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Weighing trucks at highway speeds

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COVER: Trucks can now be weighed and classified on high-speed, four-lane highways without slowing down as shown at this typical weigh-in-motion system on Route I-57/70 at Effingham, Illinois.

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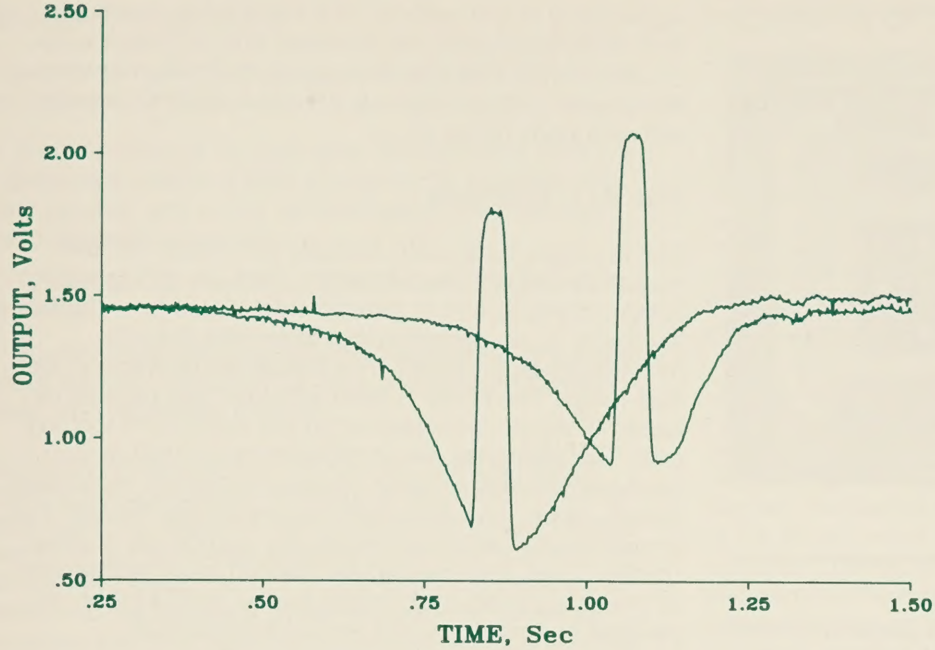
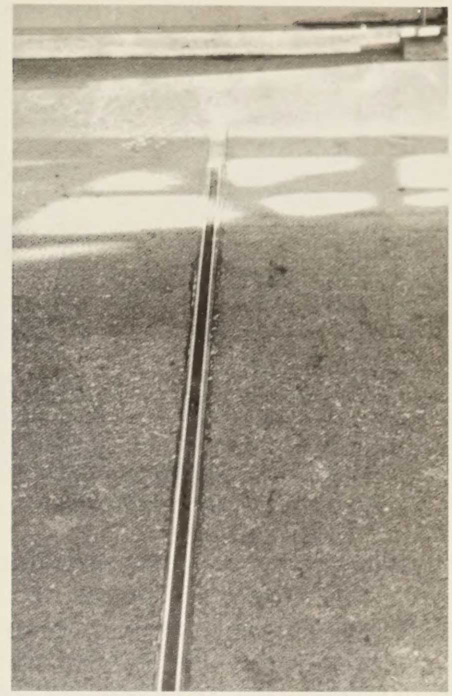
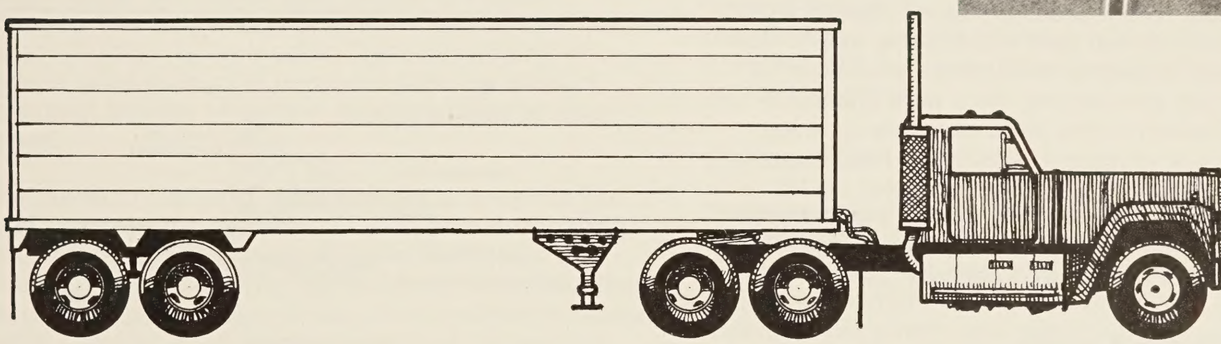






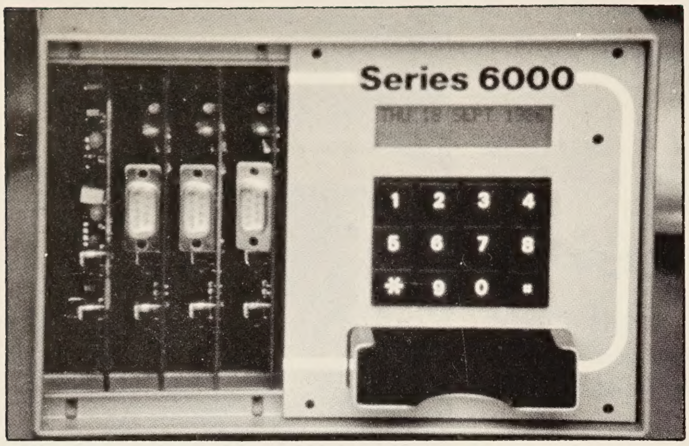
Evaluation of a Weigh-In-Motion Device at the Pavement Testing Facility

by Deborah M. Freund and Ramon F. Bonaquist

Introduction

The Federal Highway Administration (FHWA) has sponsored a number of projects in the past several years dealing with aspects of weigh-in-motion (WIM) and automatic vehicle classification equipment. These projects, sponsored by the Office of Highway Operations, Demonstration Projects Division under the Rural Technical Assistance Program, have highlighted equipment testing and evaluation, as well as coordination of data for transportation and for enforcement of vehicle weight limits.

One current project within Demonstration Project 76 which was jointly sponsored by the Office of Highway Operations Research and Development, Pavements Division, and the Demonstration Projects Division, included an activity for field testing a low-cost vehicle weight and classification system. This device, manufactured by GK Instruments, Limited, of Milton Keynes, England, uses piezoelectric cable sensors installed across the full width of a traffic lane. The sensors are connected by coaxial cable to a microprocessor unit which translates the signals into vehicle weights (loads) and determines the classification (using FHWA Scheme F) of the passing vehicles in the traffic stream.



Microprocessor-based signal translation unit.

Systems had previously been installed in portland cement concrete pavement in Iowa and in asphalt concrete pavement in Minnesota. The researchers found differences in accuracy between the two field installations; further concerns were raised regarding the system's precision. (*1*)[1] As these were field installations, there were uncontrollable aspects, primarily in the traffic exposure received. Additionally, asphalt pavement installations had not performed well, requiring a change to the channel anchoring. To better control its testing, the system was installed and evaluated at FHWA's Pavement Testing Facility (PTF) at the Turner-Fairbank Highway Research Center.

Pavement Testing Facility

FHWA's Pavement Testing Facility consists of two 200-ft (60.96 m) asphalt concrete pavements which are loaded by the Accelerated Loading Facility (ALF) machine. The ALF machine simulates truck traffic by modeling one-half of a single truck axle with dual tires. ALF can apply loads ranging from 9,400 lb to 22,500 lb (41.8 to 100.1 kN) (equivalent to 18,800-lb to 45,000-lb (83.6 to 200.2 kN) full axle loads) at a constant travel speed of 12.5 mi/h (20.1 km/h) loading the pavement once every 9.5 seconds. The pavement itself is instrumented with strain gauges, moisture sensors, and thermocouples, and dynamic deflection is measured with a surface deflection beam. (*1*) Data collection efforts—aimed at quantifying the effects of temperature, pavement roughness, location of loading along the transverse axis, and tire pressure—support the pavement performance tests. Tests at the PTF last between 1 week and 6 months, depending upon the combination of test pavement structure and load applied. In the WIM system testing conducted from May to October 1988, a pavement constructed of 7 in (177.8 mm) of asphaltic concrete over a 12-in (304.8 mm) crushed aggregate base was subjected to over 800,000 applications of a 16,400-lb (73.0 kN) load (or, because ALF models one-half of a dual-tired axle, an axle load of 33,200 lb (147.7 kN)), approximately 5.4 million American Association of State Highway Officials (AASHO) equivalent axle loads (ESAL's).

The ALF Machine

ALF is unique in its ability to apply controlled, variable magnitude loads to a pavement. Loads are changed by using a crane to add or remove steel plates from the trolley (figure 1), an operation that takes less than 20 minutes per plate moved. Five plates are available in the load range. The trolley is fitted with four load cells so dynamic loads can be measured at any point in the loading path. Tire pressures are changed manually with a standard compressed air hose. Pavement primary responses (stress, strain, and deflection) are monitored through extensive instrumentation; secondary responses (rutting, cracking, and deformation) are tracked at close intervals as they appear. As a laboratory facility, ALF is highly accessible to operations and research personnel.

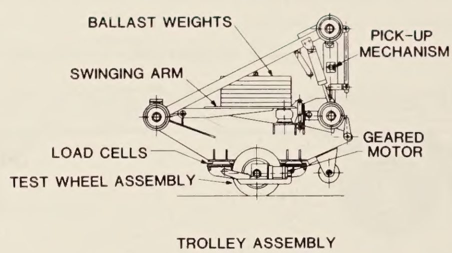


Figure 1.—Schematic of the ALF dual wheel trolley assembly.

Extending the WIM project to the PTF served several purposes.

- The protected setting made an ideal location for thoroughly checking and evaluating the sensor installation procedure.
- ALF complemented the field experiments by applying constant, controllable load at a constant speed. The relatively heavy loads applied over a short period of time provided both a clearer picture of the installation's physical aspects and an opportunity to observe and document any deterioration of the pavement or of the sensor-pavement bond.
- Finally, PTF's broad range of test and analysis equipment allowed the researchers to examine the interrelationships among ALF, the pavement, and the WIM device in ways that would be impractical in a field setting.

[1]Italic numbers in parentheses identify references on page 106.

Research Approach

There were three research goals in evaluating the piezoelectric WIM at the PTF:

1. To determine ALF's suitability for controlled testing of a pavement-mounted WIM device under repeated constant loading and under variable loads, tire pressures, and transverse locations.

2. To assess the durability of the piezoelectric cable assemblies.

3. To determine the accuracy of the piezoelectric system under varying conditions of load, tire pressure, environment, and pavement distress.

As discussed above, the PTF has two unique testing capabilities appropriate to studying the performance of WIM systems. First, the ALF testing machine can simulate 20 years of normal highway traffic during a 6-month accelerated loading test. This capability can be used to determine the durability of the piezoelectric cable assemblies and their installation. Second, the applied load, tire pressure, and lateral load location are easily changed; this facilitates evaluation of WIM system accuracy. Further, by conducting these evaluations at various times during the pavement's life, the effect of pavement distress on system accuracy could be determined.

The research plan originally consisted of installing the WIM system at the beginning of an accelerated loading test, calibrating the system using five load levels, and studying system durability and accuracy throughout the life of the pavement. Specifically, the experimental design (table 1) called for study of the effects of tire pressure, lateral load location, and temperature on WIM system accuracy. However, no repeatable calibration constants for the WIM system could be determined, due to a number of factors, and the research plan was modified to concentrate on the fundamental operation of the piezoelectric sensors themselves. A series of tests was conducted to determine the effects of load, tire pressure, and lateral load location on the output of these sensors.

