and laboratory apparatus (magnetic field disturbance).

- Influence of environment and other parameters related to field adaptability, including vibration, temperature, power required, safety requirement, accessibility required, and surface preparation required.
- Factors related to the instrumentation necessary to implement the technique, including complexity, adaptability to automation, degree of operator dependency, degree of operator skill for interpretation, and potential for development within scope of contract.

From this initial rating, five techniques, namely, Barkhausen noise analysis, eddy current, magnetoabsorption, magnetic field disturbance, and ultrasonics were selected for experimental investigation.

Specimens with details typical of bridges used during the experimental evaluations included:

- Welded and rolled I-beams cycled in the laboratory to produce fatigue cracks at various welded details and bolt holes.
- Several channel beams which had been removed from service because of fatigue cracks at bolted or riveted holes.
- Eyebar details from a dismantled bridge.
- A floor beam from a dismantled bridge with bolted/riveted construction.

The most comprehensive evaluations were completed on a 10-foot-long welded I-beam, beam 3, with several welded details which had fatigue cracks of various sizes developed during an investigation at Lehigh University. A photograph of this beam along with some of the experimental apparatus is shown in figure 3. Measured fatigue crack lengths available for the experimental investigations in these specimens ranged from approximately 0.12 inch to greater than 3.5 inches.

Experimental investigations

Comprehensive experimental data were obtained using each of the techniques selected during the preliminary appraisal, namely, Barkhausen noise analysis, eddy current, magnetoabsorption, magnetic field disturbance, and ultrasonics. Parameters such as frequency, probe sizes, scan speeds, orientation relative to crack, spacing between probe and inspection region (lift-off), surface preparation (painted, grit-blasted, mechanical scrapping), magnetic field conditions, mechanical stressing, etc., were varied in this comprehensive appraisal of the effectiveness of each method.

Ultrasonic data were also obtained at fatigue crack regions propagated from small through-the-thickness radial saw slots at 7/8-inch-diameter bolt holes in the flange of an I-beam. These data are presented in table 1. In the sensitivity column, the baseline noise background is approximately -36 dB and it is seen that the 0.22-inch-long fatigue crack at hole location **C** would not be detected under no-load conditions. With application of load, however, this crack produces a signal which is 10 times the background noise amplitude. The 0.12-inch-long crack at hole **A** produces a signal approximately 4 times the noise background when load is applied, but would be undetectable without load. The 0.05-inch-long crack at hole **B** produced a signal only slightly above the noise background even with load applied and accordingly would not be detected in most instances. By contrast, the 0.5-inch-long crack at hole **B** produces a signal that is approximately 10 times the background (0.18 V. versus 0.022 V.), and would be detected even without load applied. Note also that for a crack of this size there is only a slight change in the signal between no-load and load-applied conditions. Accordingly, there would be no advantage in applying a load. These data were obtained using a well collimated or narrow beam transducer and physically scanning the transducer in the vicinity of the hole with the scan being essentially parallel to the crack configuration. A plot of the data thus obtained is shown in figure 4.

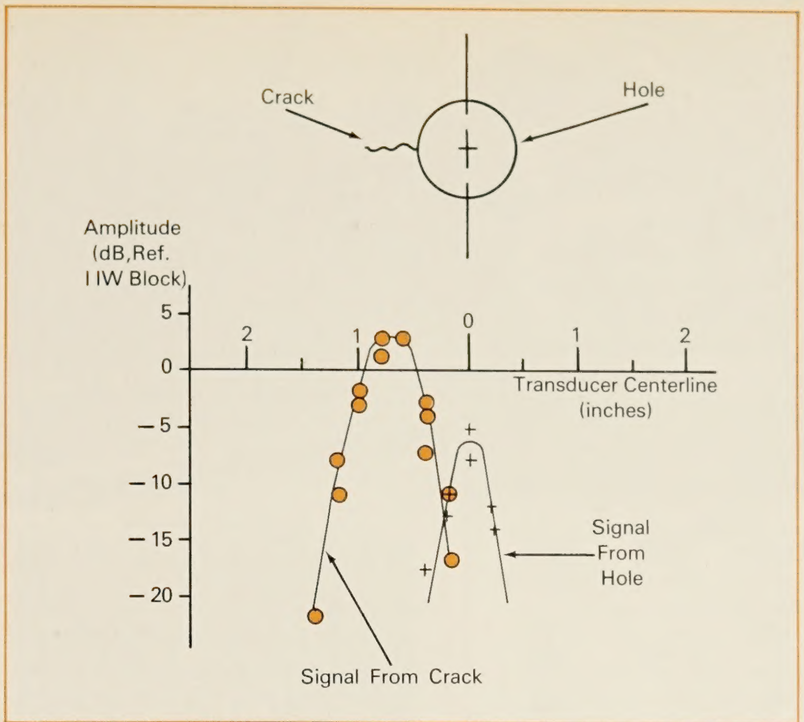

Figure 4.—Ultrasonic reflection amplitudes from "thru the flange" crack extending from bolt hole (2.25 MHz).

Table 1.—Ultrasonic responses from fatigue cracks in flange bolt holes

Hole	Crack length	Cycles[1]	Sensitivity			
			Load		No load	
	Inches		*dB*[2]	*Volts*	*dB*	*Volts*
A	0.12	190,000	-22	0.11	-35	0.025
A	0.15	220,000	-23	0.10	-32	0.035
B	0.05	140,000	-34	0.028	-36	0.022
B	0.12	180,000	-22	0.11	-35	0.025
B	0.5	226,000	-15	0.25	-18	0.18
C	0.22	180,000	-16	0.22	-36	0.022
C	0.66	226,000	-6	0.70	-7	0.63

[1] Stress not constant at each location.

[2] IIW (International Institute of Welding) Standard.

Signatures obtained from crack regions using magnetic field disturbance techniques are shown in figures 5 and 6. In figure 5 (**A, B, C, D**) the region was examined on the surface opposite the surface at which the crack initiated. A summary of the data obtained is shown in table 2.

Table 2.—Field disturbance method (180 Hz) on welds

Beam	Crack Location	Crack Length	Signal
		Inches	*Microvolts*
Lehigh (3)			
	F1	0.5	1.0
	F2	None	0.2
	F3	0.35	1.0
	F4	0.25	0.8
Fairbank stiffener (4)			
	A1	1.8	1.5
	A3	0.2	0.8
	A4	None	<0.2
Fairbank coverplate (5)			
	A1	1.2	1.5
	A2	1.4	1.2

Final selection

Results obtained using the Barkhausen noise analysis and magnetoabsorption techniques, which are primarily sensitive to the residual stresses in the vicinity of fatigue cracks, were not encouraging. The results from these two techniques, while in qualitative agreement, were difficult to interpret because stresses exist in the vicinity of welds even in the absence of fatigue cracks. Also, the magnetoabsorption technique was found to be highly sensitive to variation in spacing between the probe and the specimen (i.e., a few thousandths of an inch variation in lift-off could be interpreted as a crack). The lift-off sensitivity of the Barkhausen noise approach was not considered a critical limitation in the use of this method.

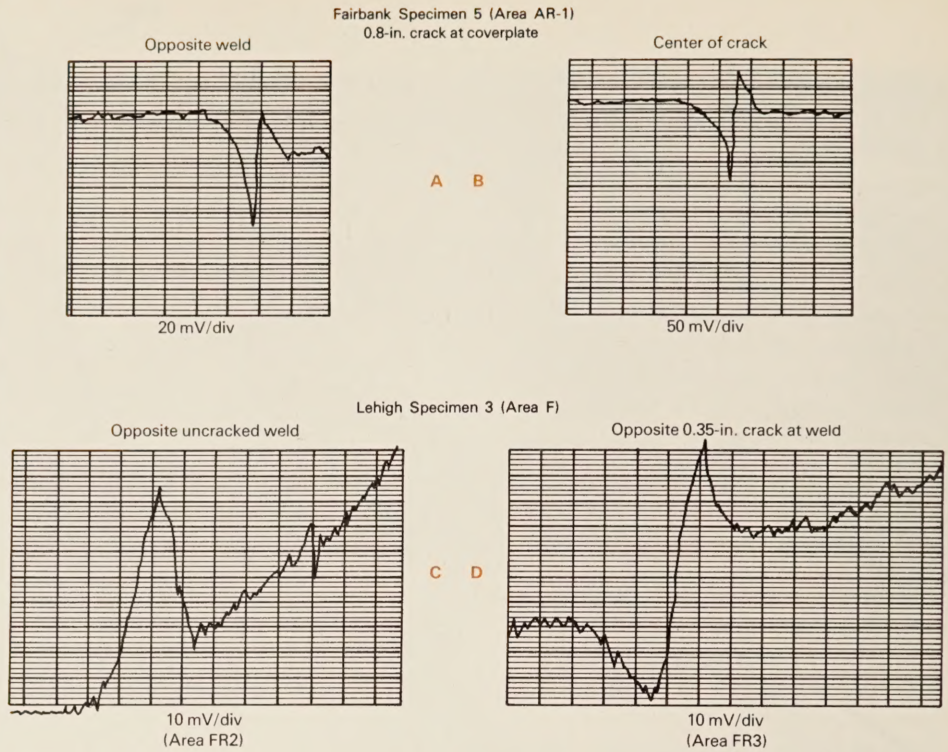

Figure 5.—Magnetic field (dc perturbation) disturbance records from cracks.

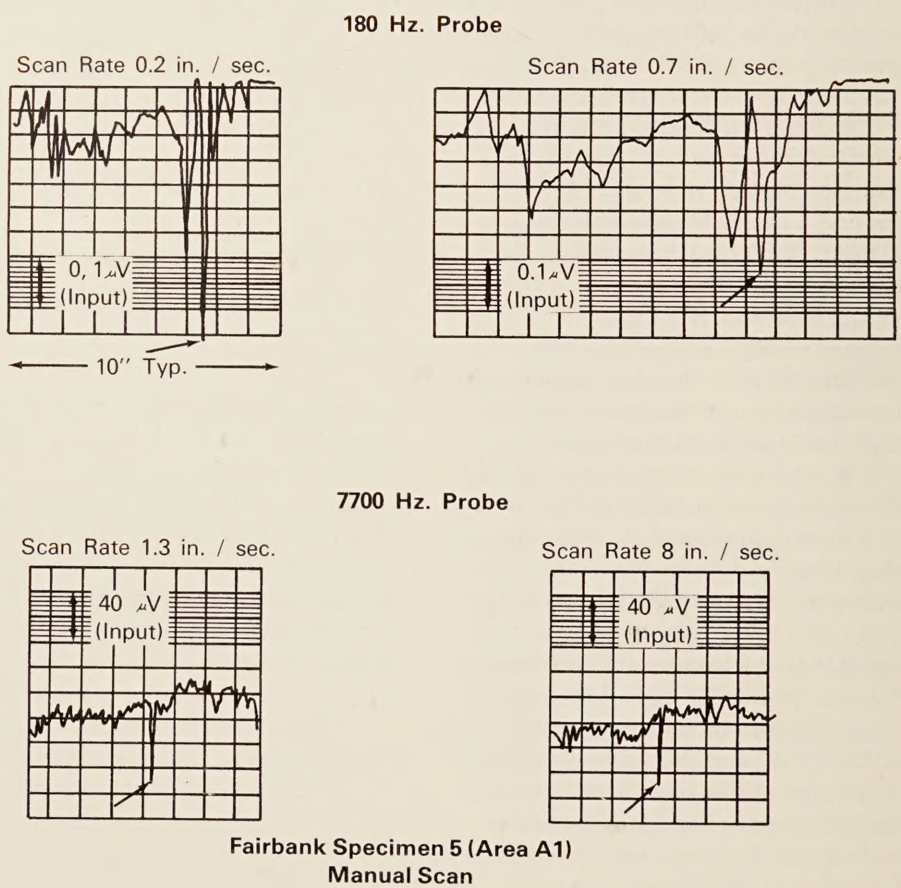

Figure 6.—Magnetic field (ac) disturbance records from cracks.

Figure 7.—Acoustic Crack Detector and Magnetic Crack Definer.

Eddy current approaches showed considerable sensitivity to welding stresses, lift-off, and nonuniform permeability—variations that are not necessarily related to defective conditions. While more advanced eddy current techniques (for example, phase-sensitive detection) were less sensitive to lift-off and spatially extended variations in welding stresses and permeability of the heat affected zone, they had poor sensitivity to fatigue cracks adjacent to the toe of the fillet welds. The advanced methods were capable of detecting cracks which extended beyond the weld and into the parent material. Both the dc and ac magnetic field disturbance techniques showed considerable promise. Cracks near welds and subsurface cracks (see **A, B, D** of fig. 5) could be detected using the dc field disturbance method (magnetic perturbation), but recognition of the crack signal was compromised by the presence of extended gradient signals from the geometrical changes in section thickness at welded details. The ac magnetic field disturbance methods readily detected cracks adjacent to welds and those extending into the parent material.

The investigation of ultrasonic techniques showed that they offered the best overall potential for development into a usable equipment for detecting fatigue cracks in steel bridges. The method is potentially capable of detecting cracks in most of the bridge details of interest, does not require immediate access to the fatigue crack region, can examine considerable material from one location, can detect cracks under welded and bolted attachments such as cover plates and spliced joints, and is a technique which has been developed to a high state. Disadvantages of such a technique are as follows: The need for surface preparation and use of a couplant to conduct the acoustic energy into the steel; the use of a cathode ray tube display and need for a skilled operator interpretation; the difficulty of precisely locating and determining the crack size and, occasionally a spurious indication can be obtained from severely undercut weld regions, surface pits, and gouges. The speed of inspection is an outstanding advantage of the ultrasonic techniques and, together with the previously indicated advantages, provided a strong basis for selection of ultrasonics as the primary method for use in field inspection of bridges.

An overall appraisal indicated that a system comprised of ultrasonic methods for routine survey of bridge elements to locate fatigue suspect regions, in conjunction with magnetic field disturbance techniques to precisely locate and define the fatigue crack length, offered the best answer to the field inspection problem. Accordingly, such techniques were recommended for development into specialized hardware.

Development and Evaluation of Hardware

Conceptual design of acoustic crack detector and magnetic crack definer

As previously indicated, it is neither necessary nor economically feasible to inspect all the material and details of each bridge; engineering analyses should be used to establish the priority of bridge inspection and also to specify which elements and details require inspection. Conceptually, the recommended inspection procedure would consist of using a simple **go no-go** survey device (based on ultrasonic pulse echo techniques)—called the ACD—to provide a means of rapidly examining the fatigue susceptible locations on bridges. Where an indication of a fatigue crack is obtained using the ACD, the next step would be to precisely locate and define the crack length. This could be accomplished using a simple **go no-go** instrument—called the MCD—and would require a precise survey over the region suspected of having the fatigue crack. In most inspections, no preparation of the surface or paint removal would be required for using the MCD. Use of the ACD and subsequent use of the MCD provides a redundant approach to minimize false alarms, and both of these procedures would be accomplished by an operator requiring relatively little training.

With the previously indicated approaches, an inspection survey could be performed rapidly, economically, and with little personnel training. The equipment concepts proposed would provide extremely high assurances that all cracks 1/2 inch or larger would be detected at a distance of 3 to 10 feet. Smaller size cracks, perhaps as small as 1/4-inch long, would probably be detected on bridge elements where the surfaces were relatively good and/or where close access to the region was possible. The ACD and the MCD are shown in use in figures 7 and 8.

Figure 8.—Typical inspection using ACD for detecting cracks between bolt holes under cover plate.

Figure 9.—Prototype system.

Breadboard evaluations

Breadboard electronic circuits, special probes, and associated apparatus were fabricated, assembled, and comprehensively evaluated both in the laboratory and during limited field trials. In general, the overall concepts proved satisfactory; however, field trials of the ACD indicated that in some instances the paint on even relatively newly painted surfaces (2 years old) might not be tightly adherent and would require removal if optimum inspections were to be obtained. In other instances, satisfactory coupling was obtained through paint 12 years old. Also, the laboratory evaluations indicated the desirability of having two separate channels for the MCD—one which is primarily sensitive to cracks that are relatively open, and the other which is primarily sensitive to the tips of cracks.

Prototype system

Figure 9 shows the inspection system consisting of an ACD and an MCD. Only very simple calibration steps are required on the ACD to accommodate various surface conditions, and once these have been properly selected, automatic indication of fatigue cracks with a digital display of the distance from the probe to the crack is obtained during routine survey. In use of the MCD, a light is illuminated and an aural tone is actuated during the time that the probe is precisely scanned on a crack; the light is out and the tone is off when the probe is not precisely alined on a crack. Accordingly, it is relatively simple to determine the precise location and approximate length of the crack. Both instruments include numerous features incorporated to ensure that they can be used with limited training of personnel. There are no complicated adjustments or interpretations required for use of either the ACD or the MCD. A tabulation of the more important features follows:

Acoustic Crack Detector (ACD)

- One hand operation.
- Audible and visual crack indication.
- Digital readout on probe automatically indicates distance in feet from probe to crack.
- Battery condition indicator on probe.
- Easily calibrated for various surface conditions.
- Accessory belt for couplant, cleaning tools, positioning fixture, measuring tape, etc.
- Coupling indicator.
- No electrical shock hazard.
- Can be worn as backpack or frontpack.
- Range—5 to 10 feet probe to crack, typical on bridges, depending on surface conditions and preparation.
- Sensitivity—detect 3/4-inch crack with high reliability over operating range, shorter cracks at close range under some conditions.
- Discrimination—will not alarm on good welds without heavy undercut.
- Eight-hour operation, from rechargeable battery.
- Size—10 1/4 in. x 12 1/4 in. x 2 1/4 in.
- Weight—pack 8 lbs.; probe 1.2 lb.


Figure 10.—Selected views of Idaho State Highway Department personnel inspecting I-beams of American Falls Dam Bridge in February 1973 (temperature 14°-30° F).