Table 1.—Planned experimental design

	Load Levels	Tire Pressure	CL Offset	Air Temperature
Accuracy	4*	1 (100 psi)	0	min variation
Temperature Study	1	1	0	varies
Location	1	1	min 3	min variation
Tire Pressure	1	up to 6	0	min variation

*11.6, 14.0, 16.4, 18.9 kips

Installation of the Piezo WIM

FHWA's Demonstration Projects Division provided the same system used in the Iowa and Minnesota projects, consisting of a pair of piezoelectric cables mounted in aluminum channels, a translation unit, a transformer, and coaxial cable. High-quality installation is critical to the sensor's long-term durability, maintenance of the pavement-sensor bond, and the sensor's ability to read applied loads correctly. To meet these objectives, installation was done with extreme care; the procedure followed was nearly identical to that performed in the field.

Once the coaxial cable sensor placement was checked, initial testing began. The piezoelectric cable channel sensor was struck with a mallet to verify that a loading signal would be generated and recorded; when the ALF was started, no readout was produced, however, because ALF's single pair of dual tires constituted a half-axle, or "unicycle," configuration which was not recognized by the classification firmware. To resolve this problem, a replacement programmable read-only memory chip was installed. Another adjustment made at this point reduced the sensitivity of the signal translation unit to accommodate the deep deflection basin produced by the 16,400-lb (73.0 kN) ALF trolley as it traversed the 7-in (177.8 mm) asphaltic pavement.

Calibration

Weigh-in-motion systems usually are calibrated under static loading conditions. However, since the ALF trolley is instrumented with load cells to monitor dynamic load variation, the WIM system installed at the PTF could be calibrated using both static and dynamic loads. Static and dynamic calibration factors were obtained at five load levels—9,400 lb, 11,600 lb, 14,100 lb, 16,400 lb, and 19,000 lb (41.8, 51.6, 62.7, 73.0, and 84.5 kN)—as per the procedure outlined in the field test report. (*2*) Load cell data were collected using the data acquisition system on the PTF microcomputer, while the WIM output was collected on a laptop microcomputer. The means and standard deviations of the ALF trolley load cells and the WIM readings were calculated (table 2). The static calibration factor was defined as the ratio of the static trolley weight to the mean of the WIM readings; the dynamic calibration factor was defined as the ratio of the mean of the load cell readings to the mean of the WIM readings. These early calibrations showed accuracies similar to those obtained from flexible pavements under mixed traffic.

Table 2.—Comparison of static and dynamic calibrations

Static Load, lb	WIM Mean, units	WIM SD readout units	Load Cell Mean lb	Load Cell SD lb	Static Cal	Dyn Cal Wt lb	Computed Static Wt lb	Computed Dynamic	% Diff, Dyn vs Stat Wt
9400	528	21	9471	28.6	1.78	1.79	9398.4	9451.2	0.56
11600	654	26	11795	42.6	1.77	1.80	11575.8	11772.0	1.69
14100	797	23	14525	69.6	1.77	1.82	14106.9	14505.4	2.82
16400	877	33	16449	66.0	1.87	1.88	16399.9	16487.6	0.53
19000	978	30	19224	88.2	1.94	1.96	18973.2	19168.8	1.03

At this point, several potential sources of systematic measurement error were known. The sensitivity of the translation unit had been adjusted to deal with the particularly deep deflection basin produced by the ALF load-pavement thickness combination, and the classification software had been modified to deal with the ALF's "unicycle" loading pattern. We were also testing at the low end of the velocity range of the system: it is designed to operate between 9 and 140 mi/h (15 and 225 km/h), and the ALF trolley travels at 12.5 mi/h (20.1 km/h). Loads were to be applied at the centerline of the lane; in the field, loads are applied near the ends of the device, in the vehicles' wheeltracks.

For the first calibration at 9,400 lb (41.8 kN), 400 passes were sampled. Data analysis indicated that the standard deviation of the WIM readings and the load cells was small enough that only 100 readings would be needed to obtain an accuracy of 1 percent at the 95 percent confidence level. The ALF loading was then changed to 11,600 lb and 14,100 lb (51.6 and 62.7 kN), and the calibration procedure repeated at these levels. The calibration procedure was then run at the higher load levels and repeated at the lower levels (table 3).

The results of these initial tests show significant variation in the mean WIM readings and calibration factors over a short period of time, as well as with temperatures. To quantify this variability, additional runs were made at the 16,400-lb (73.0 kN) load level. ALF dynamic loads measured by the load cells have a fairly small standard deviation (25 lb to 100 lb [111.2 to 444.8 N]) which varies with each load level (table 4).

While these values were highly predictable in the early tests, two of the four cells began operating erratically, making it impossible to obtain additional dynamic calibration data.

Readings misinterpreted by the WIM device generated classifications of two-axle—and occasionally three- and four-axle—vehicles at higher pavement temperatures (generally above 75 °F [24 °C]) and higher load levels (16,400 lb and 19,000 lb [73.0 and 84.5 kN]). The number of loading cycles was increased to obtain a minimum of 100 valid readings for a given test; about 25 to 35 percent (125 to 150 total) extra readings were required at the 16,400-lb (73.0 kN) level. The presence of misinterpreted readings seems to be related to the addition of a classification factor for the ALF trolley, while still permitting the device to continue to classify the original 13 vehicle types.

Table 3.—Static calibration runs, sorted by load level

Date	Load, kips	WIM Mean, units	WIM SD readout units	Cal	Total Sample	# Miss	% Miss	Usable Sample	Near Surface Temp	Avg Air Temp
5/20/88	9.4	528	21	1.78	419	20	5	399	60	60
5/20/88	11.6	654	26	1.77	107	3	3	104	60	60
5/24/88	11.6	753	28	1.54	142	36	25	106	70	69
5/25/88	11.6	734	25	1.58	128	25	20	103	62	64
5/20/88	14.1	797	23	1.77	162	10	6	152	59	59
5/24/88	14.1	808	26	1.74	157	52	33	105	74	71
5/23/88	16.4	877	33	1.87	164	13	8	151	67	65
5/24/88	16.4	900	32	1.82	156	53	34	103	73	70
6/1/88	16.4	939	36	1.75	116	16	14	100	64	66
6/1/88	16.4	931	26	1.76	200	92	46	108	73	69
6/1/88	16.4	917	32	1.79	200	80	40	120	86	80
6/2/88	16.4	1031	30	1.59	116	16	14	100	57	63
6/3/88	16.4	917	23	1.79	108	6	6	102	55	59

Table 4.—Statistics, ALF load cell readings

File name	Load (kip)	N	Min	Max	Mean	Median	SD
TestA001	9.4	399	9274	9600	9471	9468	28.6
CalA001	11.8	97	11717	11887	11795	11788	42.6
CalA002	14.1	149	14366	14783	14525	14530	69.6
CalA003	16.4	147	16310	16589	16450	16464	66.0
CalA004	19.0	150	19019	19377	19225	19224	88.2

The 12 sets of calibration data were tested for normality using the univariate procedure in the Statistical Analysis System (SAS) software package. (*3*) Applying the empirical rule at a 95-percent limit, the data may be considered as near normal, but with a slight negative skew. (*4*) While this could indicate a systematic error in the WIM unit towards underweighing, the following factors may well have played a more significant role:

- Adjustment of the translation unit's sensitivity to deal with the deep deflection basin produced by the ALF load-pavement thickness combination.
- The variation between ALF's travel speed (12.5 mi/h [20.1 km/h]) and the optimum velocity range of the WIM system (9 to 140 mi/h [15 to 225 km/h]).
- The ALF loading pattern used at the PTF (loads were applied at the centerline of the lane; in the field, they were applied near the ends of the device in the vehicles' wheeltracks).
- Modification of the classification software to handle ALF's unicycle loading configuration.

The observed inconsistencies in calibration factors from data sets collected at different load levels, as well as the issue of missed classification, emphasized the need for an alternative method of evaluating system accuracy.

Secondary Testing: Sensor Response

The basic principle upon which the piezoelectric sensor operates involves translation of applied pressure to a voltage signal. Pressure from the wheel load is converted to a voltage signal by the piezoelectric cable sensor. This voltage is transmitted from the sensor to the translation unit where voltages are converted to vehicle weights. Classifications are determined from the distance between axles, with the transducer acting as a switch. (*1*) Because the calibration factor had not been set, weight (load)-equivalent readouts were raw readings which had to be multiplied by the factor to obtain the weight (load) of the passing vehicle (or a vehicle-equivalent, in the case of the ALF trolley).

While a laboratory bench calibration gives a linear relationship between applied load and the resulting output voltage, the pavement response has the potential to delay, and ultimately change, the output. Flexible pavements are viscoelastic. They return to nearly their original dimensions after being deformed by passing loads. They also accumulate permanent deformations over longer periods of time and numerous load applications which do not disappear after the loads are removed. Deformed pavements react differently to applied loads. The deformations themselves, generally rutting in the case of repeated loading apparatus such as the ALF, cause the loads to affect the pavement differently. Because flexible pavements are also viscous to a certain degree, the pressure is not instantaneous, but is subject to a small, but measurable, time delay. The response of the flexible, viscous, pavement thus is slower than that of the stiff aluminum channel holding the cable sensor.

Although the ability to capture matched dynamic load and WIM readings had been lost with the malfunctioning of the two load cells, a rough comparison was made of differences in readings with variations in tire pressure. The first cycle was run at the performance-test inflation pressure. When the inflation pressure was raised for the next cycle at the same load level, it was discovered that the inflation pressure for the just-completed test had been considerably lower than 100 psi (690 kPa). This raised the issue as to whether the readouts from the WIM device were dependent upon more than the static load of the axle running over the sensors. To answer this question, voltage data were collected directly from the piezo cable sensors.

Before this avenue could be pursued, it was necessary to bypass the portion of the translation unit which converted the voltages to weights and classifications before passing them to the readout panel. Following the manufacturer's instructions, the point in the circuit where the voltage outputs produced by the piezoelectric cables entered the translation unit were located. A portable microcomputer with a hard disk, an external color monitor, and a Keithley Instruments data acquisition system was connected directly to that point. The Keithley system was configured to permit this microcomputer to be used as a four-channel storage oscilloscope to enable visual monitoring and digital sampling of the voltages, and to store them for later playback and comparison.

A typical trace is shown in figure 2. The time difference between the peaks represents the time to transverse the 4 ft (1.2 m) between the cable sensors. While the difference in the amplitudes of the peak voltages of the two traces is very small, the minimum and maximum output voltage levels were noticeably different. Weights (loads) are determined from the averaged outputs of the two sensors. (*1,5*) As the lifting of the ALF trolley produces second-sensor output curves that are not smooth at the trailing end, all traces which follow are those of the first (leading) sensor.

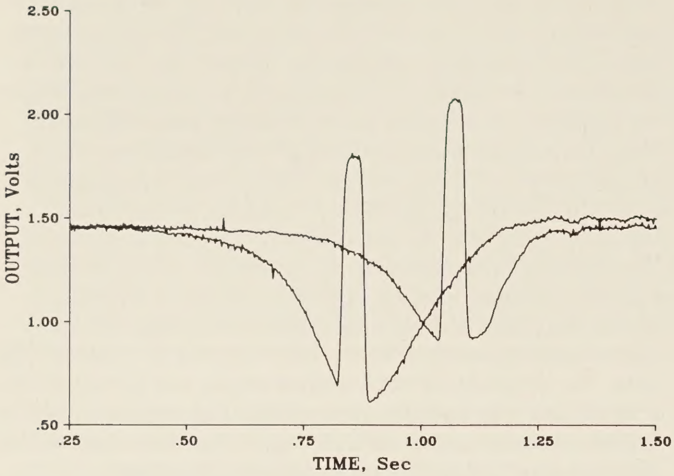


Figure 2.—Typical voltage output trace from WIM cable sensors.