Magnetic Crack Definer (MCD)

- One hand operation.
- Audible and visual crack indication.
- Lamp illuminates on probe indicating presence of and direction of crack.
- One channel detects open cracks and cracks along the toe of welds.
- One channel detects crack tip(s) in parent material.
- Both channels operate simultaneously.
- Complements ACD.
- Probe can be used to determine precise location and length of crack.
- Paint removal not required.
- Battery condition indicator on probe.
- No electric shock hazard.
- Crack definition—indicates crack length within 1/4 in.
- Size—10 1/4 in. x 12 1/4 in. x 3 1/4 in.
- Weight—pack 14.6 lbs.; probe 0.5 lb.

Laboratory and field evaluations

The ACD and the MCD have been comprehensively evaluated on specimens at Southwest Research Institute and performance is considered excellent. Actual field demonstrations in the San Antonio, Tex., area and at three different locations in Arkansas have shown that the overall instrumentation concepts are well suited for field inspection by highway inspection personnel. In addition, extensive demonstrations have been conducted during the 1972 FHWA National Bridge Engineering Seminar in Washington, D.C., and during the 1972 FHWA and AASHTO national meetings in Phoenix, Ariz. More recently, the first actual inspection of a bridge was satisfactorily conducted in February 1973 by Idaho State Highway Department personnel on the bridge across the American Falls Dam in Idaho. Approximately 8 feet of the midspan region on 126 I-beams were inspected; actual inspection time was about 5 minutes per beam. Photographs in figure 10 illustrate the inspection. No fatigue cracks were discovered during this inspection. Even though inspection conditions were very adverse with temperatures of approximately 16° F and occasionally with snow and wind, satisfactory performance of the instruments was obtained; a minor problem was encountered because the gain of the electronic system varied slightly at these extreme temperatures. (This was anticipated from previous tests conducted in the laboratory.) Only a minor readjustment was required, however, and this difficulty can be eliminated in future circuits.

Conclusions and Recommendations

It was concluded that:

- Ultrasonic and magnetic nondestructive techniques used as complementary methods offer the best approach for inspecting inservice steel bridges to reliably detect fatigue cracks.
- The ACD and the MCD performed satisfactorily in engineering field trial and can be readily used by highway inspection personnel to rapidly inspect most details in steel bridges.

It is recommended that the ACD/MCD system be incorporated into bridge inspection procedures.

ACKNOWLEDGMENTS

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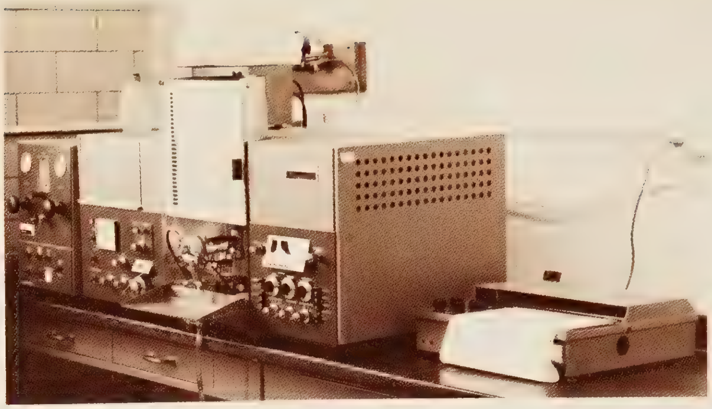
Improvements in the Rapid Analysis of Portland Cement by Atomic Absorption Spectrophotometry



by Leonard Bean

A rapid and accurate method is described for analysis of portland cement by atomic absorption spectrophotometry. The article describes the work done in cooperation with the AASHTO Subcommittee on Materials to establish an AASHTO standard for this technique and the later work by the Federal Highway Administration to improve the procedure. The modified procedure involves decomposition of the samples by use of various acids—hydrochloric (HCl), hydrofluoric (HF), and nitric (HNO_3). Most of the excess HF is complexed with boric acid (H_3BO_3). The resultant solution is stable for months. Standards for calibration may be prepared either from reagent chemicals or National Bureau of Standards (NBS) standard samples of cement. Plastic volumetric flasks and burets must be utilized, and special precautions in their application are suggested. Silica (SiO_2) can be determined on the same solutions as the other constituents of cement. In 1973 the AASHTO Subcommittee on Materials adopted the atomic absorption technique as an optional standard as a part of its methods of Chemical Analysis of Hydraulic Cement (T 105—Sections 121-127). A new study is now being planned to study the modified procedure to determine if revisions in T 105 (Sections 121-127) are warranted.

This report summarizes the results of two Federal Highway Administration reports: FHWA-RD-72-41 and FHWA-RD-73-4.

Introduction

Many useful applications of atomic absorption spectrophotometry (AA) have been developed since its introduction in 1955 by A. Walsh (*1*)[1]. During 1968 to 1970, the Federal Highway Administration (FHWA) took part in and helped coordinate two series of cooperative tests on the use of AA for portland cement analysis, conducted in collaboration with the Subcommittee on Materials of the American Association of State Highway and Transportation Officials (AASHTO). That study was under the jurisdiction of AASHTO Technical Section 3.1 on cement, which has established a Task Force on Rapid Methods of Chemical Analysis. A report describing the results obtained by the cooperating laboratories that took part in these tests has been published (*2*) and is summarized in this article along with the results of additional work that provide significant potential improvements in the method (*3*).

Principles of Atomic Absorption Spectrophotometry

Many excellent descriptions of this instrumental technique have been given (*1, 4, 5, 6, 7, 8*). In essence, the technique can be described as the inverse of the atomic emission technique known as flame photometry. The material to be analyzed is converted by a flame to an atomic vapor with most of the atoms of the elements of interest not excited but remaining in the *ground state* as free neutral atoms. Such atoms are capable of absorbing electromagnetic radiation as discrete lines of narrow band width. These are the same lines that would be emitted if the atoms were to be excited.

The narrow band widths of electromagnetic radiation which are to be absorbed are provided by a hollow cathode lamp which produces radiation characteristic of the element of interest. Some of the ground-state atoms of that characteristic element, which are generally present in a flame, absorb this characteristic radiation and are excited. The intensity of the beam is thereby reduced as it passes through the flame. An appropriate detector, filtering system, amplifier, and readout device give a signal which is a measure of the quantity of radiation which has been absorbed. The net reduction in the signal from the radiation line being emitted from the lamp is a function of the concentration of the element being determined.

Special Instrumentation Considerations

Several brands of atomic absorption spectrophotometers were used in the work reported in FHWA-RD-72-41 (*2*); however, more of the cooperating laboratories used a Perkin-Elmer (P-E) Model 303[2] than any other instrument. The P-E Model 303 was used for the work reported in FHWA-RD-73-4 (*3*). An improved burner head, manufactured by Techtron, and a

[1]Italic numbers in parentheses identify the references on page 296.

[2]The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

digital concentration readout were also used in this later study. Details of these modifications are provided in Report FHWA-RD-73-4.

Two burner heads manufactured by P-E were also used. One was a 3-slot Boling burner head for air-acetylene mixtures. The other was a burner head, designed for use with nitrous oxide, with a single, 52-mm slot and used with air-acetylene for the determination of calcium. In this determination use of the single-slot burner provided less sensitivity but better precision than did the Boling burner. The flame produced by the nitrous oxide burner head was steadier.

Early investigators have inferred that boric acid (H_3BO_3) complexes excess HF, protecting glass containers and permitting their use without resultant errors caused by HF decomposition of glass. Attempts in this study to use glass volumetric flasks with solutions containing HF plus H_3BO_3 gave very disappointing results. This corroborates findings of Langmyhr and Graff (*8, 9*) as well as Tarutani (*10*) and others that boric acid does not completely complex HF and therefore does not entirely protect glass from being attacked by HF solutions. Polypropylene volumetric flasks, as well as 10- and 25-ml burets made of the same material, became available during the course of this study. Thereafter, polypropylene volumetric equipment was used wherever feasible.

Procedures Used for Analysis

One of the methods described in the earlier report utilizes standard cements from the National Bureau of Standards (NBS) for preparing calibration curves (*4*). That method, with only slight modification, was adopted by AASHTO as an optional method for analysis of cement. In the other two methods studied, standard solutions for calibration were prepared from reagent chemicals. In one of these methods all the silica was put into solution along with the other constituents. In another method, a determination of silica on a separate sample was described. In both of these cases, the silica was present in an acidified solution as silicic acid. Such solutions cannot be stored over an extended period of time because of the eventual separation of gelatinous silicic acid.

From experience gained in the cooperative tests, it became apparent that it would be desirable to have a more refined method for analysis of cement by AA that would:

(1) Be calibrated with standard solutions that could remain stable for months, or even indefinitely;

(2) Contain silica in solution and permit its determination along with the other major constituents of cement; and

(3) Be based on standard calibration solutions which could be prepared either from chemical reagents or from NBS standard cements, whichever was more convenient to a laboratory.

Choice of Decomposition Method

As summarized in Report No. FHWA-RD-73-4 (*3*) two possible routes exist by which these three objectives might be obtained. One alternative is the use of a flux (lithium metaborate, lithium tetraborate, or a mixture of the two). The second alternative is the use of hydrofluoric acid as a decomposing agent with suitable complexing agents and other treatment to protect glassware from attack.

When using a fusion technique to decompose the sample, a flux to sample ratio of between 10 and 20 is generally recommended. After neutralization with acid, the resultant solution contains a rather high concentration of salts. When the fusion techniques were used in this study there was a tendency for the burner to become clogged. This reduced the precision of measurements. In addition, the time required to dissolve the fused material seemed excessive.

When a mixture of hydrofluoric, hydrochloric, and nitric acids is used to decompose the sample, followed by the addition of boric acid as a complexing agent, the ratio of boric acid to sample weight is generally about 7. $AlCl_3$ could not be used as the complexing agent because it was necessary to determine aluminum.

For these reasons, most of the work included in the study summarized here utilized a mixture of hydrochloric, hydrofluoric, and nitric acids to decompose the sample. Boric acid was added to complex excess hydrofluoric acid and to help protect glassware where glass was used.

This work involved the determination of seven of the constituents of cement by AA: SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, and K_2O. In the first part of the study, reagent chemicals were used to prepare standard solutions for calibration purposes. The concentrations of the stock reagent standard solutions (concentrated solutions containing mixtures of the primary reagent standards) were based on the equivalents expected from a 0.3000 g sample of cement in 100 ml solution. This made it possible, by appropriate aliquoting procedures, to obtain diluted solutions for AA measurements which would keep the response of absorbance to concentration in a linear range for all the constituents to be measured. NBS standard cements Nos. 1011, 1013, 1015, and 1016 were used as unknowns.

In the second part of the study, NBS standard cements Nos. 1011, 1013, 1014, and 1015 were used as standards. They were dissolved in exactly the same manner as the cement samples to be analyzed. In this phase, determinations were made using NBS standard cements Nos. 177 and 1016 as unknowns.

Results

Details of the comparison of results from all the originally proposed methods including the procedure for the method adopted by AASHTO are given in report FHWA-RD-72-41 (*2*), while the details of the revised method developed by FHWA are included in report FHWA-RD-73-4 (*3*). This report also includes a section on the special handling and precautions necessary in the use of plastic volumetric equipment required by the method. In general it was concluded as a result of the AASHTO cooperative work that the method now adopted as an optional procedure in AASHTO standard T 105 was the best of these procedures then available and that the agreement with the usual chemical analyses was excellent. The variability of the AA method was less than that of the chemical method.

While a multilaboratory study of the revised procedure has not yet been conducted, FHWA results showed that the revised procedure gave results for all constituents, except CaO, that were either better than or equal to the results of the method adopted by AASHTO. The slightly poorer agreement of the results for CaO is outweighed by the advantage that SiO_2 can be determined in the revised procedure from the same stock solution which is used to determine the other constituents. The present AA method requires the use of a separate sample for the determination of SiO_2.

Use of the adopted atomic absorption method by State and other laboratories who must analyze portland cement provides two significant advantages compared to standard chemical analysis. (1) More accurate results for Al_2O_3 will not be affected by the presence of TiO_2 and P_2O_5. The CaO results will not be affected by the presence of SrO, and neither the MgO or CaO results will be affected by the presence of Mn_2O_3 (if not removed). (2) A considerable saving of time. One laboratory reported an analysis time of 1.5 hours for six elements in one sample by AA. Standard chemical analysis would have taken about 8 hours. The savings of time is especially notable when a large number of cement samples are to be analyzed. Automatic aliquoting machines may help even more in speeding up AA analysis. Such instruments are available, but their use was not investigated in this study.

Adoption of the revised procedure will provide even further savings of time in that all seven elements of interest can be obtained from a single solution. The AASHTO Subcommittee on Materials is now planning a multilaboratory study of the revised procedure to determine the overall advantages of the modifications and possible revisions to the standard method.

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Environmental Research and Highways

by David Solomon

Highway transportation in the United States requires about one-seventh of the gross national product or about $170 billion in resources each year. In return, enormous mobility has been achieved for the mass of the American people. Although the highway transportation system has helped solve certain environmental problems, it has also produced other conditions that affect the environment adversely. Carefully planned and executed research and development can help solve many of these environmental problems. The purpose of this article is to describe some of the environmental research completed, underway, or planned under the Federally Coordinated Program (FCP) of Research and Development in Highway Transportation.

Benefits of highways including environmental benefits are briefly described followed by examples of adverse consequences. Research on highways and the physical environment is then described including that on air quality, noise, esthetics and visual quality, ecological problems, and water quality. Also discussed are social effects of highways, and problems due to adverse driving environments such as darkness, rain, snow, ice, and fog.

Figure 1.—Highspeed urban expressway.

Benefits of Highways

Benefits of highways include increased mobility, reduced travel time, lower vehicle operating costs, and greater opportunity for travel. Modern highways have also made travel much more comfortable and less stressful. It is now possible to travel from New York to Los Angeles in about 45 hours. In 1950, a similar trip would have taken approximately 70 hours. The developed areas of many cities can be crossed in less than half an hour. In 1950, a similar trip would have taken at least twice as long. But the real benefits of highways are in terms of their effect upon the lives of people.

Modern highways have made it possible for families to live in a reasonably dispersed private home environment. People may seek employment opportunities almost anywhere in a metropolitan area and live where they please. When one city has a shortage of jobs, the wage earner may travel a considerable distance to a nearby city to seek a temporary job without uprooting his household. Such flexibility has been particularly useful for construction workers and others with seasonal job opportunities.

Highways have permitted individuals and families to utilize extra recreational time available as a result of the 5-day, 40-hour week. Most areas of the country have recreational facilities within only a few hours of highway travel. People with middle and low incomes now can take day or weekend trips to hike, rest, fish, hunt, camp, climb, ski, swim, boat, bike, loaf, and even revel and gamble, depending on their recreational needs and desires.

It is not widely appreciated that truck transportation has had a tremendous effect on the general economy and well-being of this Nation. About three-fourths of freight transportation expenditures are accounted for by trucks. At the turn of the century, fresh fruits and many vegetables were not available in northern cities during certain seasons of the year. Today, due in large measure to truck transportation, it is possible to obtain a tremendous variety of fresh fruits and vegetables during the entire year in nearly all northern areas of the country. The efficient manufacture and distribution of most products depends upon trucks which are, in effect, part of the production line. Mobile and modular homes, the only inexpensive housing available to many occupational and income groups, require highways for shipment. Examples of the close relationship between trucks, highways, and our economy are endless. Trucks haul everything from circuses to space exhibits, from horses to household furniture.

Between 1920 and 1971, the Nation's highway mileage had only increased from 3.2 million miles to 3.8 million miles (5.1 million kilometers to 6.1 million kilometers). During the same period of time, annual travel increased from 45 billion vehicle-miles to 1,186 billion vehicle-miles (72 billion vehicle-kilometers to 1,908 billion vehicle-kilometers). A single eight-lane freeway often carries as much daily traffic as 10 or 15 arterial city streets or two-lane main rural highways. Thus, far from "paving over the country with concrete," modern highways are efficient and conserve land.

Freeways, with their easy grades and avoidance of at-grade intersections, also conserve energy. The Interstate System, for example, generally has maximum up-grades of 3 percent.

Figure 2.—Trucks—an important, integral part of the National economy.

These grades save passenger cars 20 percent in fuel consumption compared to fuel used on 6 percent grades. The comparable fuel savings for heavy trucks is 70 percent.

Proper attention to the design of highways can enhance the environment. There are numerous instances where highway construction has created recreational ponds from borrow pits and playgrounds under viaducts. Picnic areas and rest areas near highways are so numerous they are taken for granted. Highway construction can help dispose of waste materials. Sulphate and fly ash waste products have been used to pave parking areas and are suitable for base courses. It has been experimentally demonstrated that properly processed sewage sludge can be disposed of by incorporation into a highway embankment.

The safety of the Interstate System has been well documented. It is generally twice as safe as conventional highways primarily because of its key feature—full control of access. When the Interstate System is completed, 8,000 lives will be saved each year compared to the death toll if Interstate traffic were forced to use conventional highways. In 1973, the savings in lives is estimated at 6,000.

Adverse Consequences of Highways

Unfortunately, the very highways whose benefits we enjoy have resulted in adverse environmental consequences, sometimes very serious ones. The same trucks that help provide inexpensive television sets sometimes make so much noise that we can't enjoy a conversation in our own backyards—the same backyards made possible by highways which permit us to commute to work from our suburban homes. The car that carried our family to a Fourth of July weekend on the beach helped create a smoggy midweek at home. The beautifully alined freeway through gently rolling hills may become an eyesore for people living near it in our central cities if it is not designed properly. A highway that makes weekend hunting possible can destroy game if not located, designed, and operated with knowledge of wildlife in mind.

Social effects of highways may include dislocation of families, neighborhoods, businesses, and sometimes schools and other institutions. A highway at the fringe of a neighborhood can enhance the community while one insensitively located can have disasterous effects. But how is the neighborhood to be defined and how are such effects to be predicted?

Any proposed restrictions on transportation to enhance the environment will have consequences that need to be analyzed for their effect on mobility of people and goods because restrictions in mobility can have tremendous effects on how we live and work. For example, gas rationing that reduces auto travel by 80 percent could very well throw half the population out of work unless adequate alternatives were provided.

Highways and the Physical Environment

Some of the most critical problems now facing highway administrators and engineers in the planning, location, design, construction, and operation of highways relate to changes in the physical environment and the effect of these changes on human beings, plants, and animals. These include air quality, noise, esthetics and visual quality, ecological problems, and water quality. The nature of each of these problems will be briefly described, some of the research underway will be outlined and key results obtained to date will be noted.

Air quality

During the past 5 years, a good deal has been done to reduce emissions from motor vehicles. The 1976 light duty (under 6,000 pounds *[2,722 kilograms]* in weight) motor vehicle emission standards are planned to complete the job by reducing hydrocarbon and carbon monoxide emissions to about 4 percent of the levels found in 1965 light duty vehicles. Oxides of nitrogen will be reduced to about 6 percent of the 1965 emissions. Although these light duty vehicles predominate, heavier vehicles will also have substantially lower pollutant levels.

Implementation of the 1976 motor vehicle emission requirements will improve air quality in a short time because newer vehicles account for a disproportionately high share of travel mileage. A new car, for example, is typically driven about 17,000 miles (27,400 kilometers) during the first year; while a 10-year-old car is only driven about 4,000 miles (6,400 kilometers) in a year. Thus by 1980, about two-thirds of the vehicle-miles of travel will be accounted for by 1976 or later models equipped with air emission control devices designed to meet the 1976 requirements when manufactured. Proper maintenance of these vehicles, of course, will be essential to maintain low emission levels.

The question may be asked: If the vehicle emission standards are going to be so encompassing and if their effect will be so rapid, why is it necessary to do additional research relative to air quality and highways? The answer is that although the emission standards are stringent, recent analyses have shown that in numerous air quality regions (approximately equivalent to metropolitan areas), it will not be possible to meet the air quality standards even if an extension were granted to 1980. Furthermore, air quality is not uniform in many of these regions but always has been and will be variable. It is necessary to define places where air quality is poor and to relate these places to concentrations of pollutants and to possible sources of emission. Responses to local poor air quality may include modified highway operation. In any case, it is essential to have practical means of measuring and evaluating sources of air pollutants and providing recommendations for remedial measures relative to highway design and operation. A key part of the FCP project "Pollution Reduction and Visual Enhancement," will be development and validation of predictive models, including development of more accurate physical concepts, so that it will be possible to determine in advance effects on air quality of new highways and modifications in operation of existing highways.

A recently completed effort in this area has been the distribution of eight air quality manuals prepared by the California Department of Transportation under contract with the Federal Highway Administration (FHWA). These manuals are designed to help equip and train highway engineering personnel in procedures for evaluating air quality as a part of environmental impact analyses. The manuals incorporate the state of knowledge in air quality and have been used as texts for workshops sponsored by the FHWA with the assistance of the Environmental Protection Agency (EPA). The research is continuing and includes analyses, experimental studies, and evaluations of air flow and control measures to improve air quality on and near highways.

Another recently completed study by the Mine Safety Appliance Research Corporation under FHWA contract analyzed tunnel ventilation and air pollution requirements. The study shows that it may be feasible to treat three of the four pollutants from motor vehicles (all but carbon monoxide) that are normally expelled from tunnels and then vented into the ambient air. Such treatment by collecting devices or other substances would permit the cleansed air to be recirculated in the tunnel or released as appropriate. These findings are of considerable importance because, in the future, treatment of air from tunnels may become mandatory. Furthermore, the proportion of highway expenditures for tunnels is predicted to increase substantially. As it becomes more difficult to construct surface highways, it will be necessary to utilize tunnels as viable alternates to a much greater extent, particularly in urban areas. Hence tunnel air quality management will become increasingly important and is another example of how highways can improve the environment, i.e., the air discharged from highway tunnels may well be cleaner than that found along city streets.

Other research is being undertaken under the National Cooperative Highway Research Program (NCHRP) on the effects of air pollution regulations related to highway construction and maintenance. Additionally, Oregon, Tennessee, and the District of Columbia are involved in air pollution studies under the Highway Planning and Research Program (HP&R). A Colorado HP&R study investigated air quality in tunnels at elevations of 10,000 feet (3,050 meters) above sea level. Increased turbulence and atmospheric diffusion at these mountain elevations favored dispersal of pollutants. For tunnels 3,000 feet (913 meters) long, carbon monoxide concentrations were found to be satisfactory without artificial ventilation. The possibility of haze, however, suggested ventilation at these elevations for tunnels in excess of 1,000 feet (304 meters).

In New York City, the HP&R program contributed to an EPA study which showed that carbon monoxide concentrations increased with congested traffic and between buildings or semienclosed areas. Higher vehicle speeds reduced carbon monoxide concentrations.

Noise

Much of the noise emanating from highway operation comes from large trucks. Research is now underway by industry groups and the Department of Transportation to improve the design of these trucks with respect to tires, mufflers, transmissions, engines, and other components. It is not enough to reduce the noise from any one component but rather each one must be improved if substantial overall noise reduction is to take place. It will take some time to determine the appropriate designs, to manufacture improved vehicles, and to replace trucks now operating on the highway.

The amount of noise is dependent not only on the types and speeds of vehicles using the highway but also on the distance between the highway and the person hearing the noise. For these reasons, it will be necessary to provide tools to remedy highway noise beyond those applicable to the vehicle. These tools will include criteria for improved location and design of highways to minimize noise and use of barriers between the highway and the abutting property where appropriate. Aids must be provided for development of appropriate land use controls so that after a highway is built, occupants of structures subsequently constructed are not adversely affected because of their proximity to the highway. Thus, a conventional school should not be built next to a high volume freeway. If such construction is necessary, sound insulating materials, air-conditioning, double-glazing, and other acoustical techniques should be incorporated into the design of the school so that faculty and students will not be disturbed by vehicles using the highway. For existing buildings near highways, criteria are needed for application of acoustical treatment, air-conditioning, and other noise limiting techniques.

Analytic models developed under NCHRP Report 117 and computerized by the Michigan State Highway Department have been distributed by FHWA to State highway departments as an aid in making analyses of noise levels at various distances from a highway. Work is continuing on determining and remedying any limitation of these models in actual use and in expanding their scope.

Increasing use will be made of noise barriers between highways and people living and working near highways. Research is underway to develop and evaluate improved acoustic attenuation surfaces, materials, and artificial barriers. Cost tradeoffs will be made and recommendations developed for effective, economical barriers.

The problem of tire surface interaction and noise must also be considered. Rough appearing plant mix seals are no noisier than other pavements and are skid resistant. The crossbar types of tires are skid resistant but also noisy. Other tire types are nearly as skid resistant but much less noisy. Clearly, the problems of skid resistance, tire-pavement noise, and tire and pavement wear must be considered in concert.

A current problem with noise prediction methods is that criteria adequate for daytime application—annoyance, the ability to hear speech, task interference—are not necessarily applicable to a nighttime situation. In the daytime, 5 to 10 trucks per hour may interrupt speech moderately and be acceptable; at night the same 5 to 10 trucks per hour may awaken some people and be considered unacceptable. More research is needed on acceptable levels of noise relative to sleep and criteria for application to highway operation.

Use of scale models in analyzing complex highway situations shows promise and will be investigated. Such physical models are not needed for conventional highway designs, but at complex interchanges and some urban sites use of scale models for noise analyses may prove to be efficient and accurate.

Esthetics and visual quality

Over the years, the more astute highway designers have produced outstanding highways from a visual and esthetic point of view. But such designs have often been achieved after many years of experience in highway design. Guidelines are needed by which highway designers can give attention to visual values in an organized manner. Research being completed by Harvard University under an FHWA contract will provide such a guide. The results will assist highway designers in utilizing visual values in highway location and design. The guide will become available later this year. Experience in its use should suggest improvements and point toward aspects of highway esthetics and visual values requiring additional research. A related HP&R study in Florida is approaching the problem of pleasing highway location, design, and landscaping by using maps with plastic sheet overlays. Land forms, ground cover, socio-economic factors, and other environmental effects are factors being considered.

Erosion control and vegetation management

Many of the problems in these specialized areas must be solved with regard to specific climate and soil conditions. For this reason, some 43 HP&R studies are underway in 30 States to help solve local and regional problems of erosion control and vegetation management. Vegetation management was involved in 31 studies; ecology, 17; erosion control, 10; and visual enhancement or landscaping, 7. Many of the studies involved two or three subject areas

Figure 3.—Natural vegetation provides beauty, reduces maintenance costs, and eliminates driver monotony.

California is developing more effective irrigation systems that will water roadside plants with minimal traffic interference and is also developing better nonchemical means of controlling those pests which attack desirable roadside vegetation.

Montana investigated artificial means of forcing roots to reach deeper to obtain water after transplanting. An NCHRP study on control of erosion during construction will begin shortly; a synthesis study on the same topic was recently completed.

Ecological problems

Whenever a highway is constructed, some disruption to the natural environment occurs. Required are methods for predicting the nature and magnitude of the disruption and remedial measures to minimize it. Questions such as these must be answered: Is there significant wildlife in the area involved? Will the highway cut through the normal migratory paths of these animals? What can be done to minimize such disruption, such as relocation of the highway, provision of bridges rather than culverts, or other remedial measures?

Research underway with the U.S. Forest Service will investigate the effect of highway construction and operation on large game animal population and movements. Through an understanding of how game animals move, and the disruption produced by highways, it will be possible to provide strategies that highway designers can use in avoiding such situations. For example, certain kinds of roadside vegetation encourage deer to graze alongside the highway and cross the highway frequently in search of forage. A better understanding of deer habits will make it possible to plant nonsavory materials to reduce deer accidents. Inventories will be made of natural roadside vegetation that selectively controls wildlife to avoid deer accidents. Subsequent research studies will be directed at minimizing the shortterm effect of highway construction on small mammal and bird populations. The results of the research will be summarized in working manuals to aid highway designers.

Water quality

From time to time, in recent years, statements have been made about the pollutional effects of highways relative to water quality. Frequently supporting information is not presented to document these statements. It is essential that significant water pollution from highway sources be reduced as much as possible. It is also important that actual pollutional effects of highways be determined in order that they may be effectively dealt with

Three major research areas are involved in this effort. One is to provide requirements for the quantity of water to be treated and criteria for treatment of wastes at roadside rest areas. This is an important task because recently enacted legislation requires that secondary sewage

Figure 4.—Roadside rest area.

treatment standards be met by 1977. More stringent standards must be met by 1983. The problems are being addressed by an FCP project, "Reduction of Environmental Hazards to Water Resources Due to the Highway System."

West Virginia, under contract to FHWA, has instrumented roadside rest area facilities along Interstate highways in five States to measure, and ultimately to predict, usage of such facilities by correlating usage with traffic volumes on Interstate highways. Physical, chemical, and biological tests of the water and sewage will determine water quality and effectiveness of the sewage treatment process.

A related HP&R study in Illinois is investigating the feasibility of developing a recycling sewage treatment system for rest areas with limited water supply.

An Indiana HP&R study is developing a biological treatment system that will be inexpensive to operate and will provide for a highly treated effluent or for recirculation to eliminate the need to discharge effluent.

A second area of research involves determination of the type and amount of pollutants, their impact on the environment, and methods for controlling pollutants contributed by the highway system. Included are such pollutants as rubber, lead, grease, and oil which collect on the pavement surface and wash into drainage facilities. This task will provide factual information to help assess the scope of the problem and provide appropriate remedies.

A Pennsylvania HP&R study is developing a method to predict the increase in sediment loading in a stream as a result of highway construction. Such a predictive tool will help schedule construction to minimize stream sedimentation.

A Massachusetts HP&R study, jointly conducted with the U.S. Geological Survey, has been analyzing the manner in which highway deicing chemicals are transported by surface and ground water under various geologic and hydrologic conditions and highway maintenance practices.

A California HP&R study will evaluate long term effects of remedial measures to minimize degradation of water quality resulting from highway projects. Included will be analyses of water quality, ecological conditions, vegetation, and soil inventories.

A third task has as its objective the reduction of damage to water resources through accidental spills of chemicals and other materials. Initially, a staff study will define the scope of the problem and suggested methods of attack.

Social Effects of Highways

Nearly everyone wants to use highways but many people do not wish to live next to one. The problem is to determine and precisely measure the social impact of highways on people and to minimize these effects wherever possible in highway planning, location, design, and operation. These effects involve the family and neighborhood dislocation that takes place as highways are being constructed and later as they are used. They also involve many other environmental consequences that have social ramifications. For example, noise from a nearby highway may disrupt use of yards for outdoor entertainment or may disrupt sleeping or conversation indoors.

The precise location of a highway can have considerable impact on people living in the path of the proposed highway as well as those living near the new highway. Some of these effects are only superficially known and others, while known, are difficult to mitigate. Do payments for relocating people, residences, and businesses really compensate for the dislocation impact of new highways? Do pedestrian overpasses restore cohesiveness of neighborhoods? What is the impact on the relationships among people and their schools, churches, stores, clubs, and similar institutions?

Research is needed to develop methodologies for measuring, evaluating, and predicting social and economic impacts of new highways. Techniques must be developed for eliminating or lessening the adverse impacts, including guides for employing the "no build" alternative. These methodologies can then be used to establish criteria for design changes based on cost-effective considerations relative to eliminating, alleviating, or compensating for adverse environmental impacts.

The research will consider variables that may influence environmental concerns of people living near highways including age of family members, occupation, income, family size, and education. Various highway types will be considered including local collectors, arterials, and freeways as well as such traffic variables as speed, composition, and volume. Uses of land for residential, educational,

Figure 5.—Pedestrian overpass.

recreational, commercial, industrial, and agricultural purposes will be included in the analyses. The wide range of variables to be considered is one indication of the complex nature of social effects of highways and also suggests that remedial techniques will need to be customized for different combinations of conditions. These problems are being investigated under an FCP project, "Socioeconomic Factors in Highway Engineering and Location."

A research study being undertaken by the National Bureau of Standards for FHWA is investigating both objective and subjective measures of social and economic impacts and will develop methods for predicting these impacts. The methods will be tested and summarized in technical manuals. Workshops will be employed to disseminate the results and to improve the ability of highway agencies to minimize any disruption that takes place by virtue of highway construction and operation.

A completed NCHRP study on Valuation of Air Space concluded that both public and private use of air space above highways is feasible. The study provides methods for determining the commercial value of these air rights.

An ongoing NCHRP study is developing a pragmatic approach to insure that community values are properly considered in highway location and design.

A Michigan HP&R study aims to define primary social, economic, and environmental aspects and to develop procedures for analyzing and presenting these aspects clearly.

Adverse Driving Environments

In addition to adverse consequences of highways on the environment, the environment has an adverse effect on humans using the highway transportation system. These adverse driving environments must be overcome to provide optimum safety, driving comfort, and mobility. Included are problems of darkness, rain, snow and ice, fog, and dust which are being attacked under an FCP project "Improving Traffic Operations During Adverse Environmental Conditions."

Darkness

The problem of darkness in driving is somewhat different depending on whether the highway is a two-lane rural highway, an urban freeway, or a city street. For two-lane rural highways, delineation with both pavement markings and delineation panels or buttons is extremely important. The key research problem here is to devise retroreflective pavement markings that can be seen under wet night conditions and are not pulled up by snowplow blades. This problem is now being investigated under the NCHRP and HP&R programs as well as by direct contract with FHWA. Cost-effective solutions should be available soon.

The other problem on two-lane highways is that of glare. The only economical way of radically reducing glare and maintaining visibility is through a polarized headlighting system. Research undertaken by FHWA showed that such a system is feasible and recommended a full-scale 1-year field test in an isolated island location.[1] Responsibility for this area of research has now been turned over to the National Highway Traffic Safety Administration.

The problem of darkness on urban freeways can be met by fixed highway illumination. On suburban and rural freeways, high-mounted lighting systems can also be effectively employed. A good deal is known on how to design such lighting systems, including criteria for installation.

[1] "A Preliminary Cost-Benefit Study of Headlight Glare Reduction," by Roger H. Hemion, SwRI Project No. 11-1908, Report No. AR-683.

The third area is that of illumination on city streets. Again, information is available on how to design lighting systems for such streets but criteria for lighting is not as firmly indicated. Recent FHWA supported research undertaken by Franklin Institute has shown that a level of illumination of about 1 footcandle (11 lux) is optimum in terms of driver reaction to a pedestrian. Research is planned in the near future on the specific quality of illumination needed for a variety of city street types ranging from low volume residential streets to principal arterials.

Rain

Although it rains about 12 percent of the time, fully 20 percent of all accidents occur during rain. Many of these are due to skidding, which in turn depends upon a combination of quality of tire and depth of tread, type of pavement surface, speed of the vehicle, its braking system, and other variables. A comprehensive research program is underway within an FCP project, "Skid Accident Reduction," to provide information and tools to reduce skidding accidents.

The program aims to define the friction needed under wet weather conditions using both accident and behavioral studies—that is, studies of driver deceleration and side slipping. A determination will also be made as to whether various types of signing, including variable message signs, can reduce friction required by drivers under wet weather conditions. Materials needed to provide the required friction for a wide variety of conditions will also be specified, including better laboratory methods of evaluating materials in advance of construction.

Another part of the program involves analysis of the mechanics of pavement-vehicle interaction, skidding, and loss of control, including development of measurement systems for pavement friction, roughness, and hydroplaning. Development of automated measurements systems is particularly important to permit several types of skid related measurements to be made under highspeed conditions with automatic processing of the voluminous data obtained.