Table 5.—Experimental cells for sensor response experiment

	Test #	psi	Load	Load/psi
Effect of Tire Pressure	10	76	16400	218.42
at Constant Load	14	100	16400	166.00
	12	140	16400	118.57
Effect of Load at	34	100	11600	116.00
Constant Tire Pressure	28	100	14100	141.00
	14	100	16400	166.00
	20	100	19000	190.00
Effect of Load at	32	76	14100	185.53
Constant Contact Area	14	100	16400	166.00
	22	120	19000	158.33
Effect of Lateral Location	14	100	16400	166.00
	16	100	16400	166.00
	18	100	16400	166.00

Note the spikes in the signals' trailing portion. This signal noise may be read by the translation system as "ghost axles," and may have been interpreted by the system as an expectation of a signal from a trailing axle. While the classification software had been modified to accept the ALF's unicycle loading, its ability to recognize the *FHWA Traffic Monitoring Guide* classifications had not. The system's recognition of a non-unicycle classification—when in fact the ALF was incapable of producing one—led to a missed reading, not to a misclassification, as had earlier been assumed. An alternative approach to modifying the classification software (which recognized only the unicycle loading) would probably have avoided this problem. (*6*)

Load tests

A series of load tests was performed at different tire pressures, different loads, combinations of load and tire pressure which produced equivalent values of contact area, and different lateral positions. The experimental cells comprising this series of tests are shown in table 5. Careful qualitative comparison of the traces showed them to be highly consistent for applications of constant loads. The shape of the trace changes with the magnitude of the applied load, with the rise and fall becoming steeper at both increased load levels and increased tire pressures.

It was not possible to verify the techniques used to translate the voltage signals, as this is part of proprietary hardware and software. The manufacturer supplied a modification to the electronics necessary to classify the unicyicle loading pattern of the ALF; it is not known if the translation algorithm for this loading pattern is the same as that used in the production units in the field.

A series of traces at four load levels, holding tire pressure constant at 100 psi (689.5 kPa), is shown in figure 3. Under these conditions, the contact area of the tire will increase with increasing load. While the most noticeable difference among the curves is in their peak voltages, the minimum voltages at the beginning and end of the loading cycle show variations in magnitude as well. The rising slopes for the two heavier loads are less steep than those for the lighter ones.

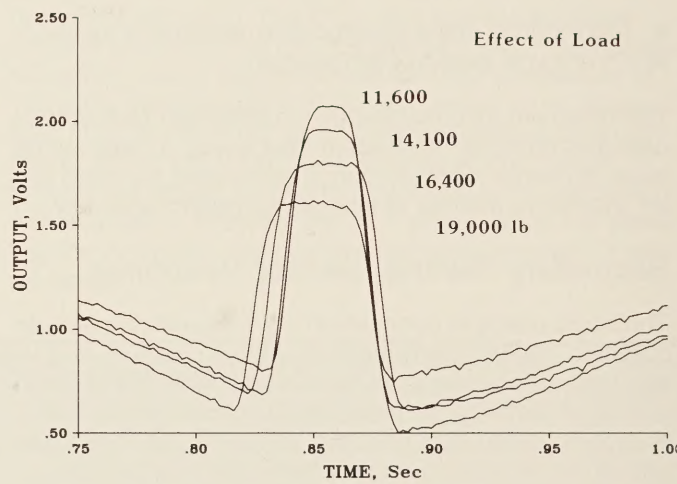


Figure 3.—Effect of load on WIM sensor voltage output.

Figure 4 illustrates the effect of changes in tire pressure while holding the load level constant. In this case, contact area increases with decreased tire pressure. Again, the condition providing the lowest contact area gave the highest amplitude voltage output: however, there is little difference in rising slopes of the three traces, and essentially none in the falling slopes. The period of the loading cycle decreased slightly at the higher tire pressures and their associated smaller footprints.

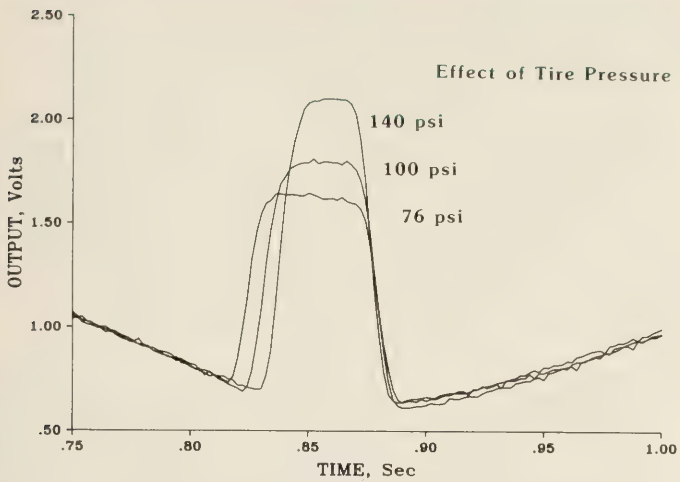


Figure 4.—Effect of tire pressure on WIM sensor voltage output.

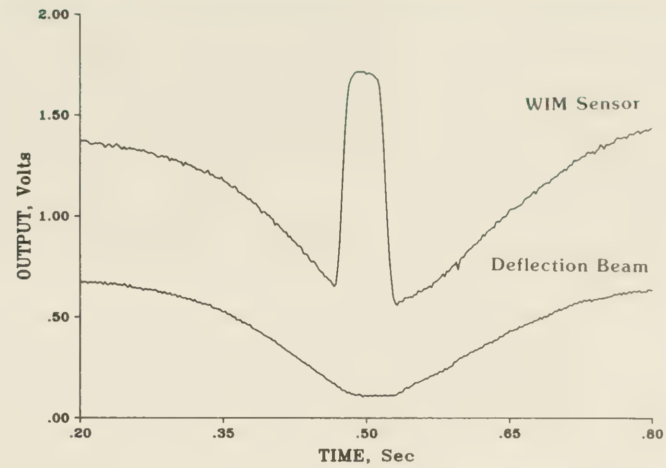


Figure 7.—Superposition of voltage output curves from WIM sensor and pavement deflection beam.

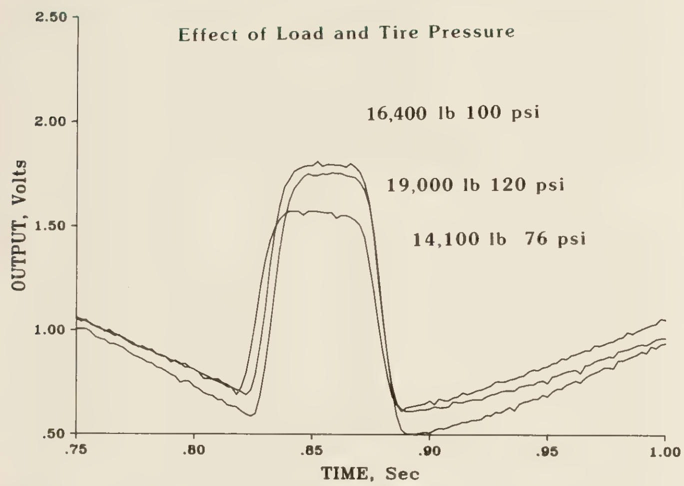


Figure 5.—Effect of load and tire pressure on WIM sensor voltage output.

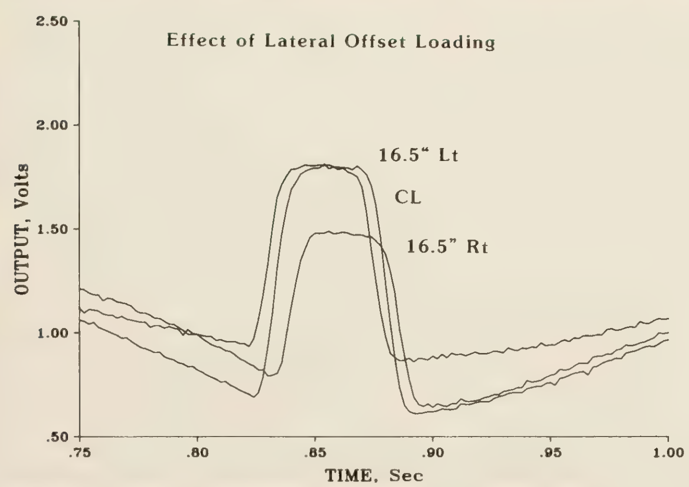


Figure 6.—Effect of lateral offset loading on WIM sensor voltage output.

The traces in figure 5 were produced from three combinations of loads and tire pressures which provided constant measured contact area. The rising and falling slopes showed a pattern most similar to those of the constant load/varying tire pressure combination in figure 4. While the peak output voltage for the heaviest load is less than that of the intermediate load, the base-to-peak amplitude is slightly higher.

Effects of lateral load location are shown in figure 6. A constant load of 16,400 lb (73.0 kN) with tire pressure of 100 psi was applied at the longitudinal centerline of the lane and at right and left offsets of 16.5 in (419.1 mm). The peak amplitudes were nearly identical for the centerline and left offset loads, while the return traces were closest for the right and left offset loads. The amplitude of the right-offset trace was somewhat lower than for the other two. Note that the ALF applies load through a half-axle, and the cable is deformed in a single deflection basin rather than in the two transverse, parallel deflection basins produced by a full axle.

Figure 7 illustrates the superposition of the WIM voltage curve with the pavement deflection basin. The basin was measured with a deflection beam and sampled at the same time as the WIM sensors, but on an independently operating microcomputer. The WIM voltage signal is located very deep within the deflection basin's trough, due to the slower reaction time of the viscous pavement and the stiff sensor channel. Another "ghost axle" spike can be seen toward the trailing end of the signal trace.

The area under the voltage curve is related to the magnitude of the passing load. (*6*) Several methods may be used to determine the area under the voltage curve within the signal analysis and translation routines:

1. Extend the deflection basin curve; this provides the most complete picture of pavement-sensor interaction, but is the most complex from an engineering and mathematical standpoint.

2. Approximate the deflection basin curve extension with a line between the inflection point and the global minimum; this introduces a degree of systematic error, because the voltage signal is not centered in the deflection basin of a flexible pavement. In a much stiffer pavement, such as portland cement concrete or a very stiff asphalt, the signal would be more closely centered and the errors would be smaller.

3. Chop off the curve at the inflection point with a horizontal line representing a low-pass filter; this has the same disadvantages as No. 2 above.

4. Chop the signal at the baseline voltage. However, if the signal is at any depth in the deflection basin, this will introduce very large errors.

Figures 8 and 9 illustrate the appearance of the WIM signals after subtracting the deflection basin as described in Method 1 above. The trends illustrated by these sets of curves are similar to their counterparts in figures 4 and 5. Figure 9 indicates a greater reliance on magnitude of load compared to that of contact area in the curve's peak amplitudes.

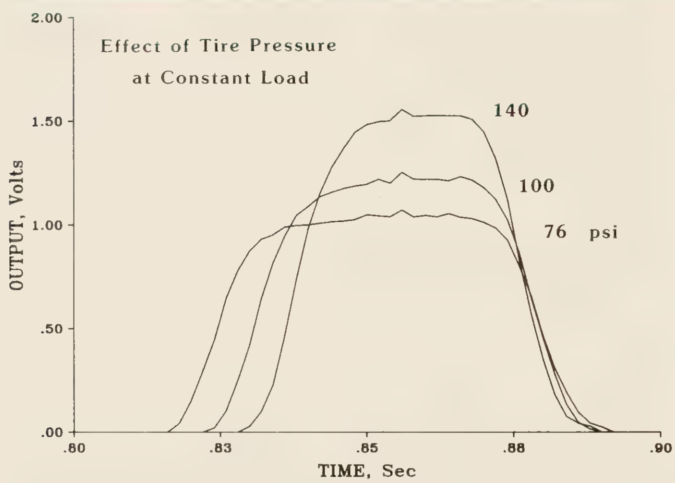


Figure 8.—Effect of tire pressure at constant load, deflection basin subtracted.