Research underway at the National Bureau of Standards is analyzing sources of error in skid measurement systems with a view to providing improved measurement techniques. In 1973, three field test centers were established by FHWA to assist State highway departments in calibrating their measurement systems, in instructing measurement personnel in the sources of error in their own measurement systems, and in minimizing such errors. A number of States have already begun using these facilities.

Snow and ice

During the last 25 years, tremendous progress has been made in facilitating operation of highways under winter conditions when snow and ice are on the pavement. Nearly all primary highways are open to traffic during the entire winter—but a number of problems remain. In some cases critical locations such as ramps, viaducts, and bridges present difficult snow and ice removal problems or develop ice before the rest of the highway system. Research is underway to develop specifications for a snow and ice detection and communication system which will respond to localized road surface characteristics that are not visually apparent. Special attention will be directed toward the problem of detecting thin layers of frost on bridge decks and providing methods for alerting motorists approaching these bridges.

Another research study being undertaken by the Dynatherm Corporation, Cockeysville, Md., is determining the feasibility of pavement heating systems which can economically prevent ice from forming at locations where critical safety hazards exist. Earth heat is employed to keep the pavement surfaces at a temperature that will prevent ice from forming. During experiments last winter at the Fairbank Highway Research Station near Washington, D.C., a heat pipe system successfully carried earth heat from 30 feet (9.14 meters) below the surface to melt ice on concrete slabs on the surface. One advantage of the system is that it has no moving parts, pumps, or valves. Heat pipes embedded in each slab and connected to the earth utilize low cost ammonia as the heat transfer medium. Heat from the earth evaporates the liquid ammonia which, in gaseous form, rises to the slab end of the pipe. After the gas loses its heat to the pavement surface through the same heat pipe and condenses, it returns below the ground as a liquid along the inside wick of the heat pipe where it is again heated, changes to a gas, and returns to the surface.

The heat pipe system promises to be of great value for specific highway situations. It should not be inferred, however, that such a heat pipe system will replace conventional snow and ice treatment or removal techniques. The amortized cost of the heat pipe system is likely to be 20 to 40 cents per square foot (1.9 to 3.7 cents per square meter) per year compared to about 1 cent per square foot (.1 cent per square meter) per year for a general snow and ice removal system. There are special locations, however, such as at interchange ramps and bridge decks, where snow and ice removal costs are 10 to 40 cents per square foot (.9 to 3.7 cents per square meter) per year because of the need for assigning a special crew or for other reasons. At these locations, a heat pipe system may be feasible and useful, particularly as experience with such systems reduces the installation cost and demonstrates that the maintenance cost is negligible as has been predicted. Research is continuing on the heat pipe system to provide design criteria, better cost estimates, and field testing.

Other research in this area will develop methods for establishing the safety, environmental, and economic implications of deploying various systems that prevent or minimize adverse effects of frost, ice, and snow in winter travel. Alternative materials for deicing streets and highways will be investigated and developed that will minimize environmental damage to pavements, highway structures, and the general environment.

Fog

Although fog accidents account for only 3 percent of all accidents—and indeed there is some evidence that the accident rate in fog is lower than during normal conditions—a very high proportion of multivehicle collisions occur in fog. A California study, for example, showed that of all accidents involving nine or more vehicles, approximately two-thirds occurred in fog. Analysis of the problem indicates that fog dispersal systems, which may be feasible in localized areas such as airports, are not likely to be feasible on highways where fog is not predictable and has to be dispersed over long sections. Furthermore, the fog tends to last only a few hours in many instances and therefore portable dispersal systems would also not be feasible. Finally, the energy cost alone of operating fog dispersal systems would exceed the cost of fog accidents even on very high volume freeways.

Accordingly, the emphasis is on systems that will provide drivers with information about the speeds of traffic ahead in fog situations so that all vehicles may reduce their speeds gradually. Research is now underway by the Oregon Highway Division under contract with FHWA to investigate a fog-speed advisory system. The research is being done in an off-highway situation so that artificial fog can be generated as needed. Work will include study of whether drivers will respond to speed information if it is given to them; how far apart the speed detectors need to be; and how far apart the advisory speed displays have to be. The "cry wolf" effect will also be investigated; i.e., if drivers are incorrectly given fog information when there is no fog, what will they do when fog occurs? The "cry wolf" effect applies to a wide variety of traffic situations beyond the fog question.

Figure 6.—Artificial fog generator.

Conclusion

The foregoing brief overview has touched on some current environmental problems relative to highways and on some of the research underway to solve these problems. Recently completed research concerning drivers, vehicles, highways, and the environment has aided in reducing noise near highways, analyzing air quality, and generally mitigating adverse consequences of highway construction and operation.

Environmental concerns reflect a serious desire to minimize man's disruption of nature. Carefully planned and executed research efforts can help provide tools for solutions of these varied environmental problems. The efforts will not be easy. Although initially only portions of these critical problems will be solved, as the work proceeds it will become clear that more general solutions are possible. The objective is to provide better transportation with minimal environmental damage and thus help to insure a better society.

Major Interchange Design, Operation and Traffic Control—Summary of Results

by Charles R. Stockfisch and James I. Taylor

The purpose of the research study summarized in this article was to develop improved design procedures and guidelines for major—freeway-to-freeway—interchanges by a thorough examination and analysis of existing design procedures and current freeway operational characteristics.

Three groups of problems associated with major interchanges were examined; those relating to policies, to design procedures, and to the design of individual elements of the interchange. Research techniques included structured interviews, workshops, and questionnaires; case studies; accident analyses; and examination of decision theory and trade-off analysis techniques for application in designing major interchanges.

The research effort produced the following: Design criteria and guidelines; two design information systems; and several design process tools, including a review of the applicability and usefulness of three-dimensional models, checklists, and computer graphics.

Future plans have been discussed for dissemination and encouraging use of the results obtained in the summarized study.

Introduction

The introduction of high-speed, limited-access highways has required an operational balance between such highways and the nodes that link them, particularly those connecting two freeways—major interchanges. Roadway designers have encountered many problems in their efforts to maintain this balance.

Although designs of interchanges are often based on evolutionary changes of past designs or on modifications of existing designs to increase capacity, improved designs tend to develop from experience and engineering judgment, a costly, time-consuming design process.

The objective of this article is to summarize the results of, and highlight the products developed from, a comprehensive study entitled "Major Interchange Design, Operation and Traffic Control" (*1*)[1] which was directed toward developing improved criteria and guidelines, information transfer systems, and process tools for major interchange design.

Major Interchange Design Problems

In general, designs of major interchanges differ from those of non-major interchanges in several important aspects:

- Connecting links between two freeways are generally considered turning roadways rather than ramps.
- Major interchanges usually allow higher speed on their approaches—up to 80 mph (129 kmph).
- Higher hourly traffic volumes are prevalent—up to 30,000 vehicles.
- Higher levels of service are desired.
- Costs are higher—construction costs range between $3 million and $65 million.

The interchange is one of the most vital parts of a freeway system. Regardless of how well the intersecting roadways are designed, if the interchange cannot accommodate the demand placed upon it, the whole system is likely to fail.

Problems surrounding the design of major interchanges can be categorized into three functional groups: (1) Policy problem areas, (2) design procedure problems, and (3) component design problems. Examples of problems within each category other than those discussed below are listed in table 1.

Policy problems

State highway departments often have diverse organizational structures which affect the design process. Some States prefer to put together a design team responsible for carrying the design from its initial stages to final plans. Other States prefer to pass the design along from one design specialist to another until final plans are completed. In some instances the traffic engineer may be

[1] Italic numbers in parentheses identify the references on page 314.

Table 1.—Major interchange problems

Policy problem areas	Design procedure problems	Component design problems
Changing priorities	Uniqueness	Left-hand ramps
Environmental, esthetic, ecological considerations	Design project management	Entrance ramp capacity
Involvement with local agencies	Selection of basic configuration	Two-lane ramps
Local access	Driver needs	Hidden ramps
Partial interchanges	Adaptability and flexibility	Collector-distributor roadways
Exclusive bus lanes	Trade-off analyses	Consecutive ramp arrangements and weaving areas
	Cost effectiveness	Lane drops
	Checklists	Grades
	Design experience of reviewers	Signing
		Nonconformance of travel paths and construction joints
		Freeway traffic control
		Nomenclature
		Traffic forecasts

included in the design process at the beginning, or he may only be asked to review the final plans for the adequacy of signing and markings.

Another problem in the design process is that priorities often change over a period of time. In the early 1960's, economics was weighted very heavily in the decisionmaking process. This was followed by a greater concern for safety, prompted to a great extent by the Highway Safety Act of 1966. More recently, environmental considerations have resulted in a third set of priorities that must be considered by the design engineer.

Design procedure problems

Existing design procedures, within the 1965 AASHTO Blue Book (2) and similar State manuals and guidelines, are brief and too general in nature to aid the highway designer in objectively evaluating alternative designs and making correct decisions. Further, alternative practices are often employed in the design process. For example, design procedures among the State highway departments are generally not standardized. Most States do not know which designs are working well in other States and there is a lack of feedback concerning operational practice for designs already implemented. Moreover, diverse design philosophies are practiced among the various highway departments. Some States begin with a basic cloverleaf design and upgrade according to site-specific requirements until an acceptable design is reached. Other States prefer to begin with a high-type directional interchange design and downgrade it according to specific location requirements until a design is reached that is operationally adequate but not cost prohibitive.

Component design problems

Another problem is that States do not seem to use economic analysis in selecting interchange types, but do evaluate costs when choosing individual interchange elements such as speed change lanes and ramps. The cost of an interchange element must seem acceptable with respect to the total interchange cost. One of the most important tools that the designer lacks is a method for cost-effectiveness evaluations. The decision to approve an interchange design appears to be based on the range of costs and benefits which have resulted from similar designs. It should not be assumed, however, that criteria such as noise, pollution, and esthetics—which are not easily quantified in terms of dollars and cents—will have comparable cost values when matched with similar interchanges. The problem lies with assigning values to those non-material factors.

Approach to the Problem

To alleviate many of the major interchange design problems discussed above, the research summarized here was undertaken. Specifically, the objectives of the research were to:

- Develop improved design procedures as aids to highway designers.
- Determine the feasibility of various major interchange configurations for inclusion in adaptive freeway control schemes.
- Provide recommendations for minimizing operational problems.
- Develop a process for classifying and inventorying information relevant to the interchange design components.
- Prepare a comprehensive state-of-the-art report and research review.

The research process included all of the following activities:

- An extensive search and review of major interchange literature, from which more than 200 articles and reports were abstracted and categorized.

- Analysis of the design and policy-making process, including that of highway planning, and the ways in which interchange design interacts with the development of the total highway system.
- Examination of business and military decision theory and trade-off analysis techniques.
- Employment of structured interviews, workshops,[2] and questionnaires to examine and analyze existing design procedures and current freeway operational characteristics.
- Examination of case studies of major interchange lane drops and exit ramps.
- Analysis of major interchange accidents.
- Examination of freeway traffic control systems as they relate to major interchange design and operation.
- Evaluation of major interchange classification and inventory techniques for use in planning and problem analysis.

Research Products

The specific outputs or products obtained from the research are shown in figure 1; Design Criteria and Guidelines, Design Information Systems, and Design Process Tools. Example outputs from each of the first two categories are provided. Products listed in the third category—design process tools—are referred to in the concluding section of this article, which delineates plans for future dissemination of results emanating from the summarized study.

Design criteria and guidelines

The number of lanes to be provided in each direction on a freeway is based upon the desired service volume of a lane and the estimated peak hour traffic volume. In freeway construction, a minimum of two lanes is provided in each direction and use of more than four lanes directional is generally not considered desirable except where an auxiliary lane is added for a short distance. Where a major change in the traffic volume occurs at a freeway entrance or exit, it may be desirable to add or drop a freeway lane for lane balance.

There is general agreement among design and operations engineers with the four basic principles for lane balance outlined in the 1973 AASHTO Red Book (3):

(1) The number of lanes beyond the merging of two traffic streams should not be less than the sum of all traffic lanes on the merging roadways minus one.

(2) In conjunction with entrances bringing two lanes of traffic into a highway, the highway beyond the ramp entrance should be at least one lane wider than the highway approaching the entrance.

(3) In conjunction with exits requiring two lanes, the number of lanes on the highway should be reduced by one lane downstream from the ramp exit.

(4) The highway traveled way should be reduced by not more than one traffic lane at a time.

Although these principles are generally accepted, there is no agreement in the design community on their implementation. This lack of agreement concerns whether a lane should be dropped within an interchange or some distance beyond the interchange, which lane should be terminated, and the geometrics of the taper where the lane is dropped. Where there is a two-lane entrance design problem, there is some disagreement regarding the design for adding the lane to the freeway.

An approach used in California does not permit lane reductions within local interchanges except at multiple lane exits where more than half of the traffic turns. In locations other than multiple lane exits, where traffic volumes decrease sufficiently to warrant a lane drop, the recommended location for the drop

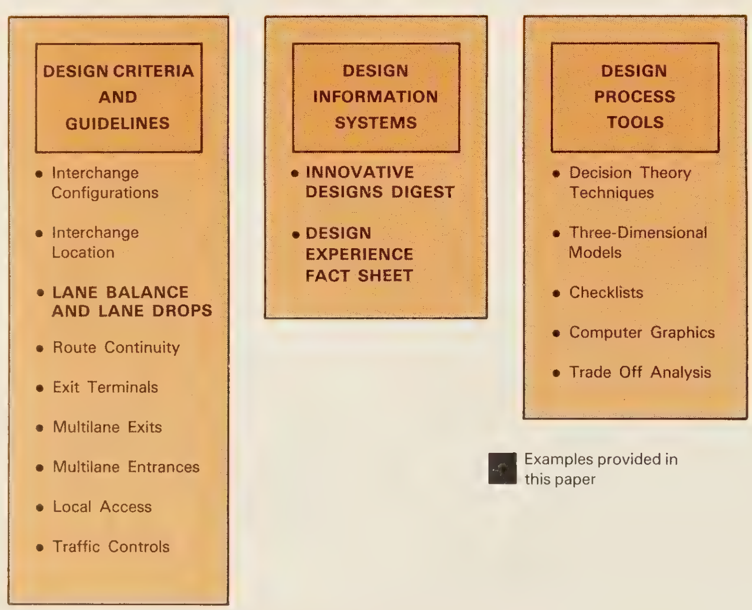


Figure 1.—Research products.

[2]Two design workshops were held at Pennsylvania State University in September 1972.

is beyond the influence of the interchange and preferably at least one-half mile from the nearest exit or entrance. Further, it is the practice for lane drops to be located on tangent alinement with a straight or sag profile for maximum visibility of the merge markings.

The pitfalls of poorly designed lane drops are noted in several studies. Hong (4) observes that:

> ... freeway egress and ingress points must be designed so as to eliminate any suspicious pocket, trap area, surprise element, or system discontinuity .... Congestion at a bottleneck can cause low overall speed, high frequency of speed changes, time loss, driver discomfort, and, above all, drastic reduction in capacity.

A paper by Jenkins[3] indicates that lane drops should be situated at major diverging forks in directional interchanges. Jenkins also noted that at directional interchanges where turning movements are heavy and separate exits for right and left turns are provided ahead of entrance roadways, it may be satisfactory to drop a lane within the interchange, preferably at the second exit. He further states that under normal circumstances, when a lane is to be dropped in the vicinity of a nondirectional interchange, the lane should be carried beyond the interchange and then terminated. With regard to the choice of which lane to drop—left or right—he indicates there is no conclusive evidence available to support one or the other. When Jenkins' paper was discussed at the two Penn State design workshops, attended by practicing design engineers and traffic operation specialists, some conferees indicated the location of each lane drop should be resolved on the basis of its unique merits.

It was emphasized in the workshops that in any discussion of lane drops it is essential to differentiate between basic freeway lanes and auxiliary lanes. It was the consensus of attending experts that auxiliary lanes which begin at the preceding upstream entrance can be dropped at a major interchange exit without any special lane drop treatment. However, the dropping of a basic through freeway lane requires special consideration, whether it occurs at an interchange exit or beyond the effect of the interchange area.

Figure 2 shows three geometric configurations for a reduction from three through traffic lanes to two lanes at a single lane exit ramp. Figure 3 indicates similar lane drops from four lanes to three lanes and figure 4 shows lane drops from four lanes to three at a two-lane exit ramp. Workshop participants were asked to rank the configurations in each of these figures in order of personal preference. In all three cases, the majority favored dropping the through lane beyond the interchange, but 35 percent favored dropping the right lane in figure 3 and approximately 45 percent preferred dropping the right lane in figures 2 and 4. Only one of 27 workshop participants preferred to drop the left lane in each of the three figures.

[3] "Balanced Freeway Design" presented by I. Jenkins at the Kansas Highway Engineering Conference, March 1969.

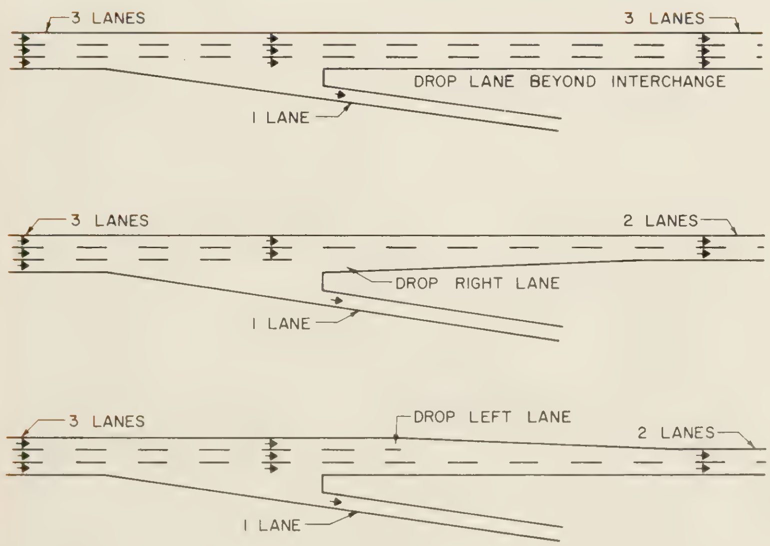


Figure 2.—One-lane exit, reduction from three lanes to two on mainline.

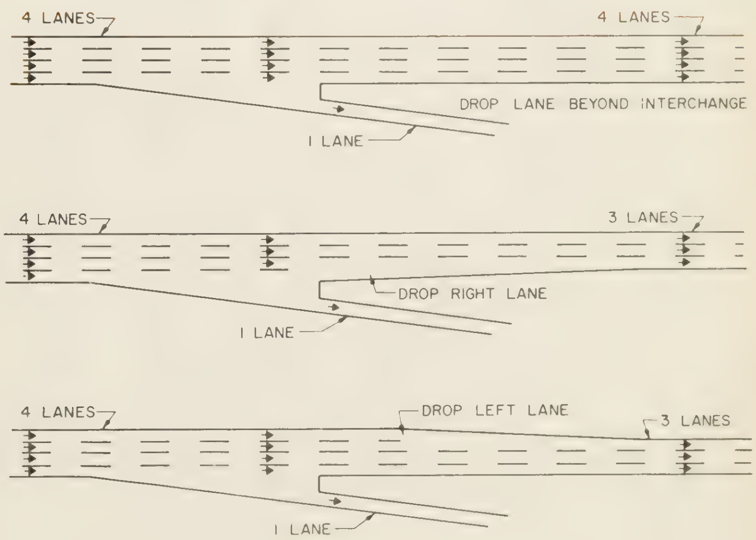


Figure 3.—One-lane exit, reduction from four lanes to three on mainline.

One workshop participant stated that lane drops are a practical consideration and no formula or equation will help decide where to design the lane drop. Because of geometric and operational specifics, the lane drop is usually designed beyond the interchange. Another participant suggested that one reason for dropping a lane beyond an exit ramp is that drivers handle the maneuver better since they expect something to happen at the exit gore.

It was almost unanimous among the participants that when the lane drop is located beyond the influence of the interchange, the right lane was the most desirable lane to be dropped. It was noted that the merge from the right was safer and what the drivers expect. It was further argued that the high speed traffic in the left lane should not be disrupted by a lane drop and that rear visibility from the vehicle is poorer from the left lane for the merging operation.

The few participants indicating a preference for the left side lane drop noted that there was usually less traffic in the left lane, particularly during offpeak hours, and consequently less lane changing required. It was also pointed out that if a future median lane was to be added ahead, the left side was the natural place to drop the lane.

None of the participants favored dropping one of the interior lanes since this puts a squeeze on all drivers.

There was general agreement on the following essential factors for good operational characteristics: Good visibility (at least desirable sight distance); tangent alinement, preferably toward the far end of sag vertical curves; and adequate advance signing to advise the unfamiliar driver of the impending lane drop.

Considerable discussion centered about whether a lane should be dropped at an exit ramp in an interchange if a lane was to be added beyond an entrance ramp. Figure 5 shows two alternative treatments of a four-lane through roadway at a major interchange with high volume exit and entrance ramps: **A** has no lane drop, while **B** shows a reduction to three lanes between the exit and entrance ramps. Several workshop participants stated that they were definitely opposed to dropping a lane at an exit and then picking it up at the next entrance. Preferably, the same number of lanes should be carried through the interchange regardless of the volume. To strengthen this point, it should be noted that many traffic problems have occurred in the Los Angeles area in the situation illustrated in figure 5**B**. State design engineers at the workshops indicated that, in the past, designs were based strictly on volumes, but now more attention is directed toward traffic operations.

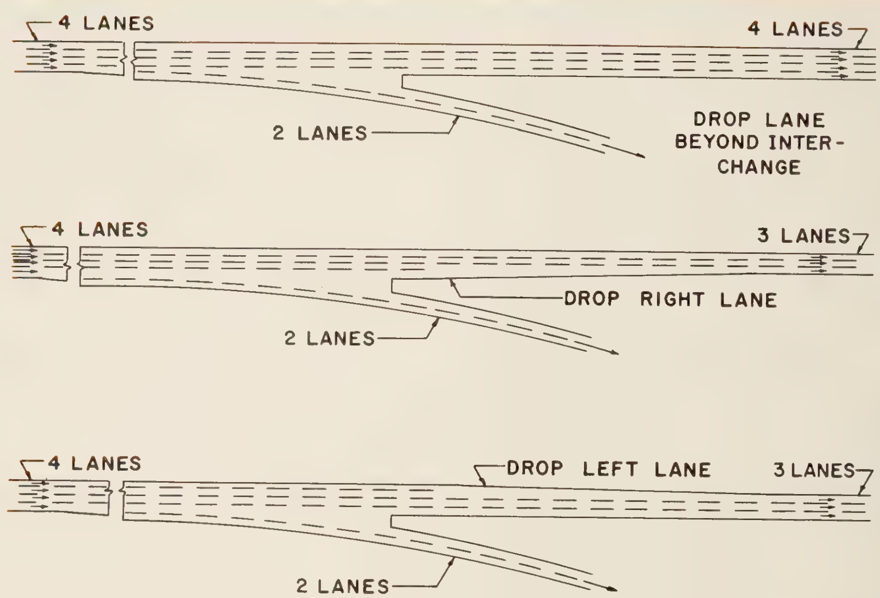


Figure 4.—Two-lane exit, reduction from four lanes to three on mainline.

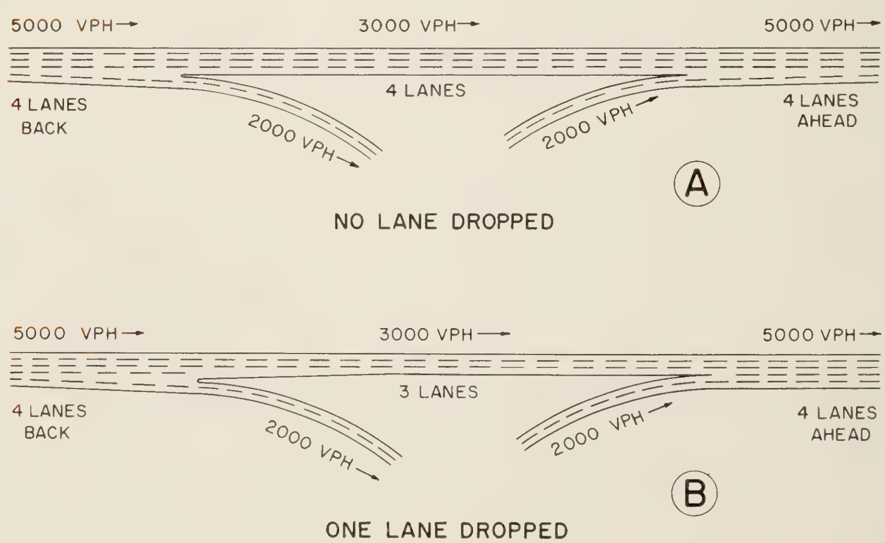


Figure 5.—Lane balance within an interchange.

A recent gore area study revealed that signing is a problem when lane drops occur in conjunction with exits. Some drivers interpret EXIT ONLY signs to mean that if one cares to exit he can do so only from that lane, but that the sign does not indicate a lane drop. Texas uses a separate black on white overhead sign reading, RIGHT LANE MUST EXIT, and has discontinued the use of EXIT ONLY signs.

A discussion of the geometric design of a lane drop beyond an exit ramp indicated that about half the workshop participants would begin a taper at the ramp nose while the other half would provide a full-width escape lane, varying in length from 150 to 1,000 feet (45 to 300 m) before starting the taper. However, with full-width paved shoulders (which can serve as a recovery area), the full-width escape lane may not be necessary. The taper rate preferred at lane drops varied from 30:1 to 100:1, with 50:1 the most frequently mentioned. One respondent to the preworkshop questionnaire recommended a taper length equal to the design speed times the lane width. This results in a 50:1 taper for a 50 mph (80 kmph) design speed and correspondingly flatter tapers for higher design speeds.

From the preceding discussion, it can be concluded that according to many experts:

- When the downstream traffic volume justifies a reduction in the number of through traffic lanes at a major interchange, the preferred location for the lane drop is beyond the influence of the interchange.
- Except where economic considerations dictate, there should be no reduction in the number of lanes through an interchange.
- When a lane is to be dropped immediately beyond an exit terminal, the right through lane should always be the lane dropped.
- When a lane is to be dropped beyond the influence of an interchange, the right lane is the preferred lane to be dropped; but the left lane may be dropped, particularly where a future continuation of the left lane is contemplated. An interior lane should never be dropped.
- The most important considerations in designing lane drops are to provide adequate visibility of the lane drop configuration and to inform the driver of the impending situation. Therefore, lane drops should be on tangent alinement, preferably on sag vertical curves, and ample advance signing should be provided.
- The taper at lane drops should be designed as acceleration lanes, with a minimum taper ratio of 50:1.

Other interchange component design problems addressed in the research are listed in table 1.

Design information systems

Not listed as a problem in the referenced table, but equally important, has been the lack of an adequate forum for exchanging ideas and experiences on major interchange configuration selection and evaluation and specific element design decisions. Promising new design features and interchange configurations have not been given wide exposure outside the State of origin. A number of possible approaches to spread ideas and experience were investigated in the research effort. Two relatively simple information transfer systems evolved from this effort—the Innovative Design Digest (5) and the Design Experience Fact Sheet (1). The Digest draws attention to novel interchange designs or design features in order to provide a wider audience among the engineering community for consideration of these ideas in future interchange configurations. The designs include:

- Turbine interchange
- Arch-supported interchange
- Double diamond interchange
- Directional interchange with left turn first
- Major fork configuration for direct left connections
- Antiweave designs
- Local access diamonds
- Multinode interchange complex

Two examples from this digest are illustrated in figures 6 and 7.

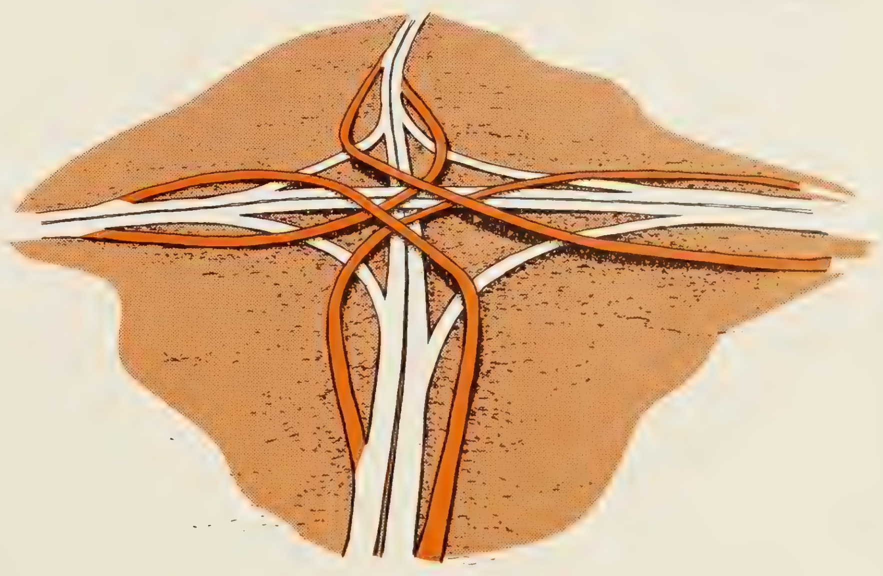


Figure 6.—Directional interchange with left turn first.

(1) Directional interchange with left turn first (fig. 6). This configuration contains a semidirect left turn connection which precedes the right turn exit. It has been criticized by some engineers who object to it on the grounds that drivers expect right turn exits to precede left turn exits (or expect the two to be coincident); however, Texas Highway Department officials report no driver objections to such designs employed in Dallas at two interchanges—those of Interstate routes I-30 and I-20 with I-635.

This design permits a more compact arrangement of the turning roadway and thus requires less right-of-way than the standard semidirectional interchange.

(2) Local access diamonds (fig. 7). Providing for local access presents problems and frequently forces modifications to standard designs when the connections are made in the vicinity of a major interchange. There are times, however, when ingenuity can preserve the integrity of the major interchange design and still furnish local service. For example, figure 7 shows that the ramps on the directional interchange have been lengthened and swung somewhat wider to make room for two diamond interchanges. California Department of Transportation officials observe that this tucked-in design operates smoothly in practice.

The second useful design information system is the Design Experience Fact Sheet. While the

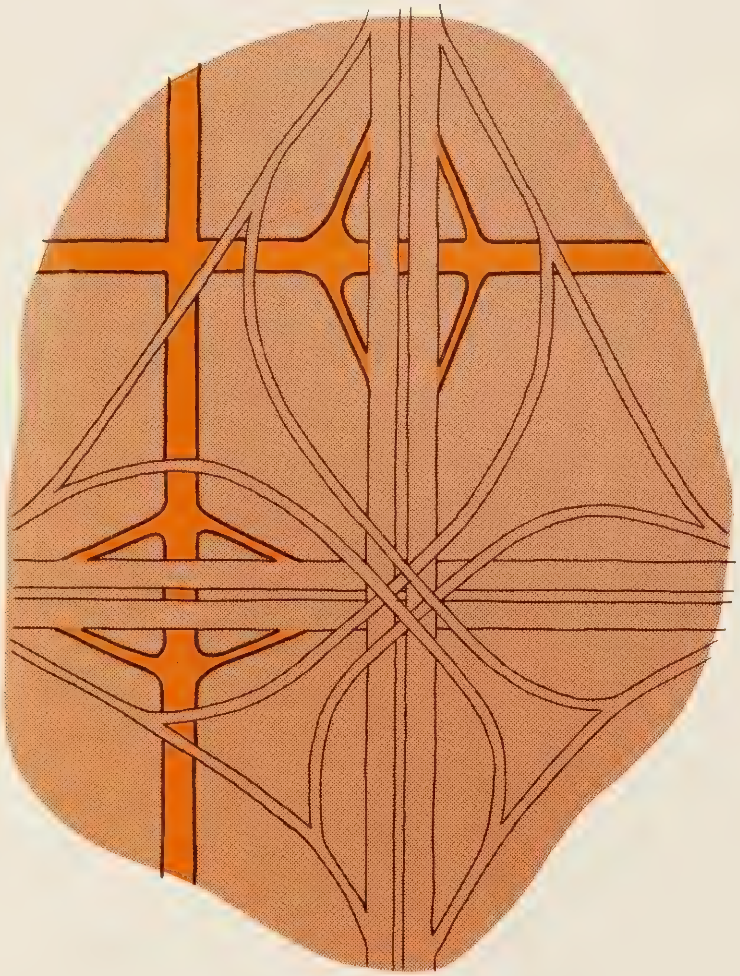


Figure 7.—Local access diamonds.

Entrance Ramp, Two Lane

Location

- U.S. 6/75 (Douglas Street) entrance ramp to Route I-480 at Missouri River Bridge connecting Omaha, Nebr., and Council Bluffs, Iowa.

General design features

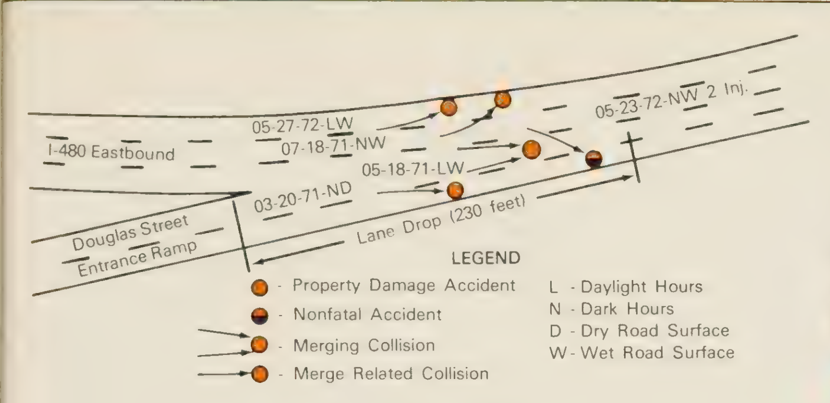
- Average daily traffic (ADT) on the bridge at the time of design (1962)—30,830 vehicles. All eastbound traffic to be carried solely on the entrance ramp.
- Projected volumes for 1984—ADT of 76,000 and design hourly volume (DHV) of 8,665. Entrance ramp DHV of 2,630.
- Trucks = 4 percent
- Directional split = 63 percent
- Design speed, through road—50 mph (80.5 kmph)
- Nearest exit—0.35 miles (0.56 km) downstream
- Nearest entrance—0.39 miles (0.63 km) upstream
- Area type—urban with heavy commuter traffic
- Combined population of municipalities = 360,000

Special conditions

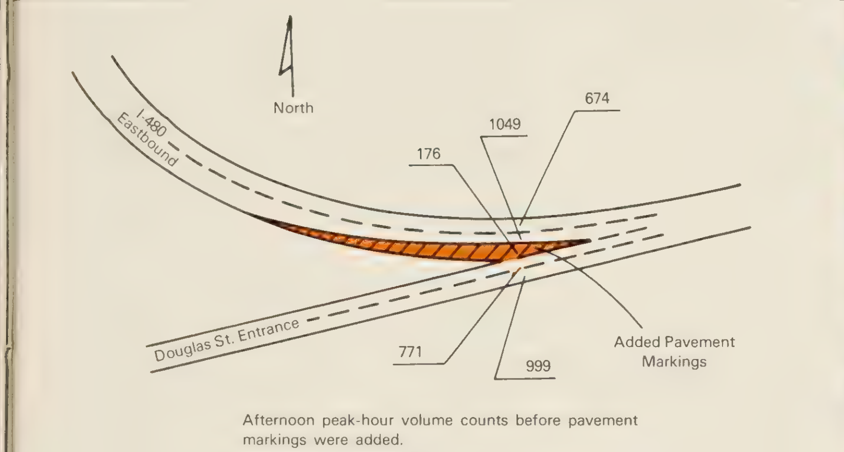
- Due to staged construction, the entrance ramp was required to carry all eastbound bridge traffic until completion of the upstream through lanes.
- The bridge is limited to four lanes in each direction.
- The elevation of the bottom and the length of the entrance ramp were dictated by the location of railroad tracks at Ninth Street at the beginning of the ramp. (See location photograph.)