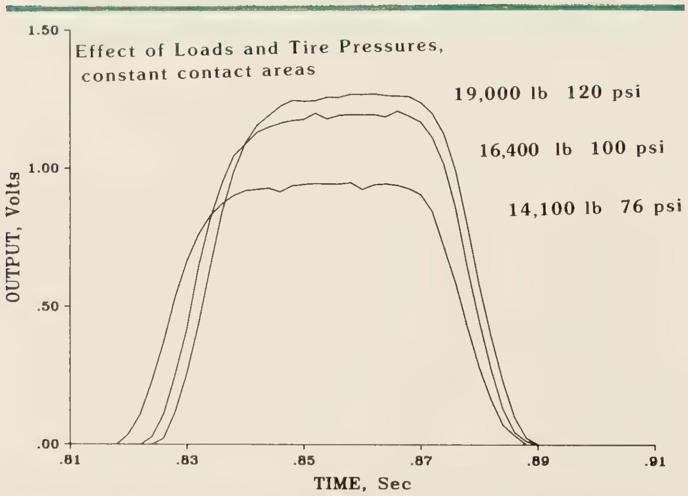


Figure 9.—Effect of loads and tire pressures (constant contact area), deflection basin subtracted.

Table 6 shows a comparison of three computations of the areas under the voltage curves taken for a trolley load of 16,400 lb (73.0 kN) at tire pressures of 76, 100, and 140 psi (524.0, 689.5, and 965.3 kPa). Method 1 utilizes the full deflection curve, Method 2, the straight-line approximation, and Method 3, the signal chopped at the baseline voltage. The first line of each entry represents the area in volts x seconds, the second represents the ratio of the areas for each method, assuming the value at 76 psi (524.0 kPa) to be the baseline. Excellent agreement was noted among the sets of three readings for Methods 1 and 2, as would be expected for a constant load. Method 3 provided very poor agreement.

Table 6.—Comparison of areas under voltage-time curves: 16,400-lb load; 3 tire pressure levels

	76 psi	100 psi	140 psi
Method 1	0.0558	0.0562	0.0578
	1.00	1.01	1.04
Method 2	0.0515	0.0532	0.0540
	1.00	1.03	1.05
Method 3	0.00591	0.0109	0.0183
	1.00	1.84	3.10

units ratio (base = 76 psi)

These comparisons were extended to the amplitudes and areas of the curves to observe their relationships, if any existed, to tire pressure as well as load (figures 10-13). The strongest linear relationships were observed between amplitude and tire pressure (figure 10), and between load and area (figure 13). In the latter, the relationship broke down at the 19,000-lb (84.5 kN) load, possibly because the amplifier's range had been exceeded.

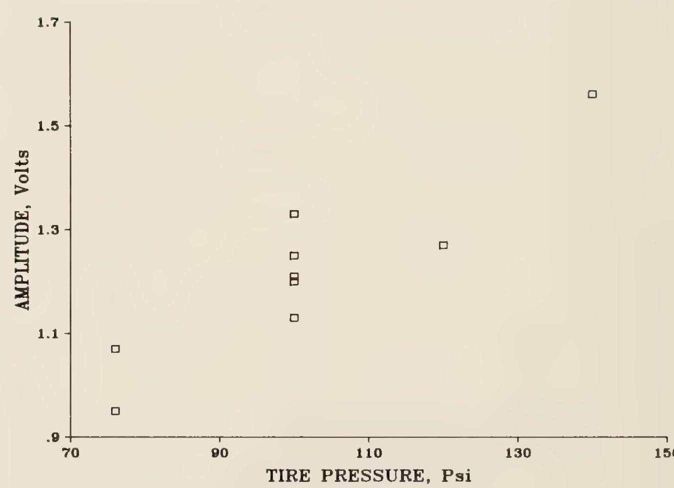


Figure 10.—Tire pressure vs amplitude.

Figures 10 through 13: Relationships between amplitudes and areas of WIM sensor voltage curves and loads and tire pressures applied.

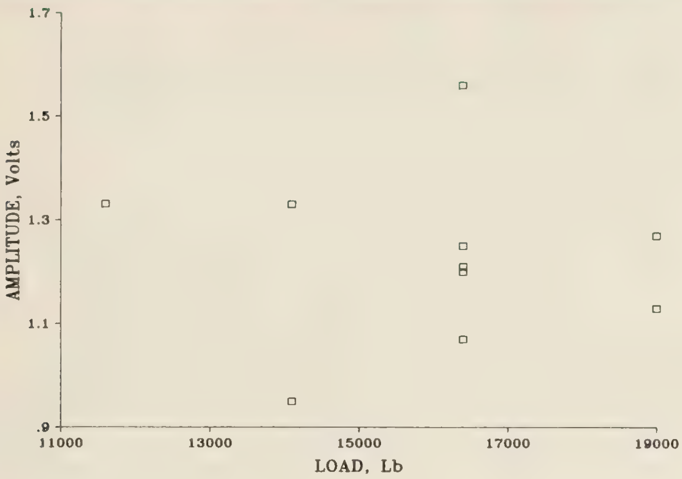


Figure 11.—Load vs amplitude.

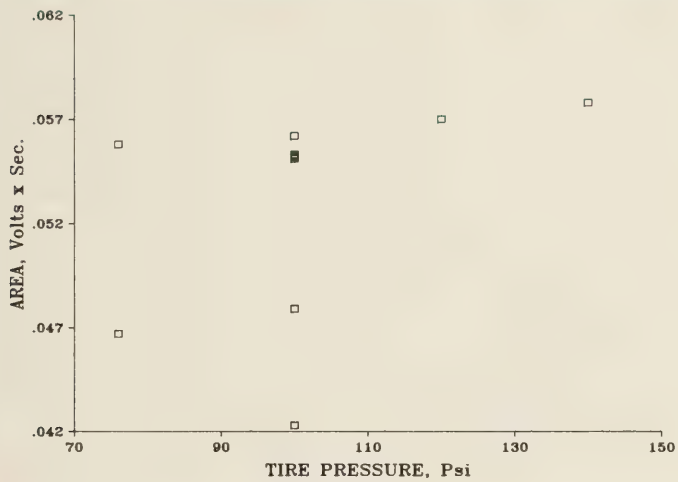


Figure 12.—Tire pressure vs area.

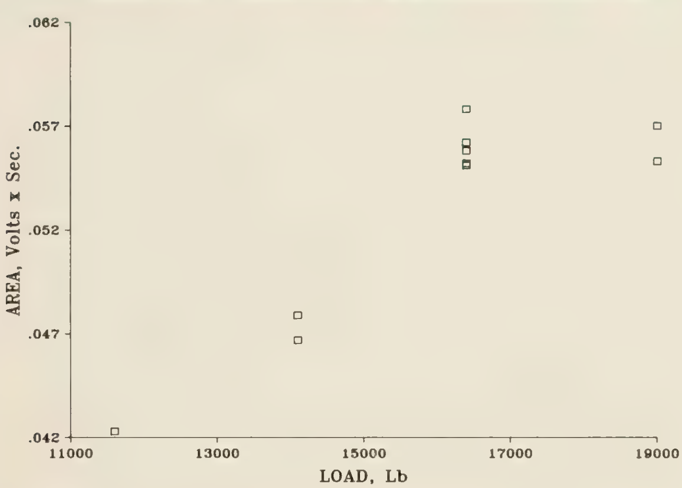


Figure 13.—Load vs area.

Durability

The aluminum channels holding the cables seated themselves to conform to the contours of the pavement. Ruts reached a depth slightly over 1/2 in (12.7 mm) after 550,000 cycles. No localized distress was noted until 500,000 cycles (approximately 3.4 million ESAL's) of loading, the same time cracking began in other areas of the test pavement. After approximately 725,000 cycles (4.9 million ESAL's), the bonds broke between the second sensor and the pavement. The piezoelectric cable sensors continued to generate a consistent electrical signal. After this point, the pavement began to deteriorate more rapidly. An ellipsoidal cracking pattern developed along the major axis of both sensors. After approximately 763,000 passes (5.2 million ESAL's), the voltage traces showed a significantly higher amplitude from the second sensor. This indicated that the sensor's deflection was now independent of that of the pavement.

Summary

A GK Instruments piezoelectric weight and classification system has been undergoing field testing in Iowa and Minnesota under Demonstration Project 76. The Demonstration Projects Division and the Pavements Division extended the project to include a series of controlled tests at the PTF/ALF located at the Turner-Fairbank Highway Research Center. The system was installed in May of 1988 and tested until October.

The original experimental plan called for a factorial design to determine the accuracy of the system under changing loads, tire pressures, and transverse loading locations. There was no systematic pattern to calibration factors determined at different temperatures under constant weight. The potential sources of this variation stemmed from the ALF loading pattern, variation in the manner in which the cables sensed loads, and variation in the translation of the voltages to weights (loads) and vehicle class readouts. In addition, the signal analysis and translation system itself had been modified to handle the ALF's unicycle loading configuration, and the sensitivity level of the device had been reduced to deal with the deep deflection basin imparted by the ALF trolley to the pavement section. Finally, the ALF's travel speed of 12.5 mi/h (20.1 km/h) is near the lowest range of the WIM device (9 to 140 mi/h [15 to 225 km/h]).

As several modifications had been made to the signal translation unit, the plan was altered to concentrate on the output voltage signals themselves instead of the translated weight (load) and classification readings. These direct voltage plots have been quite consistent at constant loads, and have also shown systematic variation with changes in load. A second series of tests at different tire pressures showed variability similar to that observed in the early calibrations. Combinations of loads and tire pressures which provide a constant tire contact footprint appear to indicate that the system may be sensitive to the unit load as well as to total load. This leads to concern that different combinations of loads and tire pressures may not be properly weighed.

Conclusions

The tests performed have provided a unique picture of the operation of the WIM device. Use of the ALF to apply constant repeated loads and variable loads and tire pressures has been invaluable in system assessment. The range of applied loads as recorded by load cells on the ALF trolley is very small, on the order of 1.9 percent to 3.4 percent over the ranges tested. Care must be taken to place the sensors within the longitudinal range of constant loading to avoid the problems of trolley bounce at the ramp (load) end and temperature-affected variation in load transfer to the loading frame at the pickup end. Because it was not known if the device would accelerate localized pavement deterioration, sensors were placed near the end of the test pavement section. Had the device introduced localized pavement distress within the middle portion of the test section, the entire planned 6 months of pavement performance testing would have been adversely affected.

The WIM cable assemblies installed in the pavement appear to be very durable. Even though the ALF's centerline, unicycle-loading subjected the sensor channel to higher bending stresses than would normally be the case in a field operation, there was no pavement-sensor bond distress noted until after approximately 3.4 million ESAL's of loading.

System accuracy is still in question. Additional time is needed to explore in more detail how the device translates the voltage signals into vehicle weights and how it combines weight readings to perform classifications.

More time also is needed to evaluate the operation of the electronics and the weight (load) and classification translation methods. For this reason, cable sensors will not be installed in the last test pavement during the current series of PTF tests. During the second series of PTF tests, the WIM unit should be installed in both flexible and rigid pavements to verify field results and develop a higher degree of confidence in system operation.

Acknowledgments

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Rollover Potential of Vehicles on Embankments, Sideslopes, and Other Roadside Features

by Karen K. Ajluni

Introduction

As the National trend toward smaller cars continues, concern increases regarding the potential hazards—in terms of vehicle rollover—of various existing roadside features (ditches, embankments, and sideslopes). Rollover accidents are generally more severe than nonrollover accidents, and small, light vehicles are more likely to roll over.

A recent Federal Highway Administration (FHWA) study examined the vehicle interaction with various roadside features to determine key roadside-feature design criteria based on their potential for inducing vehicle rollover. (*1*)[1] The Highway-Vehicle-Object Simulation Model (HVOSM) computer program was used in the study to determine differences between large and small vehicles and their performance capabilities with regard to various roadside features. (*2*) The HVOSM was modified to improve its application to rollover situations. This article describes the study's methodology and discusses the principle findings of the study.