Final design

- See location photograph.

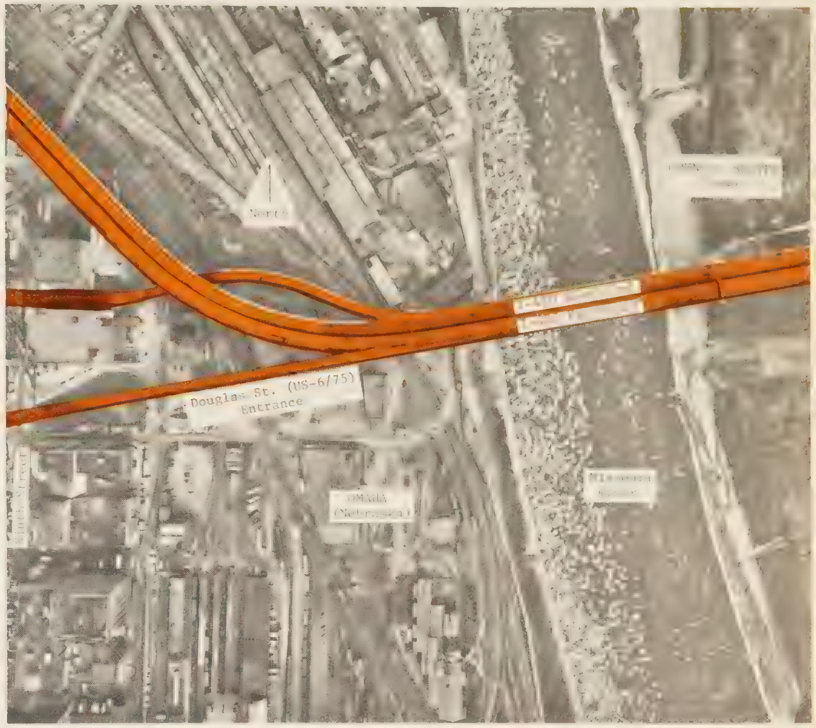


COLLISION DIAGRAM



VOLUME COUNTS AND CORRECTIVE MEASURES DIAGRAM

Figure 8.—Design experience fact sheet.



- The ramp is on a 6 percent upgrade and has two 15-foot (4.6 m) lanes.
- There are three through lanes prior to the merge and four lanes, total, after the merge.
- There are 3-foot (.9 m) solid parapets along both the elevated freeway and bridge.

Operational evaluation

- After the through lanes were opened, a merging problem was created by the limited sight distance—a result of the grade on the entrance ramp and the parapets on the roadways.
- The reduction in the number of lanes soon after the merge point added to the problem. Evaluation based mainly on public opinion and accident records. (The collision diagram shows the accidents definitely traced to the merging problem.)

Remedial action

- A lane-by-lane vehicle volume count was made to determine the actual traffic distribution. The results of this count are shown in the volume counts and corrective measures diagram.
- Based on this traffic data, pavement markings and signs were installed to discourage through I-480 traffic from using the lane nearest the entrance ramp. The pavement markings are shown in the volume counts and corrective measures diagram.

Evaluation after remedial action

- Not available at this time.

Lessons learned

- Lane drop. The lane drop very near the merge point was unsatisfactory. A decision on a second maneuver (lane change due to lane drop) was required immediately after completion of the first maneuver (merge), with virtually no time for information processing. Remedial action at this location included moving the lane drop which eliminated the merge situation.
- Grades, entrance ramp. The relatively steep grade (6 percent) was a major factor in the unsatisfactory operations. It added to the merge problem created by the restricted sight distance and sudden lane drop.
- Sight distance. Sight distance at the merge point was not sufficient. It was restricted by the use of parapets on the entrance ramp and elevated through roadway. This problem was compounded by the fairly steep (6 percent) grade on the entrance ramp.
- Entrance, two lane. The two-lane entrance ramp did not function adequately. It might have functioned better if the lane drop had been moved further downstream and the rear and forward sight distances had been longer.

findings of research studies are usually published and distributed through governmental or institutional channels, the design experiences of individual engineers are not often collected, organized, or made available to those who would find such material useful. The Fact Sheet provides a simple method of gathering, indexing, and publishing information which permits the freeway designer to compare and evaluate his design with designs used in similar situations. It includes a description of the local environment and traffic characteristics, special conditions to be observed, a description of the final design with an evaluation of the subsequent operations, the remedial actions initiated as a result of operational problems, and the lessons learned from the experience.

By way of illustration, a two-lane entrance ramp in Omaha, Nebr., was studied in depth to determine what information needed to be collected, analyzed, and presented to describe effectively the design and operational characteristics for a specific design situation. A sample Fact Sheet for this case study is included as figure 8.

Other research products

Additional information on the three example outputs and other outputs are available in the final report (*1*) and three interim reports (*5, 6, 7*) for the research summarized in this article. Copies of the final report, which pulls together the material from the three interim reports, can be obtained from the Federal Highway Administration, Traffic Systems Division, HRS-30, Washington, D.C. 20590.

The first interim report analyzes the design procedures employed by the several States in conjunction with the Federal Government and serves to identify the problem areas associated with those procedures. The second interim report contains condensed descriptions of three broad ranging highway design aids—models, checklists, and computer graphics—and a review of the design community's attitudes toward and utilization of these aids derived from two workshop sessions and a nationwide questionnaire survey. The third interim report contains novel interchange designs.

Future Efforts

Because of the importance of problems attacked within the research, emphasis will be given to providing summarized articles on future research outputs. For example, an article on how to apply decision theory techniques in the selection of major interchange design elements and configurations will be published in a future issue of *Public Roads*. It is believed that some decision theory techniques can be applied toward making better decisions in evaluating alternative interchange designs. The Bayesian Decision Theory developed in the Harvard Business School and covered in the final report will be summarized in the future *Public Roads* article. It will show how a designer can reduce the possibility of a wrong decision and enable him to explain the reasoning for his final choice.

The Implementation Division of the Federal Highway Administration (FHWA) will work with the FHWA operations offices in deciding what other actions and/or articles may be necessary to insure implementation of the many useful products originating from the research.

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(*4*) H. Hong, "Some Aspects of Interchange Design," *Traffic Engineering*, July 1966.

(*5*) R. Slavecki and J. Taylor, "Major Interchange Design, Operation and Traffic Control," Interim Report No. 3, "Innovative Designs Digest," *Pennsylvania State University*, 1973.

(*6*) J. Taylor, R. Slavecki, and R. Hostetter, "Major Interchange Design, Operation and Traffic Control," Interim Report No. 1, "Current Practices and Research Review," *Pennsylvania State University*, 1972.

(*7*) R. Slavecki and J. Taylor, "Major Interchange Design, Operation and Traffic Control," Interim Report No. 2, "Design Aids Digest," *Pennsylvania State University*, 1972.

Figure 1.—Modern Interstate rest area.

Rest Areas

by[1] Earl A. Disque

Introduction

The Federal-aid Highway Act of 1938 permitted the States to use Federal funds to provide sanitary and other facilities for the accommodation of the public. Since then more than 7,500 rest areas have been built on the various highway systems. Years ago a rest area was little more than a shoulder turnout with a picnic table and trash barrel under a shade tree. Today most Interstate rest areas are fully developed facilities that may include: Ample parking for all vehicle types; a toilet building with flush fixtures, lavatories, hand dryers, and drinking water; picnic shelters, tables, and benches; cooking grills or fireplaces; telephones; lighted, landscaped grounds; a water supply and sewage disposal system; and, frequently, an information center (fig. 1).

Design

Location and size

Most States have followed the recommendation of the American Association of State Highway and Transportation Officials (AASHTO) Guide[2] that rest areas be spaced at about one-half hour's driving time. In practice this means about 30 to 40 miles (48 to 64 km) apart. Usually a

[1]This article is a summary of "Rest Areas," an NCHRP Synthesis report prepared by Earl A. Disque which is available from the Highway Research Board, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

[2]"A Guide on Safety Rest Areas for the National System of Interstate and Defense Highways," *American Association of State Highway and Transportation Officials*, 1968.

Rest Area Research

Rest area research is an important part of the "Reduction of Environmental Hazards to Water Resources Due to the Highway System" project of the Federally Coordinated Program (FCP) of Research and Development in Highway Transportation. Under this project, the Federal Highway Administration, Office of Research, has an administrative contract with West Virginia University; "Establishment of Roadside Rest Area Water Supply, Water Carriage, and Solid Waste Disposal Requirements," which began in June 1971. The purpose of the study is to determine quantity requirements for roadside rest area water supply and waste treatment systems, and provide guidelines for improved and more efficient waste treatment and disposal methods.

Moreover, a three-phase Highway Planning and Research (HP&R) study conducted by Purdue University for the Indiana State Highway Department on "Treatment of Sanitary Wastes at Interstate Rest Areas" has been in progress since January 1971. The first phase dealt with development of design criteria for a biological treatment system that can be operated at low cost and will produce either a highly treated effluent or a recirculating system that would eliminate the need for any effluent discharge. The second phase provided an evaluation of the basic parameters involving costs, usage, and problems of existing systems. The third phase will evaluate two full-scale waste disposal systems for rest areas—one of the recirculating design and the other of non-recirculating design as developed in the first phase.

In early 1972, an HP&R study was initiated at the University of Illinois for the Illinois Department of Transportation on rest area waste water treatment and disposal. The purpose of the study is to analyze problems associated with the treatment of waste water from rest areas, develop a strategy for satisfying appropriate water quality standards, and investigate the practicality of developing a recycle system in rest areas with limited water supply.

The 1972 Federal Water Pollution Control Act (Public Law 92-500) requires upgrading of all rest area treatment facilities by 1977 to "best practicable technology." To meet the requirement, an FHWA administrative contract for "Sewage Treatment Methods to Meet the 1977 Requirement of the Federal Water Pollution Control Act" should be awarded soon and research into "Cost Effective Rest Area Components" will begin shortly.

pair of rest areas is built (one for each direction of travel), but a few have been built in widened medians or at an interchange so that one rest area serves both directions.

Important site selection factors, other than distance between sites, are availability of potable water, proximity to urban areas, sewage disposal, terrain, view, and cost of land. The size of a rest area is affected by these factors as well as by traffic volume and types of vehicles. Rest areas range in size from 2 to 200 acres (8,000 to 800,000 m^2) although most are between 10 and 40 acres (40,000 and 160,000 m^2).

Parking

Most highway agencies use the Federal Highway Administration (FHWA) formula[3] to determine the number of car and truck parking spaces. The formula may be modified by some agencies depending on local experience. Newer rest areas usually have separate areas for cars and trucks. The preferred arrangement is for truck parking behind the comfort station to facilitate police surveillance from the highway and so that truckers, as they leave the rest area, have departing rest area passenger car traffic on their left as they merge onto the exit ramp from the rest area.

Buildings

Buildings may have a simple exterior design (fig. 2) or one that reflects historic or traditional architectural treatment (fig. 3). Some interiors may have only restroom facilities, whereas others may also provide information services. And, of course, almost any variation or combination can be found. Some States use the

[3]FHWA Circular Memorandum, Aug. 15, 1969.

Figure 2.—Building with simple exterior design.

Figure 3.—Building with historical architectural treatment.

Figure 4.—Rest area with picnic tables, shelters, and cooking grills.

same architectural style throughout the State; others use several motifs to suit different regions of the State.

Materials and fixtures are functional, vandal-resistant, easy to operate, and inexpensive to repair or replace.

Convenience facilities

The convenience facilities found at rest areas—picnic tables, shelters, cooking grills, drinking fountains, etc. (fig. 4)—are usually designed to reflect and complement the overall architectural concept of the rest area. Public information services may be provided by maps, folders, and displays in building lobbies or at separate bulletin stands.

Water supply and sewage treatment

Because most rest areas are located in remote or rural areas, dependence has been placed on drilled wells for water. An adequate water supply should be verified before final site selection. Both quantity and quality are important. Storage tanks are frequently used to meet peak demands. Where available, use of a municipal water system is highly desirable. In all instances, the water supply system must comply with all Federal, State, and local regulations relevant to public health and safety.

Figure 5.—Disposal facility for recreational vehicle holding tank.

Figure 6.—Sidewalk ramp for use of handicapped.

The type of sewage treatment used depends on the soil; available land; proximity to a municipal system; and Federal, State, and local health regulations. At least 11 different systems are used, including chemical vault holding tanks, municipal sewage disposal systems, natural drainage to adjacent public lands, oxidation ditches, package aerobic or aeration plants, septic tanks, and stabilization ponds or lagoons.

Several States provide disposal facilities for recreational vehicle holding tanks (fig. 5). These are connected to the rest area sewage disposal system.

Power and communications

Electricity is usually provided by a public utility, although remote rest areas may have an onsite generator. Pay telephones are usually provided for the use of the public and some States provide the custodian with a two-way radio.

Handicapped persons

Rest areas are now being designed to accommodate the handicapped. The designs include ramps to sidewalks and buildings (fig. 6), wide doors, wide toilet stalls with grab bars, and reserved parking spaces close to buildings. These features are being added to many older rest areas.

Design guides and costs

Guidelines used in the design of rest areas have been promulgated by AASHTO and FHWA. Site plans generally are developed by highway agency personnel. However, buildings are usually designed by consultants. Sometimes a standard building will be designed that can be adapted to several sites by the highway agency. Costs of buildings vary depending on size, location, materials, type of fixtures used, climate (heating and air conditioning), etc. It is important to recognize that a building with a higher first cost may be more resistant to wear and vandalism and may require less maintenance.

Operation

A properly designed rest area should operate in a safe manner with a minimum of supervision. This means that pavements have proper sight distances and turning radii, walks and paths have easy grades and adequate width, sufficient lighting is provided inside and out, signs are located as needed, etc.

At most rest areas, vandalism is not considered to be a major problem. Mirror and fixture damage along with the usual written, scratched, and carved bits of literary offerings are the most common problems.

Personnel

A custodian is usually assigned to operate one rest area or, sometimes, a pair of rest areas. Previous training or experience is generally not required and training is on-the-job. Many States require custodians to wear a uniform that is consistent in style and color throughout the State. A few States provide living accommodations for the custodian at remote rest areas.

The daily work routine of the custodian includes cleaning, mopping, and polishing of building interiors, and resupplying towels, toilet tissue, and soap. He is responsible for picking up waste material from picnic areas, walks, and roadways, and he may also be required to operate irrigation systems and lighting if these are not automated.

Although most rest areas are open 24 hours a day, they are usually manned for only 8 hours. In a few States, rest areas are manned 16 or 24 hours per day and there seems to be a growing trend to 24 hours, especially at high traffic locations.

Utilities

Utility systems usually require little operational attention, as they are highly automated. In some States, law requires that a waste water disposal system be operated and maintained by a licensed operator; periodic training courses are conducted by State agencies.

Trash removal

Most States now use some form of landfill disposal system, usually a city or county refuse disposal area. Although some States still use incinerators, others have found them to be difficult to operate, expensive to maintain, and sources of odors and pollution.

Maintenance

Operation and maintenance activities and requirements for rest areas are interrelated and interdependent. Most often both functions are performed by the same person or crew. The maintenance tasks include replacement of window glass or screens, touchup painting, repair or replacement of fixtures, and routine maintenance of picnic tables, shelters, and trash collectors. Major work that requires the service of electricians, plumbers, carpenters, or other skilled tradesmen may be requested as needed from the highway agency or hired under contract.

In some States, the maintenance of grounds is being performed under an agreement with a nonprofit organization known as Green Thumb, Inc. This is an organization sponsoring the employment of older, retired farmers, gardeners, nurserymen, or handymen who are looking for occasional employment to supplement low retirement incomes.

Conclusions

Rest areas on Interstate and other limited-access highways are serving travelers' needs and are considered to be an integral element of a modern highway facility. There is general acceptance of the 30 to 40 mile (48 to 64 km) spacing for rest areas, although there are variations. Most agencies attempt to locate rest areas in attactive surroundings, often with an eye-appealing view. Each proposed site should be investigated to determine that there is an adequate water supply and that a satisfactory sewage disposal system can be installed.

The size of parking areas, buildings, water supply, and sewage system are dependent on: Total volume of traffic on highway; percent of traffic stopping at rest area; mix of cars, trucks, and recreational vehicles; number of persons per vehicle; average length of stop; amount of water used by each person; and other factors. Limited experience indicates that each stopping vehicle will contain about three people, stop from 20 to 30 minutes, and use from 3 to 5 gallons (11 to 19 l) of water per person.

It is desirable to have truck parking at the rear of the rest area to facilitate merging with other rest area traffic and to avoid blocking the view of the rest area by police from the roadway. Angle pullthrough parking is usually more desirable for trucks and recreation vehicles.

Recommendations

Although some research on rest areas is currently underway (States, universities, FHWA), additional needs exist. Specifically:

- There is an immediate need for information on the types of waste water systems that will meet water quality standards proposed for 1983.

- Up-to-date manuals and handbooks are needed for rest area design, operations, and maintenance. An example of an ongoing effort is the AASHTO maintenance manual which will have a section on rest areas. Other manuals include the "Water Supply and Waste Disposal Series" by the FHWA Office of Research and "Guidelines" prepared by the Hydraulics Branch of the FHWA Office of Engineering. Because a manual cannot be written that will apply throughout the country, each State will need to modify any manual to meet geographic, climatic, and other conditions.