Literature Review and Accident Data Analysis

The study began by reviewing existing literature and available data on rollover accidents. Findings of this review included the following:

- About 25 percent of all off-roadway accidents result in rollover (table 1).
- About half of all accidental departures from the roadway occurred at path angles greater than 15 degrees.
- The vast majority of rollovers occurs within 30 ft (9.1 m) of the roadway. Relatively few rollovers occur or are initiated on the shoulder.

[1] Italic numbers in parentheses identify references on page 113.

Table 1.—Incidence of any rollover

Location of first harmful event

Vehicle type	On roadway No. SVAs[1]	On roadway % RO[2]	Off roadway No. SVAs	Off roadway % RO	% RO on and off roadway combined
Utility vehicles	24	79.2	65	60.0	65.2
Pickup trucks	76	34.2	430	40.7	39.7
Vans	33	18.2	86	34.9	30.3
Station wagons	143	6.3	668	23.2	20.2
Passenger cars	302	7.6	1,346	24.6	21.5
2,000 lb or less	33	24.2	105	49.5	43.5
2,100–2,500 lb	31	22.6	204	35.3	33.6
2,600–3,000 lb	30	13.3	227	30.8	28.8
3,100–3,500 lb	69	2.9	323	21.1	17.9
3,600–4,000 lb	67	3.0	264	15.2	12.7
4,100–4,500 lb	51	0.0	167	12.6	9.6
4,600 lb or more	21	0.0	56	14.3	10.4
All vehicle types	578	14.4	2,595	28.1	25.6

1 lb = 0.4536 kg

[1]SVA = Single Vehicle Accidents
[2]RO = Rollover

- The likelihood of rollover increases with embankment steepness, height, and ditch depth.
- For passenger cars, the frequency of rollover decreases as vehicle weight increase.
- In most (50 to 80 percent) rollover accidents, the vehicles skidded out of control at a large sideslip angle prior to overturning.
- The majority of vehicles in rollover accidents have estimated speeds less than 40 to 50 mi/h (64 to 80 km/h).
- Accident data files usually lack vital information on terrain geometry, and on whether rollover was caused by vaulting or tipping of the vehicle due to the wheels hitting a small obstacle or digging into soft soil.
- Ejection is the leading cause of serious and fatal injuries, accounting for more than half of the fatalities incurred in rollover accidents.
- The fatality rate for occupants of rollover vehicles is approximately twice that for occupants of vehicles in nonrollover impacts.

HVOSM Modifications

Certain analytical refinements and computer program extensions enable application of the HVOSM to rollover situations. Critical HVOSM modifications included the tire and tire/deformable-soil interaction models. The HVOSM modifications were verified by performing two series of tests on an instrumented 1979 Volkswagen Rabbit automobile.

The first series of verification tests was performed on flat, rigid pavement. These results were compared to initial data used in the computer simulation model. In the second series of tests, the vehicle traversed natural roadside terrain to assess the predictive capability of HVOSM employing the deformable-soil model. Motion-resistance force was measured to determine the tire/ground friction coefficient as well as the overall validity of the HVOSM deformable-soil model. The average friction coefficient obtained for automobile tires sliding on sod ground was about 0.5. This agrees with the coefficient reported by the Texas Transportation Institute, but is less than half the value measured in similar tests performed at the General Motors Proving Ground. (*3,4*)

Correlation between the car's simulated and measured responses was good except for the yaw response created in test two. As a result of the yaw discrepancy, the path of the vehicle after exit from the ditch deviated from the actual trajectory. This deviation, however, does not affect variables related to rollover.

HVOSM Simulations

Over 200 HVOSM computer runs were made in examining the rollover tendencies of vehicles traversing various sideslope, fill-embankment, and ditch configurations. The roadside cross sections included an 8-ft (2.4 m) wide shoulder and a 4-ft (1.2 m) rounding of the shoulder/frontslope breakline. The rounding profiles defined by the American Association of State Highway and Transportation Officials (AASHTO) equations (called "optimum rounding" herein) also were used in some of the sideslope simulations. The ground beyond the shoulder was assumed to be deformable-soil, with characteristics defined by Bekker's soil constants for sod. (*5,6*)

Two small cars and one large, heavy car were simulated. One of the small cars was represented by the HVOSM input data set developed for the Volkswagen Rabbit used in the verification tests; this car weighed 2,410 lb (1.1 Mg), including the driver. The other small car weighed 1,800 lb (0.8 Mg) and was identical to the first except for values of those parameters (moment of inertia, center of gravity location, etc.) affected by the different weight. The third vehicle was assumed to weigh 4,450 lb (2.0 Mg) and represented the large, heavy class of cars at the opposite end of the size and weight spectrum.

Both tracking and nontracking vehicle departures from the roadway were considered. Table 2 shows the departure conditions used. A back-to-the-road steer maneuver also was simulated in all computer runs. The first departure is defined as one of the test conditions recommended for evaluating the safety performance of highway appurtenances. For this departure, the vehicle was assumed to be oriented at a 15-degree yaw angle, so it was tracking with zero sideslip. For the second departure condition, the vehicle left the roadway at a lower speed and higher angle while skidding at a 30-degree sideslip angle. This departure was selected as an example of an out-of-control pre-crash condition. (*7*)

Table 2.—Departure conditions considered

Variable	Departure No. 1	Departure No. 2
Speed, mi/h	60	45
Path angle, degrees	15	25
Sideslip angle, degrees	0	30

60 mi/h = 96.6 km/h
45 mi/h = 72.4 km/h

Rollover Behavior

The first round of computer simulations investigated the rollover behavior of the vehicles operating on 2:1, 3:1, and 4:1 slopes with both 4 ft (1.2 m) and optimum shoulder rounding. An assumed value of 0.6 was used for the tire/ground friction coefficient. The results indicated that rollover tendency was greater for the non-tracking departure and, as expected, increased with increasing steepness of the sideslope. Both small cars rolled over on the 2:1 slope; the 2,410-lb (1.1 Mg) car also rolled over on the 3:1 slope. However, rollover of these vehicles did not occur on the slopes with optimum rounding, this shows the importance of such rounding in maintaining vehicle stability. The large, heavy car did not roll over on any of the slopes and had less tendency to spin out than did the smaller cars. No rollovers occurred in any of the simulations of the tracking departure, although each of the vehicles came very close to overturning on the 2:1 slope with 4-ft (1.2 m) rounding. The finding that the small, lightweight cars rolled over more readily than the large, heavy car corresponds with conclusions found in the accident data.

Ground Friction Effects

Real terrain includes irregularities such as small depressions, tree stumps, and vegetation which cannot be included explicity in the HVOSM terrain model. To remedy this, the effectiveness friction coefficient of the ground may be used to describe these irregularities. Simulations were performed to determine the minimum values that would result in rollover for various sideslopes. The ground friction effects for small, lightweight cars are summarized in tables 3 and 4.

Some unexpected findings here further illustrate the complexity of the rollover phenomenon. For instance, in the case of the 2:1 sideslope, spinout of the 2,410-lb (1.1 Mg) vehicle occurred for values of friction coefficient 0.75 and lower. The car rolled over in runs performed with friction coefficients of 0.8 and 0.9, but followed a stable return path toward the road for coefficients ranging between 1.1 and 1.25. Further increases of friction coefficient to 1.3 and 1.4 again resulted in vehicle rollover. Similarly, on the 3:1 sideslope, rollover occurred only for the nar-

Table 3.—Threshold of ground friction coefficient for rollover of 1,800-lb (0.8 Mg) car

Sideslope ratio	Friction coefficient	Maximum roll angle, degrees	Comments
45-mi/h and 25-degree (30 degree side/slip) departure			
2:1	0.45	45.2	Car spins out and slides down sideslope.
2:1	0.50	Rollover	Rollover 25.6 ft from EOP.
3:1	0.75	32.1	Car begins return to road, stops on side-slope; maximum lateral distance 26.2 ft from EOP.
3:1	0.80	Rollover	Rollover 21.5 ft from EOP.
4:1	0.90	24.7	Car returns to road at high angle; maximum lateral distance 19.3 ft from EOP.
4:1	0.95	Rollover	Rollover 18.3 ft from EOP.
5:1	1.0	24.3	Car returns to road at high angle; maximum lateral distance 16.6 ft from EOP.
5:1	1.05	Rollover	Rollover 12.6 ft from EOP on return path to road.
60-mi/h and 15-degree (tracking) departure			
2:1	0.95	43.5	Car spins out on sideslope.
2:1	1.0	Rollover	Rollover 50.7 ft from EOP.
3:1	0.90	24.9	Car begins return to road, spins out.
3:1	0.95	Rollover	Rollover 27.9 ft from EOP on return path to road.
4:1	0.95	20.8	Car begins return to road, spins out.
4:1	1.0	Rollover	Rollover 14.6 ft from EOP on return path to road.
5:1	0.85	16.8	Car begins return to road, spins out.
5:1	0.90	Rollover	Rollover 16.2 ft from EOP on return path to road.

1 mi/h = 1.609 km/h
1 ft = 0.3048 m
EOP = Edge of pavement

Table 4.—Threshold of ground friction coefficient for rollover of 2,410-lb (1.1 Mg) car

Sideslope ratio	Friction coefficient	Maximum roll angle, degrees	Comments
45-mi/h and 25-degree (30-degree sideslip) departure			
2:1	0.30	49.6	Car spins out and slides down sideslope.
2:1	0.35	Rollover	Rollover 21.3 ft from EOP.
3:1	0.50	29.2	Car spins out and backs down sideslope.
3:1	0.55	Rollover	Rollover 39.3 ft from EOP.
4:1	0.70	26.8	Car begins return to road and spins out on slideslope.
4:1	0.75	Rollover	Rollover 21.2 ft from EOP.
5:1	0.75	22.8	Car returns to road; maximum lateral distance 20.2 ft from EOP.
5:1	0.80	Rollover	Rollover 19.0 ft from EOP.
60-mi/h and 15-degree (tracking) departure			
2:1	0.75	46.4	Car slides on return path to road.
2:1	0.80	Rollover	Rollover 76.1 ft from EOP on return path to road.
2:1	1.25	46.8	Car on stable return path to road.
2:1	1.30	Rollover	Rollover 55.1 ft from EOP.
3:1	0.65	26.5	Car spins out on sideslope.
3:1	0.70	Rollover	Rollover 46.4 ft from EOP.
4:1	0.70	17.9	Car begins return to road, spins out.
4:1	0.75	Rollover	Rollover 30.2 ft from EOP on return path to road.
5:1	0.75	18.0	Car begins return to road, spins out.
5:1	0.80	Rollover	Rollover 16.5 ft from EOP on return path to road.

1 mi/h = 1.609 km/h
1 ft = 0.3048 m
EOP = Edge of pavement

row range of friction coefficients between 0.7 and 0.8. Below this range, the car spun out on the slope; for higher values (up to 1.7), it was steered on a stable trajectory back to the road without rolling over.

Rollover of the 4,450-lb (2.0 Mg) car occurred on the 2:1 sideslope for the sideslipping departure condition with friction coefficients of 0.8 or higher. However, the vehicle otherwise did not roll over, even for values as high as 1.6. For the tracking departure, the vehicle spun out on the slope for friction coefficients up to 1.2 and returned to the road with further increases of the coefficient.

It is interesting to note that when the vehicles did not roll over, the maximum roll angles were always much less than the critical roll angle—particularly for the shallower slopes—and changed only slightly with changes of the friction coefficient. This suggests that various combinations of key variables (e.g., speed, orientation, linear and angular velocities, and driver control inputs) can act together to create a threshold condition for rollover. The inconsistencies of real-world terrains, which may cause only small variations in the effective friction coefficient, can mean the difference between whether a vehicle safely traverses or rolls over on a particular sideslope.

Embankment Effects

To determine if protective barrier systems on roadway fill sections are needed, simulations of vehicles traversing fill embankments were compared with the current AASHTO criteria. The type of embankments considered were those with 2:1, 3:1, and 4:1 slopes; these varied in height from 3 ft (0.9 m) to 17.5 ft (5.3 m). A friction coefficient of 0.6 was used and the rounding of the toe was provided based on the rate of 0.3 ft (0.9 m) per degree change of slope for avoiding bumper impact with the ground. (*8*) Embankment configurations are summarized in table 5.

Embankment analysis showed that fill sections with front slopes of 2:1 are hazardous, regardless of the height of the embankment. It also appears that a 3:1 embankment slope is marginally safe, since rollover of one of the small cars was shown to occur on embankments 5 ft (1.5 m) or more in height. In view of this finding, a roadside barrier may be justified if front slopes are steeper than 3:1. This would help protect against rollovers of small, lightweight vehicles.

Ditch Design Effects

The effects of ditch design variables on vehicle rollover tendencies were investigated in only a few simulations which were taken from three selected ditch configurations. Two of these ditches had combinations of front and back slopes within the AASHTO criteria for preferred cross section. (See figure 1.)

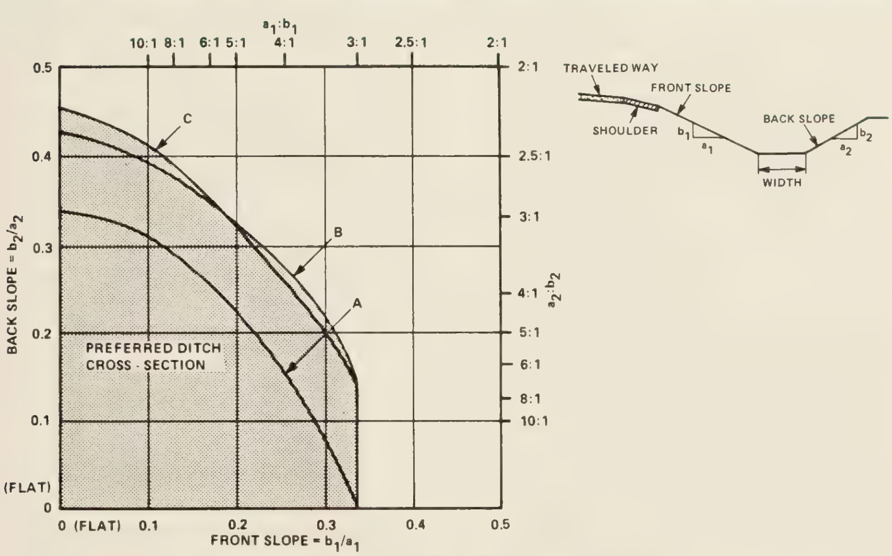
Table 5.—Summary of fill-embankment simulations

Vehicle weight	Departure mi/h @ deg	Sideslope ratio	Fill height (ft)	Remarks
1800	60 @ 15	2:1	3.2	Airborne
1800	60 @ 15	2:1	5.5	Airborne
1800	60 @ 15	2:1	10.0	Rollover
1800	60 @ 15	3:1	3.0	Spins out
1800	60 @ 15	3:1	5.0	Returns to road
1800	60 @ 15	3:1	10.0	Stable (Ret. to rd.)
1800	60 @ 15[1]	3:1	17.0	Stable
1800	60 @ 15[1]	4:1	17.0	Stable
1800	45 @ 25	2:1	3.2	Rollover
1800	45 @ 25[1]	2:1	5.5	Rollover
1800	45 @ 25	3:1	3.0	Stable (Ret. to rd.)
1800	45 @ 25	3:1	5.0	Stable (Ret. to rd.)
1800	45 @ 25	3:1	10.0	Stable (Ret. to rd.)
1800	45 @ 25[1]	3:1	17.0	Spins out
1800	45 @ 25[1]	4:1	17.0	Spins out
2410	45 @ 25	2:1	3.2	Rollover
2410	45 @ 25	2:1[2]	6.5	Returns to road
2410	45 @ 25	3:1	5.0	Rollover
4450	60 @ 15	2:1[2]	6.5	Returns to road

[1]Simulations with zero steer input
[2]Simulations with optimum shoulder/sideslope rounding

1 mi/h = 1.609 km/h
1 ft = 0.3048 m
1 lb = 0.4536 kg

Note: The cross sections all included 4-ft (1.2 m) rounding of the shoulder/sideslope juncture except for those indicated otherwise.



1 ft = 0.3048 m

Curve - A Envelope:
- Vee ditch
- Round ditch, bottom width < 8 ft
- Trapezoidal ditch, bottom width < 4 ft
- Rounded trapezoidal ditch, bottom width < 4 ft

Curve - B Envelope:
- Trapezoidal ditch, bottom width = 4 ft to 8 ft
- Round ditch, bottom width = 8 ft to 12 ft

Curve - C Envelope:
- Trapezoidal ditch width > 8 ft
- Round ditch, width > 12 ft
- Rounded trapezoidal ditch, width > 4 ft

Figure 1.—Envelopes of front and back slope combinations for preferred ditch sections.

A deep vee ditch and a deep round bottom ditch were used in the simulation tests. The results of these simulations for an 1,800-lb (0.8 Mg) small car are summarized in table 6. Based on the vehicle responses observed in the simulations, it appears that the existing AASHTO guidelines provide designs with low vehicle rollover potential. (*9*) These guidelines limit the front slope of ditches to no steeper than 3:1, regardless of the steepness of the backslope and the width or depth of the ditch.

Conclusions and Recommendations

1. Results of the full-scale tests and computer simulations show that 3:1 slopes are only marginally safe for traversal by small, lightweight automobiles. This agrees with the abundant evidence, taken from accident data analyses, that small, lightweight vehicles tend to roll over more frequently than large, heavy vehicles.

2. Ditches having front slopes no steeper than 3:1 appear relatively safe with respect to vehicle rollover potential.

3. A recent FHWA study noted that sideslopes of 3:1 were comparable to those of 2:1 or steeper. (*10*) This indicates that decreasing the sideslopes from 2:1 or steeper to 3:1 has little or no effect in reducing the severity of single-vehicle accidents. More attention should be focused on sideslope effects on single-vehicle rollover accidents.

4. All roadside terrain slope breaks should be rounded as much as possible to reduce the potential of vehicle rollover due to tripping on sag vertical curves. The need for adequate rounding of crest vertical curves, such as the break line of shoulder and sideslopes, also cannot be overemphasized. Such rounding not only affords drivers greater opportunity to maintain or regain control of their vehicle, but also decreases the likelihood of rollover by preventing the vehicle from achieving large values of angular momentum about the roll axis.

Table 6.—Summary of ditch simulations (1,800-lb (0.8 Mg) car)

Departure mi/h @ degrees	Slopes, front/ back	Depth ft	Dist from EOP, ft	Bottom rounding, ft	Max. roll, deg	Max lat encroach, ft	Comments
				Vee Ditches			
60 @ 15[1]	4:1/6:1	17.0	76.0	0	17.0/−23.7	>133	Car stable on slightly curved path away from road.
60 @ 15	3:1/4:1	3.0	17.5	0	Rollover(−)	21.0	Severe impact with back slope caused "flip"-type rollover.
45 @ 25	3:1/4:1	3.0	17.5	0	48.8/−22.2	20.4	Airborne after impacting backslope. Sprung-mass right-front corner impact with back slope prevented rollover.
				Round Bottom Ditch			
60 @ 15	4:1/4:1	3.0	20.0	8	20.9/−11.6	28.1	Car returned to road, very stable.
45 @ 25	4:1/4:1	3.0	20.0	8	19.6	22.5	Car returned to road, did not contact back slope.

[1]Simulation with zero steer input

1 mi/h = 1.609 km/h
1 ft = 0.3048 m

5. Relatively few simulations in this study resulted in vehicle rollover. This reinforces the complexity of the rollover phenomenon, caused by the fact that there are many nonindependent factors involved in vehicle rollover. Among the most important information needed is data for tire properties. Most rollover events occur because of the high tire load and large slip and camber angle conditions. The deficiency in the HVOSM data base could be corrected by acquiring test force characteristics of tires for slip and camber angles ranging up to 90 degrees and for loads including extreme overload.

6. Ultimately, the potential for vehicle rollover associated with roadside features is reflected by real-world accident experience. From the literature review performed, it is apparent that the existing accident data base lacks the comprehensive and detailed information necessary to define the conditions leading to rollover for the different vehicle types. For example, data contained in such accident files NASS (National Accident Sampling System) and FARS (Fatal Accident Reporting System) usually provide little or no information on accident site geometrics (e.g., steepness of slopes, embankment height, and roundings), whether the vehicles were tripped by a surface irregularity or as a result of tire ruts in soft soil; or where rollovers were initiated with respect to the terrain feature (sideslope, backslope, and toe of embankment) vehicle trajectory, etc.

7. The modified HVOSM can predict the response of vehicles operating on off-road terrain with reasonable accuracy. Further, the HVOSM deformable-soil model allows simulation for the effects of tire sinkage, a factor identified as one of the leading causes of rollover. However, evidence of the deformable-soil model's validity is still very limited. A more rigorous validation could be achieved by tests measuring the sinkage and motion-resistance forces of tires in soft soil for various tire loads and sideslip angles from 0 to 90 degrees.

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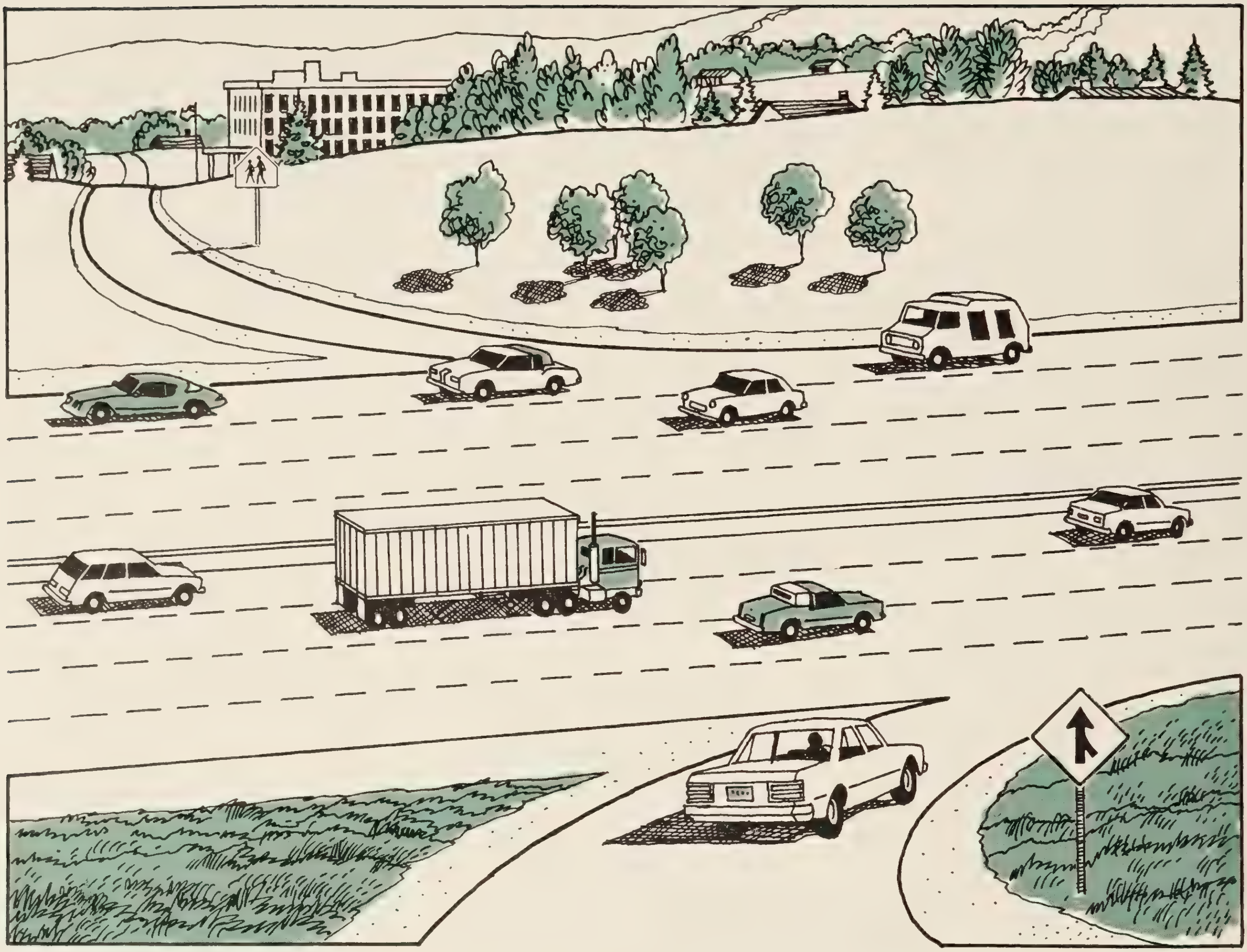


Loglinear Models in Traffic Studies

by Harry S. Lum

Introduction

Model development procedures for categorical data are neither as simple nor as familiar as are the corresponding regression procedures for continuous data. Such procedures are relatively new to traffic engineers—and even to some statisticians—in accident research. Nevertheless, they are important techniques since much of the data used in highway accident research is categorical in nature. Consequently, the new categorical techniques produce models that are stronger and more meaningful than those developed using less appropriate regression techniques. (*1*)[1]

Given the complexity of these procedures, and because the concept of "odds" (rather than the traditional use of percentages as the basic measure of statistical variation) is new to traffic engineers and accident researchers, they should consult a knowledgeable statistician regarding the use of these powerful techniques.