- More data is needed concerning the numbers and types of vehicles that stop at rest areas (including numbers of persons per vehicle) in relation to total traffic, type of traffic, location of rest area, and other factors. The cooperation of highway agencies in providing data will be welcomed.

- Research is also recommended on the need to provide additional motorist services, such as food and drink, in rest areas. If the need is found to be significant, changes in State and Federal legislation may be required.

- Although there is a great deal of communication and coordination among the States, FHWA, AASHTO, and the Highway Research Board (HRB), there should be more communication between these organizations and others, such as the Environmental Protection Agency, State and local public health and environmental agencies, etc., whose responsibilities affect the design and operation of rest areas. There also should be an awareness of research being performed in the field of water and sewage treatment for housing and industry.

Review of Report of Noise Levels Associated with Plant Mix Seals

Report by L. B. Steere, Colorado Division of Highways
Review by R. E. Olsen

Introduction

The promotion and use of open graded plant mix seals—now referred to as *open graded asphalt friction course*—has been hindered, to a degree, by the belief among some highway engineers that traffic on this type of pavement surface may generate more noise than on conventional surfaces and thus be objectionable from the general public's point of view. In order to further encourage and promote the use of skid resistant open graded surfaces, it was necessary to determine the comparative noise levels generated by traffic on this and other types of pavement surfaces.

In the spring of 1973, a cooperative effort between the Federal Highway Administration and the Colorado Division of Highways, sponsored by the Offices of Research and Development, was initiated to investigate the relative levels of noise generated by a moving vehicle on various types of pavement surfaces. Colorado was chosen to make this investigation because of their experience in noise level measurement and because they were actively engaged in determining noise levels of various pavements and construction processes.

The results of this investigation are contained in a report by L. B. Steere, Colorado Division of Highways.[1]

[1] "Noise Levels Associated with Plant Mix Seals," by L. B. Steere, Colorado Division of Highways, prepared for the Federal Highway Administration, Offices of Research and Development, Report No. FHWA-RD-73-50—Final Report, May 1973. This report (Stock No. PB 224379) is available from the National Technical Information Service, Springfield, Va. 22151.

These results will be incorporated into a more comprehensive study presently being conducted for the Office of Development by FHWA Region 9 concerning the noise characteristics of open graded surfaces versus those of other surface types.

The scope of the study was limited to obtaining data on the comparative noise levels generated by a moving automobile on open graded asphalt friction courses and other conventional types of pavement surfaces. No attempt was made to investigate different types of vehicles, different locations of the decibel meter in the vehicle, different vehicle speeds, or the noise gradient at distances other than 25 feet (7.5 m) from the roadway. It was felt that the measurements made were sufficient to achieve the objective of the study.

Test Procedures

The vehicle used for the test series was a 1969 Ford station wagon[2] operated at 45 miles per hour (72 kmph). Three types of rear wheel tire conditions were used (fig. 1):

- New tires, Goodyear "Power Cushion" used approximately 4,000 miles (6,400 km), and showing a minimum of 5/16 inch (.8 cm) of tread.
- Old tires, Goodyear "Power Cushion" used approximately 16,000 miles (25,600 km), and showing less than 1/8 inch (.31 cm) of tread.

[2] The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

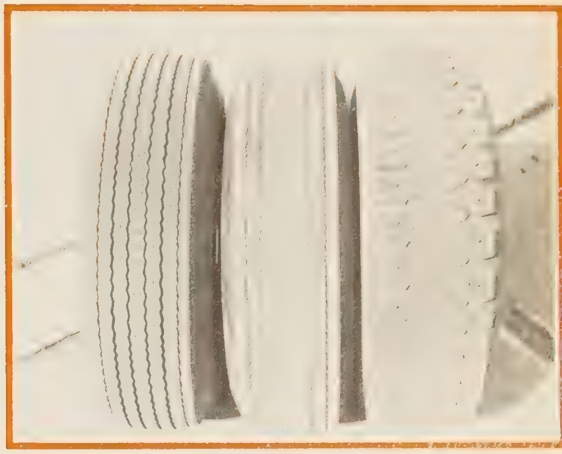

Figure 1.

- Snow tires, unstudded Goodyear "Suburbanite" used approximately 10,000 miles (16,000 km), and showing a minimum of 5/16 inch (.8 cm) of tread.

Fifteen pavements were selected for investigation:

- Type "A" open graded asphalt friction course—100 percent pass 3/8 sieve, 14 percent pass No. 8 sieve (three sites).
- Type "B" open graded asphalt friction course—100 percent pass 3/8 sieve, 34 percent pass No. 8 sieve (four sites).
- Dense graded bituminous concrete, both new and old pavements—new (three sites) and old (three sites).
- Portland cement concrete, both new and old pavements—new (one site) and old (one site).

Figure 2.

Noise levels were obtained at two locations:

- From the passenger viewpoint: The decibel meter (fig. 2)[3] was placed on the right side of the back seat of the vehicle. This position minimized noise pickup from the engine compartment and the other three wheels and wind noise from the window areas. It was determined that the vehicle, when jacked up from the pavement and operated with a speedometer reading of 45 mph (72 kmph), produced 58 decibels inside and 64 decibels 25 feet (7.5 m) from the vehicle.

- From the pedestrian viewpoint: The meter was located 4 1/2 feet (1.35 m) above the pavement surface and 25 feet (7.5 m) from the nearest test vehicle wheel path.

Multiple runs were made at 45 miles per hour (72 kmph) on each test surface and each test condition until repeatability within 1/2 decibel was attained. Readings in heavy traffic areas were made during the early morning hours to minimize other vehicular and background noise. No readings were made when the steady wind velocity exceeded 5 miles per hour (8 kmph). All of the test sites were considered to be essentially the same in configuration.

Texture measurements were made with a 15-probe Texas Probe Meter. There appears to be poor correlation of texture, as measured by this means and the noise levels measured during this test program. This cannot imply, however, that pavement texture as measured by other means is not related to noise generated by a moving vehicle.

Discussion

The data collected during the course of this investigation indicate that the type of tire mounted on the test vehicle was not a critical factor in making comparative noise measurements as related to the type of pavement surface. With a few exceptions, the snow tires were 4 to 6 decibel numbers higher than the new and old regular tread tires, and the new tires were generally 1 to 2 decibel numbers lower than the old regular tire. This was true for noise measurements taken from the passenger's point of view, as well as from the pedestrians' point of view.

There was no great difference in the noise levels of the various pavements when measured from inside the moving vehicle. With the new regular tires, the readings varied from 70 dB(A) for the type "A" open graded mixture to 73.5 dB(A) for an old dense graded bituminous concrete. This indicates that the background noise inside the vehicle has a great influence on the noise level experienced by a passenger, and that the type of pavement the vehicle is riding on has a lesser influence. However, from the pedestrian's point of view, the same tire series produced noise levels varying from 71.75 dB(A) on the type "A" open graded mixture as compared to 80.5 dB(A) on an old dense graded bituminous concrete.

The type "A" open graded mixture showed an average of 72.9 decibels when measured 25 feet (7.5 m) from the vehicle equipped with new regular tread tires. This is 4.7 decibels lower than the average of the other pavements tested. When the test vehicle was equipped with old regular tires the difference was 4.9 decibels, and when equipped with the snow tires, the difference was 4.1 decibels. These are significant differences in noise level when considering that a difference of about 10 decibels in this range means that the loudness, as experienced by a listener, is doubled.

During the test program, it was noted that differences in the noise tone and sound frequency inside the vehicle were quite noticeable between the various types of pavements, and these variances in tone may impress the passenger even though the change in decibel readings might be insignificant. This factor will be further analyzed in a follow-on study presently being conducted by the FHWA Region 9 personnel in San Francisco for the Office of Development. This study will also determine noise contours or profiles up to 250 feet from the roadway.

The results of the Colorado study show conclusively that, under the conditions of this test program, the open graded asphalt friction course is less noisy than other types of pavement surfaces from a pedestrian's point of view up to 25 feet (7.5 m) from the vehicle and not noisier from a passenger's point of view. This is in agreement with and confirms the general impression of those agencies using the open graded asphalt friction courses, that these surfaces do not generate objectionable noise.

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[3]Decibel readings, dB(A), were made using a Sound Level Meter, Model 2010, procured from Electra-Sonic Control Automation Engineering, Monteca, Calif.

Our Authors

Anthony Leone, prior to his retirement from the Federal Highway Administration in June 1973, was Chief of the Bridge Division in Region 6, Fort Worth, Tex. He was field coordinator for the FHWA administrative research contract "Highway Bridge Inspection Devices." From 1948 to 1961 Mr. Leone was Division Bridge Engineer in Little Rock, Ark., and from 1946 to 1948 he was Division Bridge Engineer in Pierre, S. Dak.

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David Solomon has been the Chief of the Environmental Design and Control Division, Federal Highway Administration, since March 1973. His career in research and development spans 2 decades. Mr. Solomon's research papers cover many aspects of traffic operations and safety.

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R. E. Olsen, Highway Engineer in the Implementation Division, Office of Development, FHWA, monitors a wide variety of research studies and development programs in the bituminous field and is involved in the use of waste materials for highway construction. He is experienced in the research and development areas of materials, design, and construction of bituminous pavements.

Implementation/ User Packages "how-to-do-it"

The principal tool for implementing research and development is the implementation/user package which provides "how-to-do-it" information to the potential user. The package converts research findings into practical tools. The packaging requirement is accomplished between the identification and promotion stages of implementation.

The following items are brief descriptions of selected packages which are actively being developed, or have been recently completed, by State and Federal highway units in cooperation with the Implementation Division, Offices of Research and Development, Federal Highway Administration (FHWA). All completed packages will be placed in the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Va. 22151.

Packages Completed

Concrete Structure Surface Coatings

by Nevada Department of Highways

Painting of concrete structures in lieu of hand rubbing has been implemented by several States. A

user package has been prepared by Nevada describing their experience and includes construction details, materials or paint used, cost, and recommended specifications. This method is more esthetically pleasing than hand rubbing and is relatively maintenance free.

Vegetation and Erosion Control Under Guide Rails and Median Barriers

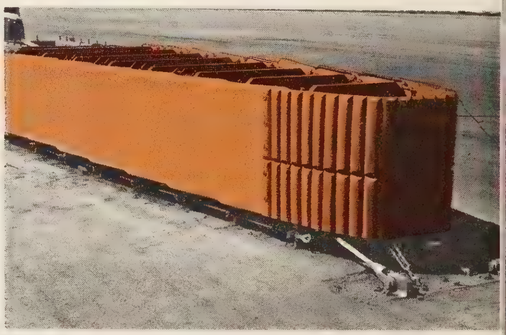
by Connecticut Department of Transportation

A combination of Bunker "L" oil and a soil sterilant have proven effective in eliminating vegetation and controlling erosion under Connecticut guide rails for 3 to 4 years. This eliminates expensive and hazardous hand mowing and provides erosion control which cannot be realized by use of soil sterilant alone. The implementation package includes illustrations, mixing and placement methods, costs, and some of the State's experience.

Hi-Dri Cell Crash Cushion

by FHWA Implementation Division

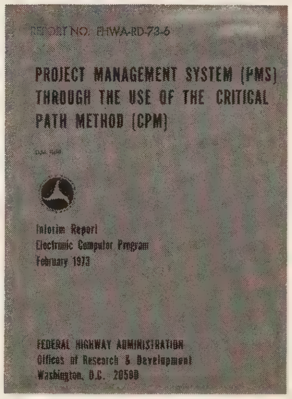
A design manual concerning the design, installation, and maintenance aspects of the Hi-Dri Cell Crash Cushion has been developed. This manual shows how the crash cushion, developed by the Energy Absorption Systems, Inc., can be designed for a variety of roadside hazards. The crash cushion concept has been approved as an alternate design for serviceable hardware on the Federal-aid Highway System.



Project Management System Utilizing the Critical Path Method

by FHWA Implementation Division

An extremely useful computer program for scheduling emergency



REPORT NO. FHWA-RD-73-6

PROJECT MANAGEMENT SYSTEM (PMS) THROUGH THE USE OF THE CRITICAL PATH METHOD (CPM)

Interim Report
Electronic Computer Program
February 1973

FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D.C. 20590

relief projects that must be put into service in a minimum time has been documented for implementation. The system was successfully used in Pennsylvania in scheduling construction to replace a bridge destroyed by hurricane Agnes. The refined user manual for the system combines methods of networking, critical path computations, and project management techniques (NTIS PB 222009).

Open Graded Bituminous Mixtures for Pavements

by FHWA Region 10, Portland, Oreg.

For several years the U.S. Forest Service has successfully used open graded emulsified asphalt mixtures for pavement construction. These open graded mixes have been low in cost and have demonstrated good stability and internal drainage qualities. The implementation package includes background and experience, construction features, cost data, and guide specifications. The Forest Service cold mix procedure outlined in the report is relatively pollution free.

Computerized Bridge Rating System

by Wyoming Highway Department

This package explains the use of the developed computer software system which analyzes and rates highway bridges. The rating system has been developed specifically to assist State highway organizations in accomplishing the structural rating requirements of the national bridge inspection standards. The package can serve two separate needs—as an operational manual for automatic data processing specialists and as a user manual for bridge engineers and technicians. Distribution of the package has been made to the States and FHWA field offices.

Packages in Preparation

Aerial Drainage Survey Computer Program

by Wyoming State Highway Department

In recognition of the need for timely and economic methods to determine hydraulic design parameters, the Wyoming State Highway Department is developing a procedure for extracting hydrologic and hydraulic data from aerial photographs in stereoscopic pairs using the latest photogrammetric techniques. The procedure will include computer analysis techniques to be used by highway design engineers. The State's effort will result in an implementation/user package which includes a user manual.

Use of Rubber Snowplow Blades

by Washington Department of Highways

The Washington Department of Highways' Maintenance Division has used rubber snowplow blades for over 4 years in the western portion of the State. Based on this experience and the results of field tests now being conducted in areas east of the Cascades, the State will prepare a package on the use of this equipment under varying snow and ice conditions.

Urban Traffic Control/Bus Priority Systems (UTCS/BPS) Hardware Specifications

by FHWA Implementation Division

During the UTCS/BPS systems development in Washington, D.C., a set of procurement specifications was prepared for all hardware components. A restructured version of these specifications is now in preparation which updates the contents and deletes that which is specific only to Washington, D.C.

The document is intended to serve as a guide to cities in developing their own specifications for a system of this type.

Urban Traffic Control/Bus Priority Systems (UTCS/BPS) Brochure

by FHWA Traffic Systems and Implementation Divisions

In many cities, highway agencies are currently planning for or installing digital computer controlled traffic signal systems. In order to familiarize these agencies with FHWA technology and research in this area, a multicolor brochure is in preparation which describes the FHWA's Washington, D.C. systems, research activities, and implementation aspects.

Prestressed Concrete Panels for Highway Bridge Decking
by Texas Highway Department

Computerized Roadway Design System
by Texas Highway Department

Slotted Underdrains for Pavement System Drainage
by FHWA Region 8, Denver, Colo.

Texas Crash Cushions
by Texas Highway Department and FHWA Region 6, Fort Worth, Tex.

Breakaway Barricades
by Nevada Department of Highways

Encapsulated Subgrades
by U.S. Army Corps of Engineers

Culvert Outlet Protection Program
by Wyoming State Highway Department

New Publications

Standard Plans for Highway Bridges—Volume IVA, Typical Continuous Bridges (Load Factor Design) is a useful guide for State, county, and local highway departments in developing suitable and economical bridge designs for primary, secondary, and urban highways. The plans will be particularly valuable to smaller highway departments with limited engineering staffs.

Volume IVA, based on load factor design, supplements volume IV (1969), based on working stress. Since both contain the same bridge types and geometry, they illustrate the possible effects of AASHTO's 1973 Load Factor Specifications on bridge design.

This is the sixth FHWA publication in a series of Standard Plans for Highway Bridges which are informational only and are not intended to indicate a preference for bridge types or spans.

Typical Continuous Bridges (Load Factor Design), June 1973, is available for $1.40 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (Stock Number 5001-00055).

Selecting Digital Computer Signal Systems provides administrative decisionmaking criteria with which advanced traffic-signal systems may be selected. The criteria can be used to evaluate each element of a complete signal system, including geographical control areas, control techniques, surveillance systems, intersection equipment, communication systems, and data-processing equipment. This report provides a good introduction for the practicing traffic engineer with regard to computer traffic signal system capabilities and costs, and it makes comparative evaluations of digital computer traffic signal systems with fixed-time and analog systems.

This is one of a number of reports being published by the Offices of Research and Development of the FHWA to put research results into engineering practice.

The report is available for $1.05 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (Stock Number 5001-00057).