Background

Traditionally, contingency table analyses have been used in analyzing categorical or qualitative response variables for their statistical relationship. In such analyses, which are usually limited to two variables at a time, percentages are calculated for each cell; these are then compared to the percentages expected if there was no relationship between the variables. The chi-square test is the test statistic. If the chi-square value calculated from the observed data is greater than the chi-square value tabulated for some preselected probability level, there is statistical evidence to reject the null hypothesis (i.e., no relationship between the variables) and accept the alternative hypothesis.

[1]Italic numbers in parentheses identify references on page 118.

The required computation of the test statistic for one-way and two-way tables is straightforward, since simple explicit expression for estimating cell frequencies in terms of observed frequencies is available. For tables of order greater than two-way, iterative numerical procedures are used which are time consuming and tedious, because calculations must be carried out to several decimal places to ensure reasonable accuracy of the estimates.

The advent of high-speed mainframe computers greatly eased data manipulations and computations, thereby providing impetus for statisticians to develop and apply sophisticated models and methodologies to previously "unsolvable" problems in a wide variety of fields. Much of this development may be termed loglinear modeling in the same sense one speaks of analysis of variance and regression analysis in dealing with quantitative or continuous variables.

Loglinear Modeling

Loglinear modeling permits researchers to try different models in the same way that multiple linear regression is used to fit data. This is extremely useful in exploratory analysis, where there is no theoretical guidance to assist researchers in determining what variables should be included in their models. How are the effects of each of the many possible variables and the relationships among them segregated, especially when they may be multiplicative rather than additive in nature?[2]

Multiway contingency table analysis, as an extension of two-way contingency table analysis, was a natural candidate for loglinear modeling.Although some theoretical work was done in the 1930's, there was little progress until the 1960's when high-speed computers were readily available. Subsequently, there was a surge in contingency table analysis via loglinear modeling, and a proliferation of methods and ad hoc procedures for various types of problems.

The multiway contingency table approach used here is based on the principle of minimum discrimination information (MDI), which leads to exponential families of the parameters yielding loglinear models. (*2*) A key feature of the MDI approach is that it provides the necessary rationale for a uniform treatment of the many ad hoc procedures and seemingly different approaches to contingency table analysis. Reference (*3*) provides the statistical foundation and theory for this approach.

Estimation Problems

Gokhale and Kullback broadly categorize estimation problems and hypothesis testing into two classes: (1) internally constrained problems (ICP) or restricted models, and (2) externally constrained problems (ECP) or unrestricted models. (*2*) When estimates of the expected frequency are derived and constrained by the observed data—such as the sum of the cell estimates must equal the observed marginal totals—the problem is an internally constrained one. When, on the other hand, constraints are imposed on the basis of some hypothesized values not necessarily suggested by the data set, the problem is an externally constrained one. For the ECP's some constraints may be imposed internally while others may be imposed externally. A numerical example of each class, selected on the basis of application to the traffic engineer, is given below.

The technique of applying the MDI principle is termed the analysis of information; this is analagous to the analysis of variance or regression analysis. As with these techniques, there is a design matrix in which the constraints are reflected and a set of parameters is to be estimated. In particular for multinomial samples, the loglinear equation or model is:

$$\ln[p^*(\omega)/\pi(\omega)] = \tau_0 + \tau_1 c_1(\omega) + \cdots + \tau_r c_r(\omega) \qquad (1)$$

where $\omega = 1, 2, \ldots \Omega$ are cell identifiers.

and $p^*(\omega)$ is the probability of an observation falling into cell ω,

and $\pi(\omega)$ is some arbitrary probability of the observation falling into cell ω.

A letter with an asterisk (p^*) denotes an estimate. For ICP problems, $\pi(\omega)$ is usually the uniform distribution; ceil estimates are constrained by the observed data such that the sum of the cell estimates must equal the observed marginal total. For ECP problems, $\pi(\omega)$ is an hypothesized distribution supplied by the user. The τ's are parameters to be estimated as in a multiple regression equation. A multiway contingency table may be viewed as a multinomial sample and equation (1) is its loglinear representation.

Example 1 - Internal Constraint Problem. The first example tests the hypothesis of no second-order (three-factor) interaction among three variables—severity of accident (severe/not severe), size of vehicle (small/standard), and ejection from vehicle (yes/no)—to determine if there is a relationship among the three factors.

The data were abstracted from reference (*4*) and manipulated to form a smaller set in order to: (1) provide simple illustration of the technique, and (2) demonstrate how one observation—miscoded or for whatever reason—could change the outcome of the statistical test. A detailed analysis of the whole set of data is given in reference (*2*).

Figures 1 and 2 are graphic presentations of the data, together with their estimates.[3] The data in figure 1 are the same as for figure 2, except the frequency for cell

[2]Note that in exploratory analysis one is interested in keeping the type II error (failure to detect) small; in hypothesis testing, on the other hand, it is not desirable to conclude that a relationship exists unless there is strong evidence that the null hypothesis should be rejected. By convention, type I error is usually set to the .05 or .01 significance level. Setting a small type I error automatically increases type II error. In exploratory analyses it may be necessary to compromise with a higher type I error, (e.g. 0.10 probability level). Increasing the sample size would decrease both types I and II errors, but this is not always possible.

[3]These figures are particularly helpful in gaining an understanding of the use of dot notation to indicate summing over an index.

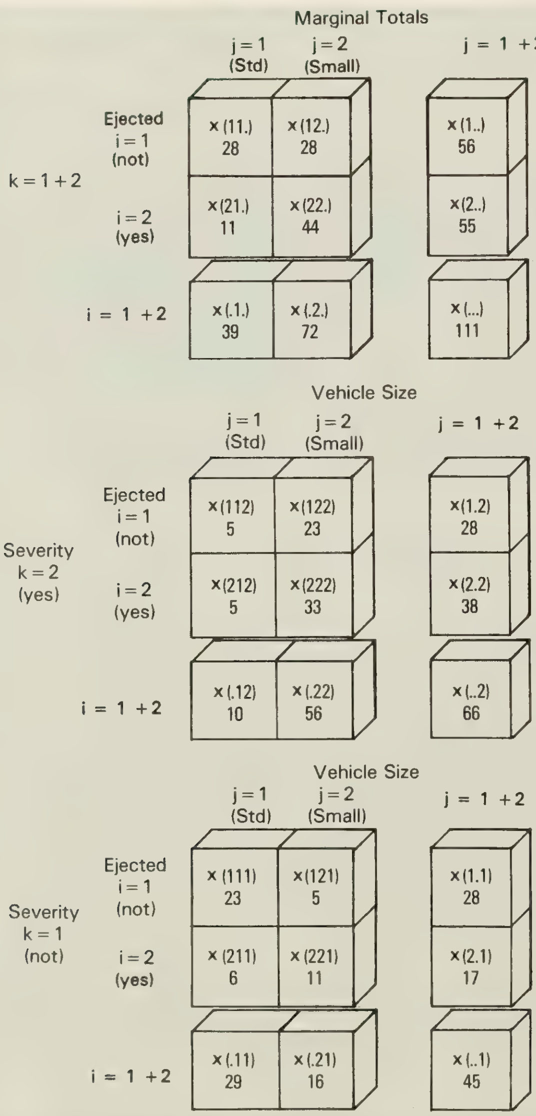
x(212) = 5 has been increased by 1 to 6, and cell x(222) = 33 was reduced by 1 to 32. The constraints to be imposed are that the cell estimates must total to the observed one-way marginal and also to the two-way marginals. (See figures I and 2.) The design matrix reflecting these constraints is:

identifier	ω =	1	2	3	4	5	6	7	8
row	i =	1	1	1	1	2	2	2	2
column	j =	1	1	2	2	1	1	2	2
depth	k =	1	2	1	2	1	2	1	2
Constraints:	1.	1	1	1	1	1	1	1	1
	2.	1	1	1	1	0	0	0	0
	3.	1	1	0	0	1	1	0	0
	4.	1	0	1	0	1	0	1	0
	5.	1	1	0	0	0	0	0	0
	6.	1	0	1	0	0	0	0	0
	7.	1	0	0	0	1	0	0	0

The total number of cells is represented by the number of columns; the number of constraints is represented by the number of rows. The cell estimates shown in figures 1 and 2 were calculated using a mainframe computer program developed in PL/1 computer language by the George Washington University in Washington, D.C. The design matrix and the observed cell counts are the required input to the program. (Note that the program assumes a basic knowledge in probability and statistics using matrix algebra notation.)

The MDI test statistic $2I = 2\Sigma\Sigma\Sigma x(ijk) \ln [x(ijk)/x^*(ijk)] = 3.28$[4] in figure 1 is statistically not significant at the 5 percent level for the chi-square distribution with 1 degree of freedom. In figure 2, the test statistic 2I = 4.32 is statistically significant at the 5 percent level. That a single data point can change a statistical result from not significant to significant should demonstrate to researchers the need to be careful in defining their variables and in coding the data.

[4]The indexes of summation have been omitted for printing convenience. It should be understood that summation is to be taken over the number of row, columns, and depth categories.