New Research in Progress

The following items identify new research studies that have been reported by FHWA's Offices of Research and Development. These studies are sponsored in whole or in part with Federal highway funds. For further details, please contact the following: Staff and Contract Research—Editor; Highway Planning and Research (HP&R Research)—Performing State Highway Department; National Cooperative Highway Research Program (NCHRP)—Program Director, National Cooperative Highway Research Program, Highway Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

FCP Category 1—Improved Highway Design and Operation for Safety

FCP Project 1G: Safer Traffic Guardrails and Bridge Railings

Title: Traffic Barrier Performance and Design. (FCP No. 51G1122)
Objective: Investigate modifications to BCT terminal design for cost reduction and increased performance. Verify modification effectiveness by crash test. Develop test criteria and procedures for traffic barrier systems.
Performing Organization: Southwest Research Institute, San Antonio, Tex. 78284
Expected Completion Date: October 1974
Estimated Cost: $80,000 (NCHRP)

FCP Project 1H: Skid Accident Reduction

Title: An Investigation of the Durability of the Skid Resistance of Wire Combed PCC Pavement Surfaces. (FCP No. 41H1274)
Objective: Determine friction wear factors, using the Missouri skid trailer, for a number of portland cement concrete pavements constructed to have improved skid resistance.
Performing Organization: Missouri State Highway Commission, Jefferson City, Mo. 65101
Expected Completion Date: December 1977
Estimated Cost: $97,000 (HP&R)

Title: An Investigation of Skid Resistant Asphaltic Mix Designs. (FCP No. 41H1284)
Objective: Determine friction wear factors for a number of flexible pavement surface mixes designed to have improved resistance to skidding as determined with the Missouri skid trailer.
Performing Organization: Missouri State Highway Commission, Jefferson City, Mo. 65101
Expected Completion Date: December 1977
Estimated Cost: $112,000 (HP&R)

Title: Friction in Cornering and Braking, Steady State and Transient. (FCP No. 21H2243)
Objective: Show whether there are correlations between tire-pavement friction measured in steady state and transient modes, in cornering and braking. Determine the mode of friction testing which best correlates with friction demands of automobiles in cornering and braking.
Performing Organization: Federal Highway Administration, Washington, D.C. 20590
Expected Completion Date: September 1976
Estimated Cost: $96,000 (FHWA Staff Research)

Title: Accident Rates and Surface Properties—An Investigation of Relationships. (FCP No. 41H5204)
Objective: Evaluate the relationship between surface skid resistance and accident rate in the context of different traffic and road conditions by developing a method for measuring contributing non-surface variables.
Performing Organization: Michigan State Highway Commission, Lansing, Mich. 48904
Expected Completion Date: October 1975
Estimated Cost: $52,000 (HP&R)

FCP Project 1J: Improved Geometric Design

Title: Safety Evaluation of Highway Cross-Section Design Criteria. (FCP No. 31J1082)
Objective: Determine the traversability of highway cross-section slopes for run-off-the-road situations by the use of computer simulation analyses. Simulation testing of selected combinations of slopes, rounding, and drainage features to permit preparation of comprehensive summary of the effectiveness for safely reducing the severity of vehicle impacts.
Performing Organization: Calspan Corporation, Buffalo, N.Y. 14221
Expected Completion Date: November 1974
Estimated Cost: $116,000 (FHWA Administrative Contract)

FCP Category 3—Environmental Considerations in Highway Design, Location, Construction, and Operation

FCP Project 3E: Reduction of Environmental Hazards to Water Resources Due to the Highway System

Title: Acid and Iron Pollution Abatement (FCP No. 43E2062)
Objective: Demonstrate that acid and iron pollution resulting from oxidation of pyrite, exposed as a result of highway construction, can be abated with the application of limestone to the surface of the pyrites and the establishment of a permanent plant cover.
Performing Organization: Penn State University, University Park, Pa. 16802
Funding Agency: Pennsylvania Department of Transportation
Expected Completion Date: October 1976
Estimated Cost: $105,000 (HP&R)

Title: Water Pollution Aspects of Particles Which Collect on Highway Surfaces. (FCP No. 43E2072)
Objective: Determine the physical, chemical, and biological nature of constituents of highway surface runoff.
Performing Organization: California Department of Transportation, Sacramento, Calif. 95807
Expected Completion Date: December 1978
Estimated Cost: $58,000 (HP&R)

FCP Project 3F: Pollution Reduction and Visual Enhancement

Title: Natural Environmental Hazards and Their Relationships to Planning, Location, and Design of Transportation Facilities. (FCP No. 43F1582)
Objective: Develop methods for evaluations of impacts of highways on natural factors and natural factors on highways; develop a means of broadly mapping such relationships; and develop a means of conveying useful information for system, corridor, and location and design study stages. Natural factors include tides, floods, snows, subsidence, wind, fog, frost, erosion, and Earth movements and Earth heat.
Performing Organization: California Department of Transportation, Sacramento, Calif. 95814
Expected Completion Date: March 1977
Estimated Cost: $100,000 (HP&R)

Title: Analysis, Experimental Studies, and Evaluation of Control Measures for Air Flows and Quality Near Highways. (FCP No. 33F3082)
Objective: Development of principles and guidelines for management of highway vehicles' air contaminants on and near highways by analyses and measurement of air flows as affected by traffic conditions and roadway geometry.
Performing Organization: Stanford Research Institute, Menlo Park, Calif. 94025
Expected Completion Date: June 1976
Estimated Cost: $395,000 (FHWA Administrative Contract)

Title: Field Validation of Air Quality Diffusion Modeling Techniques for Predicting the Environmental Impact of Motor Vehicle Transportation. (FCP No. 43F3092)
Objective: Review air quality diffusion models and select two or three for tests on highway sites. Compare air quality measurements made for various wind conditions and high traffic volumes with models. Adjust models.
Performing Organization: University of Washington, Seattle, Wash. 98195
Funding Agency: Washington State Highway Commission
Expected Completion Date: October 1975
Estimated Cost: $87,000 (HP&R)

FCP Category 4—Improved Materials Utilization and Durability

FCP Project 4A: Minimize Early Deterioration of Bituminous Concrete

Title: An Investigation of the Effectiveness of Asphalt Durability. (FCP No. 44A1253)
Objective: Study the ability of various laboratory tests to measure asphalt durability and to determine if a useful critical void content range can be ascertained which can be related to various pavement environments and to asphalt durability.
Performing Organization: California Department of Transportation, Sacramento, Calif. 95807
Expected Completion Date: June 1978
Estimated Cost: $157,000 (HP&R)

FCP Project 4B: Eliminate Premature Deterioration of Portland Cement Concrete

Title: Epoxy Resin Coated Reinforcing Steel. (FCP No. 44B1314)
Objective: Epoxy coated rebars will be evaluated, over a 10- to 14-year period, by embedding in laboratory concrete and by using in bridge decks.
Performing Organization: Michigan Department of State Highways, Lansing, Mich. 48904
Expected Completion Date: June 1989
Estimated Cost: $159,000 (HP&R)

Title: Investigation of Concrete Polymer Materials. (FCP No. 44B2113)
Objective: Develop a field technique for impregnation and polymerization of a monomer in the hardened surface of portland cement concrete. An evaluation will be made as to the extent that deteriorated concrete can be rehabilitated by the treatment.
Performing Organization: California Department of Transportation, Sacramento, Calif. 95814
Expected Completion Date: June 1976
Estimated Cost: $121,000 (HP&R)

FCP Project 4F: Develop More Significant and Rapid Test Procedures for Quality Assurance

Title: A Study of Nuclear and Vacuum Extractor Procedures for Determining Asphalt Content in Asphalt Concrete. (FCP No. 44F2014)
Objective: Determine, by laboratory and field evaluation, if the Troxler Nuclear Asphalt Content Gage, Model 2226, and/or the Vacuum Extractor can be used to precisely and rapidly determine asphalt content in asphalt concrete and the preferred or recommended procedure to use, based upon performance and cost.
Performing Organization: California Department of Transportation, Sacramento, Calif. 95807
Expected Completion Date: June 1975
Estimated Cost: $78,000 (HP&R)

FCP Category 5—Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

FCP Project 5C: New Methodology for Flexible Pavement Design

Title Louisiana Experimental Base Project (FCP No. 45C3204)
Objective: Ascertain the accuracy of predictions concerning the performance and serviceability of flexible pavements by using Louisiana's current AASHTO design guide and obtain fundamental materials properties for making rational predictions of the pavements' performance.
Performing Organization: Louisiana Department of Highways, Baton Rouge, La. 70804
Expected Completion Date: July 1976
Estimated Cost: $232,000 (HP&R)

FCP Project 5F: Bridge Safety Inspection

Title: Traffic Warrants for Premium Pavement Requiring Reduced Maintenance. (FCP No. 35F1012)
Objective: Determine the range of dollar justification for premium pavements based on reduction of highway maintenance cost, motor vehicle operating costs, and time delays of traffic.
Performing Organization: Wilbur Smith & Associates, Columbia, S.C. 29202
Expected Completion Date: September 1974
Estimated Cost: $92,000 (FHWA Administrative Contract)

Title: Strength and Behavior of Anchor Bolts. (FCP No. 45F3042)
Objective: Make a survey and classify currently used anchor bolt materials; determine the concrete cover and embedment lengths required to develop specified stress levels in bolts; evaluate the performance of anchor bolts with end anchorage devices.
Performing Organization: University of Texas, Austin, Tex. 78712
Funding Agency: Texas Department of Transportation
Expected Completion Date: August 1975
Estimated Cost: $80,000 (HP&R)

Title: Probability Theory for Highway Bridge Fatigue Stresses (Phase II) (FCP No. 45F4012)
Objective: A previously developed fatigue prediction model for highway bridges will be updated using the latest field and laboratory information. Application will be made to simple and continuous spans.
Performing Organization: Case Western Reserve University, Cleveland, Ohio 44106
Funding Agency: Ohio Department of Transportation
Expected Completion Date: September 1975
Estimated Cost: $66,000 (HP&R)

Title: Column Moments Due to Superstructure Shortening (FCP No. 45F5022)
Objective: Determine moments and stresses in columns resulting from superstructure shortening caused by post-tensioning, shrinkage, creep, and temperature changes.
Performing Organization: California Department of Transportation, Sacramento, Calif. 95814
Expected Completion Date: June 1979
Estimated Cost: $355,000 (HP&R)

FCP Project 5I: Improved Structural Design and Construction Techniques for Culverts

Title: Rigid Pipe Proof Testing. (FCP No. 45I2172)
Objective: Develop field test data to permit revision of current allowable overfill tables on rigid pipe culverts.
Performing Organization: California Department of Transportation, Sacramento, Calif. 95814
Expected Completion Date: October 1977
Estimated Cost: $561,000 (HP&R)

FCP Category 6—Development and Implementation of Research

FCP Project 6Z: Implementation of Research Projects

Title: Implementation of Research. (FCP No. 46Z1703)
Objective: Special efforts to insure that the results of research and development projects are brought into operating practice.
Performing Organization: Kansas State Highway Commission, Topeka, Kans. 66612
Expected Completion Date: December 1974
Estimated Cost: $60,000 (HP&R)

Title Implementation of Research (FCP No. 46Z1713)
Objective: Special efforts to insure that the results of research and development projects are brought into operating practice.
Performing Organization: California Department of Transportation, Sacramento, Calif. 95814
Expected Completion Date: December 1974
Estimated Cost: $70,000 (HP&R)

Title Implementation of Research (FCP No. 46Z1723)
Objective: Special efforts to insure that the results of research and development projects are brought into operating practice.
Performing Organization: Washington Department of Highways, Olympia, Wash. 98501
Expected Completion Date: December 1974
Estimated Cost: $113,000 (HP&R)

Non-FCP Category 0—Other New Studies

Title: Development of a Standardized Short Span Bridge System (FCP No. 40S1512)
Objective: Develop one or more standardized systems for constructing short span bridges to replace numerous badly deteriorated bridges in the State.
Performing Organization: West Virginia University, Morgantown, W. Va. 26506
Funding Agency: West Virginia Department of Highways
Expected Completion Date: June 1975
Estimated Cost: $96,000 (HP&R)

Title: Evaluation of Soil Properties for Arkansas Bridge Foundations (FCP No. 40S3262)
Objective: Review recent advancements in bridge site investigations, laboratory tests, and methods for analysis and design of bridge foundations; develop recommendations for practices most suited to Arkansas conditions.
Performing Organization: University of Arkansas, Fayetteville, Ark. 72701
Funding Agency: Arkansas State Highway Department
Expected Completion Date: September 1976
Estimated Cost: $133,000 (HP&R)

Highway Research and Development Reports Available from National Technical Information Service

The following highway research and development reports are for sale by the National Technical Information Service, Sills Building, 5285 Port Royal Road, Springfield, Va. 22151.

Other highway research and development reports available from the National Technical Information Service will be announced in future issues.

STRUCTURES

Stock No.

PB 222997 Cut-and-Cover Tunneling Techniques.
Vol. I—A Study of the State-of-the-Art.
PB 222998 Vol. II—Appendix.
PB 223104 Compacted Cohesive Test Embankment—Design Installation and Operation of Field Instrumentation.
PB 223120 Model Studies of Skew Box Girder Bridges.
PB 223404 Bridge Deck Deterioration—A Summary of Reports.
PB 223407 Stress History of Highway Bridges—Final Report.
PB 223636 Evaluation and Revision of Texas Highway Department Rigid Pavement Design Procedure.
PB 223695 Measuring Pavement Roughness Spectra Using the Modified BPR Roughometer with Additional Refinements.
PB 223796 Measurement of Mechanical Stresses Using Piezoelectric Crystals.
PB 223932 Recent Experimental PCC Pavements in California.
PB 224192 A Correlation Study of the Mays Road Meter with the Surface Dynamics Profilometer.
PB 224877 Aeroelastic Stability of Long-Span Bridges.
PB 224894 Evaluation of Pavement Serviceability.
PB 224902 Prestress Losses in Pretensioned Concrete Structural Members.
PB 224913 Probability Theory for Highway Bridge Fatigue Stresses.
PB 224914 Estimating the Frequency of Multiple Truck Loadings on Bridges.
PB 224916 The Behavior of Statistically Heterogeneous Excavated Earth Slopes.
PB 224922 Prestressed Concrete Highway Pavement at Dulles International Airport—Research Progress Report to 100 Days.
PB 224924 A Loading History Study of Selected Highway Bridges in Louisiana.
PB 224974 Investigation of Soil-Structure Interaction—Flexible Culvert Pipes.
PB 224976 The Behavior of Axially Loaded Drilled Shafts in Sand.
PB 224979 A Survey of Earth Slope Failures and Remedial Measures in Texas.
PB 224998 Thick-Walled Rings for Energy-Absorbing Bridge Rail Systems.
PB 224999 Corrugated Metal Arch Barrier. Phase I—Scale Model Study.
PB 225072 The Optimization of a Flexible Pavement System Using Linear Elasticity.
PB 225427 Benefit Analysis for Pavement Design Systems.

MATERIALS

Stock No.

PB 222652 Stabilization Procedures for Puerto Rico Low-Grade Soils.
PB 223390 An Investigation of Concrete Quality Evaluation Methods.
PB 223391 Evaluation of Shrinkage Compensated Cement—Final Report.
PB 223409 Polymer-Impregnated Concrete for Highway Applications.
PB 223946 Soil Shear Strength.
PB 224532 Feasibility of Using Highway Litter in Highway Construction and Maintenance—Final Report.
PB 224605 A Radioisotope Backscatter Gage for Measuring the Cement Content of Plastic Concrete.
PB 224655 Time-to-Corrosion of Reinforcing Steel in Concrete Slabs.
Vol. I—Effect of Mix Design and Construction Parameters.
PB 224685 Summary Report on the Feasibility of Using Highway Litter in Highway Construction and Maintenance.
PB 224835 Linseed Oil Retreatments to Control Surface Deterioration of Concrete Bridge Decks.

PB 224934 Development of a New Low-Profile Highway Striping for Wet-Night Visibility. Phase II—Road Tests.
PB 224954 Shallow Seismic Techniques—Final Report.
PB 224962 The Remote Identification of Terrain Features and Materials at Kansas Test Sites—An Investigative Study of Techniques.

TRAFFIC

Stock No.
PB 223408 Meaning and Application of Color and Arrow Indications for Traffic Signals.
PB 224084 TRANSYT Method for Area Traffic Control.
PB 224085 Program Source Tape.
PB 224102 Evaluation of the Datamate Model D-16 as a Traffic Controller.
PB 224103 Study of Traffic Responsive Ramp Closure Control.
PB 224157 Diamond Interchange Traffic Control.
User's Guide for Computerized Traffic Control Program.
PB 224158 Program Manual for Microscopic Simulation Model of Diamond Interchange Traffic Operations.
PB 224159 Interface Unit.
PB 224160 Test and Evaluation of Computerized Traffic Control System.
PB 224161 Functional Specifications for a Diamond Interchange Signal Controller.
PB 224162 An Analysis of Diamond Interchange Signalization.
PB 224163 Development and Evaluation of Real-Time Control Algorithms.
PB 224164 A Comparison of Signal Control Strategies on a Digital Computer Simulation Model.
PB 224165 Summary Report on Control and Geometric Design of Diamond Interchanges.
PB 225022 Design Manual for Computerized Traffic Control System.
PB 225044 Arterial Progression Control as Developed on the Mockingbird Pilot Study.

ENVIRONMENT

Stock No.
PB 223708 Establishment and Management of Roadside Vegetation, 1971.
PB 223937 Comparisons of Full-Scale Embankment Tests with Computer Simulations.
Vol. I—Test Results and Comparisons.
PB 224091 A Statistical Summary of the Cause and Cost of Bridge Failures.
PB 224304 Roadway Illumination Systems.
PB 224469 Evaluation of Woody Plants and Development of Establishment Procedures for Direct Seeding and/or Vegetative Reproduction.
PB 224470 Computation of Uniform and Nonuniform Flow in Prismatic Conduits.
PB 225178 Assessment of Target Visibility in a Scale-Model Simulator Under Different Layouts of Conventional Fixed Lighting.

IMPLEMENTATION

Stock No.
PB 223583 A Study of Accident Investigation Sites on the Gulf Freeway.
PB 224379 Noise Levels Associated with Plant Mix Seals.
PB 224407 Managing Highway Maintenance—Training Guide and Catalog.
PB 224686 Communication Systems Handbook for State Highway Departments.
PB 224842 Implementation Package for Use of Liquid Calcium Chloride to Improve Deicing and Snow Removal.

PLANNING

Stock No.
PB 224519 Spokane Metropolitan Transportation Study—Summary of Final Report.
PB 224626 Spokane Metropolitan Transportation Study—Final Report. Survey Findings, Data Projections, Recommendations.
PB 224656 A Critical Review of Mathematical Diffusion Modeling Techniques for Predicting Air Quality with Relation to Motor Vehicle Transportation.
PB 225308 Guidelines for Joint Development on State Highway Transportation Ways.

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