Legend

Cell(ijk)		Observed	Estimates
x(111)	=	23	23.15
x(112)	=	5	6.85
x(121)	=	5	6.85
x(122)	=	23	21.15
x(211)	=	6	7.85
x(212)	=	5	3.15
x(221)	=	11	9.15
x(222)	=	33	34.85

Two-way Marginals

Cell(ijk)		Observed		Estimates
x(11.)	=	28	=	21.85 + 6.85
x(12.)	=	28	=	6.85 +21.15
x(21.)	=	11	=	7.86 + 3.15
x(22.)	=	44	=	9.15 +34.85
x(1.1)	=	28	=	21.15 + 6.85
x(1.2)	=	28	=	6.85 +21.15
x(2.1)	=	17	=	7.85 + 9.15
x(2.2)	=	38	=	3.15 +34.85
x(.11)	=	29	=	21.15 + 7.85
x(.12)	=	10	=	6.85 + 3.15
x(.21)	=	16	=	6.85 + 9.15
x(.22)	=	56	=	21.15 +34.85

One-way Marginals

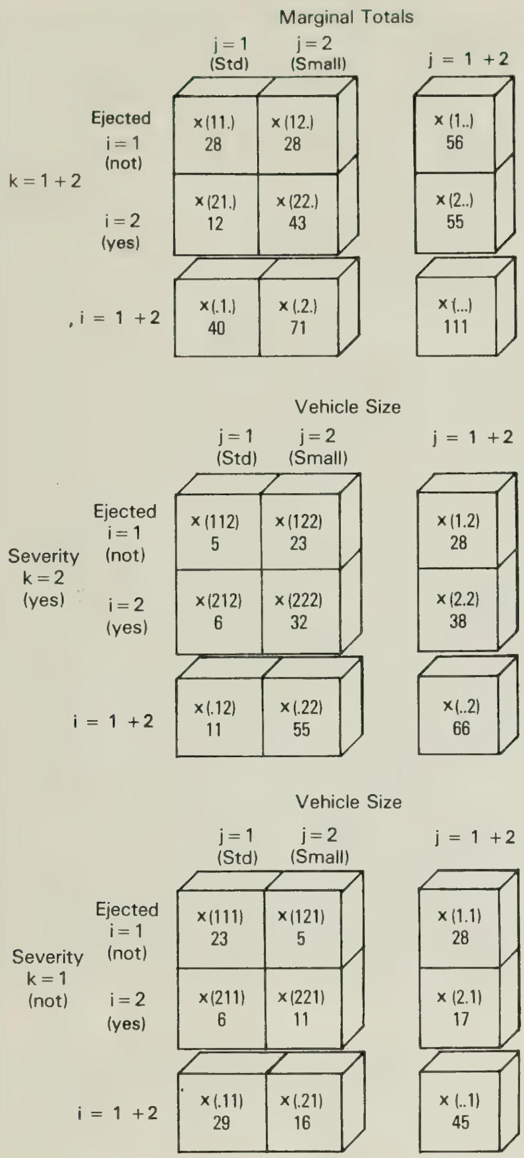
Cell(ijk)		Observed		Estimates
x(1..)	=	56	=	56
x(2..)	=	55	=	55
x(.1.)	=	39	=	39
x(.2.)	=	72	=	72
x(..1)	=	45	=	45
x(..2)	=	66	=	66

Overall Total

x(...) = 111

Test Statistic: 2I = 3.28

Figure 1.—Graphic representation of a 2 by 2 by 2 contingency table and cell estimates under hypothesis of no three- factor interaction.



Legend

Cell(ijk)		Observed	Estimates
x(111)	=	23	20.81
x(112)	=	5	7.19
x(121)	=	5	7.19
x(122)	=	23	20.81
x(211)	=	6	8.19
x(212)	=	6	3.81
x(221)	=	11	8.81
x(222)	=	32	34.19

Two-way Marginals

Cell(ijk)		Observed		Estimates
x(11.)	=	28	=	20.81 + 7.19
x(12.)	=	28	=	7.19 + 20.81
x(21.)	=	12	=	8.19 + 3.81
x(22.)	=	43	=	8.81 + 34.19
x(1.1)	=	28	=	20.81 + 7.19
x(1.2)	=	28	=	7.19 + 20.81
x(2.1)	=	17	=	8.19 + 8.81
x(2.2)	=	38	=	3.81 + 34.19
x(.11)	=	29	=	20.81 + 8.19
x(.12)	=	11	=	7.19 + 3.81
x(.21)	=	16	=	7.19 + 8.81
x(.22)	=	55	=	20.81 + 34.19

One-way Marginals

Cell(ijk)		Observed		Estimates
x(1..)	=	56	=	56
x(2..)	=	55	=	55
x(.1.)	=	40	=	40
x(.2.)	=	71	=	71
x(..1)	=	45	=	45
x(..2)	=	66	=	66

Overall Total

Cell(ijk)		Observed
x(...)	=	111

Test Statistic: 2I = 4.32

Figure 2.—Graphic representation of data shown in figure 1 with one miscoded data point.

Example 2 - External Constraint Problem. In a driving simulation experiment, 24 male and 24 female subjects were asked to drive a route, laid out by researchers, on the driving simulator HYSIM (Highway Simulator) located at the Turner-Fairbank Highway Research Center, McLean, Virginia. They were instructed to drive the route normally, as if they were on the road. The speed of each subject's trip was recorded, without the subject's knowledge, by the computer attached to the simulator. Median speed was calculated, and the numbers of male and female subjects traveling above or below this median speed were tabulated; these are shown in figure 3.

It is fairly evident from both the data and the small chi-square test statistical values that there is no statistical difference between the male and female subjects for each of three signs. (Note the closeness of the two test statistics, 2I and X^2.) An interesting note is that more drivers traveled above the median speed for the parkway sign, while the opposite was true for the other two signs. Thus, based on the data, it is obvious that the driver-subjects behaved differently as they approached different signs. Regardless, the MDI approach to testing the homogeneity of the three tables is illustrated below as an example of an external constraint problem.

In this problem, the constraints are imposed on the cells rather than on the marginal totals as in the first example. The required constraints and the computed cell estimates

	i = 1 (School Sign)			i = 2 (Parkway Sign)			i = 3 (Merging Sign)		
	k = 1 (Male)	k = 2 (Female)	Total	k = 1 (Male)	k = 2 (Female)	Total	k = 1 (Male)	k = 2 (Female)	Total
j = 1 (Above Median)	6	7	13	19	15	34	9	4	13
j = 2 (Below Median)	18	17	35	5	9	14	15	20	35
Total	24	24	48	24	24	48	24	24	48

Test Statistic 2I = .106 (X^2 = .105)   2I = 1.63 (X^2 = 1.61)   2I = 2.69 (X^2 = 2.64)

Constraints:

1. x*(111) + x*(112) + x*(121) + x*(122) = 48
2. x*(211) + x*(212) + x*(221) + x*(222) = 48
3. x*(311) + x*(312) + x*(321) + x*(322) = 48
4. x*(111) = x*(211)
5. x*(211) = x*(311)
6. x*(112) = x*(212)
7. x*(212) = x*(312)
8. x*(121) = x*(221)
9. x*(221) = x*(321)

Cell Estimates Under Constraints

	k = 1 (Male)	k = 2 (Female)	Total
j = 1 (Above Median)	11.22	8.22	19.55
j = 2 (Below Median)	12.30	16.15	28.45
Total	23.52	24.58	48.00

Note: Estimates are denoted by an asterisk, e.g., x*(ijk).

Figure 3.—Graphic representation of a three sample contingency table with constraints imposed to test for homogeneity.

are shown in figure 3. The design matrix reflecting the constraints for input to the computer program is:

identifier	ω	=1	2	3	4	5	6	7	8	9	10	11	12
sample (signs)	i	=1	1	1	1	2	2	2	2	3	3	3	3
row	j	=1	1	2	2	1	1	2	2	1	1	2	2
column	k	=1	2	1	2	1	2	1	2	1	2	1	2
Constraints:	1.	1	1	1	1	0	0	0	0	0	0	0	0
	2.	0	0	0	0	1	1	1	1	0	0	0	0
	3.	0	0	0	0	0	0	0	0	1	1	1	1
	4.	1	0	0	0	−1	0	0	0	0	0	0	0
	5.	0	0	0	0	1	0	0	0	−1	0	0	0
	6.	0	1	0	0	0	−1	0	0	0	0	0	0
	7.	0	0	0	0	0	1	0	0	0	−1	0	0
	8.	0	0	1	0	0	0	−1	0	0	0	0	0
	9.	0	0	0	0	0	0	1	0	0	0	−1	0

The computed test statistic 2I = 2ΣΣΣx*(ijk) [ln x* (ijk)/x (ijk)] has a value of 30.71, which is statistically highly significant beyond the .001 significance level for 6 degrees of freedom for the chi-square distribution. Note the differences in the computational formulas for the internal and external constraint problems.

No traffic engineering substance is intended with these two examples. Rather, the purpose is to demonstrate an analysis technique, which is unfamiliar to most traffic engineers, applied to two problems that frequently arise in their research efforts.

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Mower-Thrown Object Accidents

by Kurt M. Marshek, Rowan E. DaSilva, Srikanth M. Kannapan

Introduction

The incidence of tractor mower-thrown object (MTO) accidents involving the public during the maintenance of highways and adjoining rights-of-way has become an ever-increasing problem to the Texas State Department of Highways and Public Transportation (TSDHPT). In fact, approximately 20 percent of the 900 insurance claims submitted to TSDHPT's insurance carriers in 1984 were directly related to MTO accidents. In an effort to curb accident frequency and severity and improve public relations, TSDHPT recently sponsored a research investigation to evaluate the effectiveness of various mower design improvements and identify possible remedial measures to the MTO problem.

More specifically, the objectives of the research investigation were to:

- Study existing TSDHPT equipment, mowing practices, and accident data together with available reports on mowing practices and equipment of approximately 30 other States.
- Visit mower manufacturers in Texas to review past and present developments related to the reduction of MTO accidents.
- Form a data base to help identify specific patterns in accident causes.
- Recommend changes in equipment design.
- Evaluate the effectiveness of various bat-wing mower design improvements by performing field tests and studies.

- Identify possible remedial measures to reduce the MTO problem, and explore the potential for implementing these solutions in Texas.

Accident Control Measures

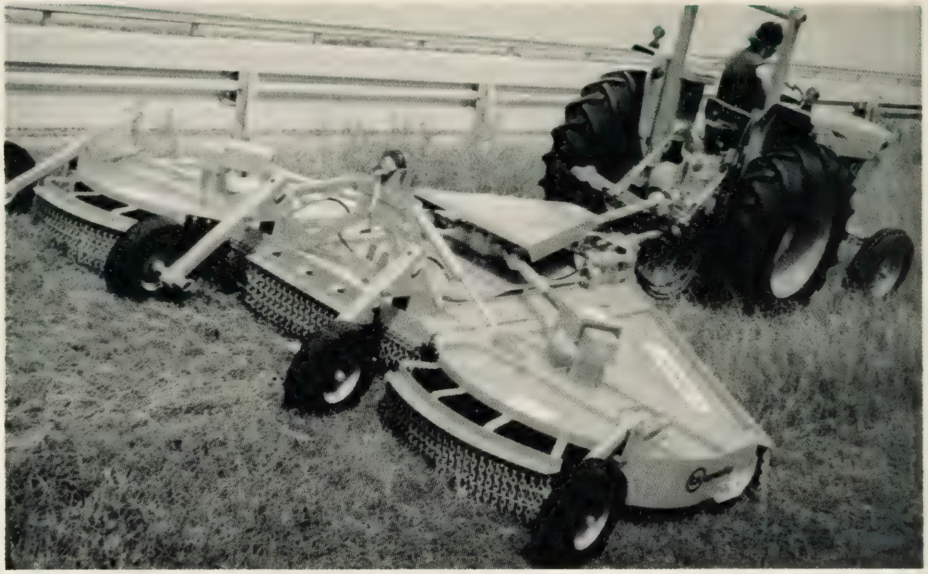
The most popular mower for State highway departments is the rotary blade type, which gave the best results over a broad spectrum of roadside conditions, had the highest production rates, and had the least maintenance and downtime costs. However, the rotary blade also was the type with the highest MTO accident rate. To control this problem, States have taken several measures, including:

- Restricting the height of cut to 6 in.
- Using chain guards.
- Choosing proper equipment.
- Using herbicides and retarders.
- Enhancing operating training.
- Cleaning area prior to mowing.

TSDHPT Data Analysis

Almost 150 accident reports for 1984 were obtained from TSDHPT, entered into a data base, and analyzed to develop correlations between accidents and variables (such as time of day and mower-motorist orientation); these correlations were developed to provide insight into how and why MTO accidents occur.

Time of day. Time of day seemed to have some correlation with the number of accidents but its significance is questionable. It is not known if a reduction in the number of accidents was due to fewer motorists or fewer mowers being operated. As shown in figure 1, few accidents occurred before 9 a.m., possibly because there were fewer motorists in the morning. The number of accidents also fell during the noon hour and after 4 p.m., probably because of a decrease in the number of mowers. The largest number of accidents occurred in the early afternoon, most likely due to large numbers of motorists and mowers.



Most popular mower is the rotary blade type.

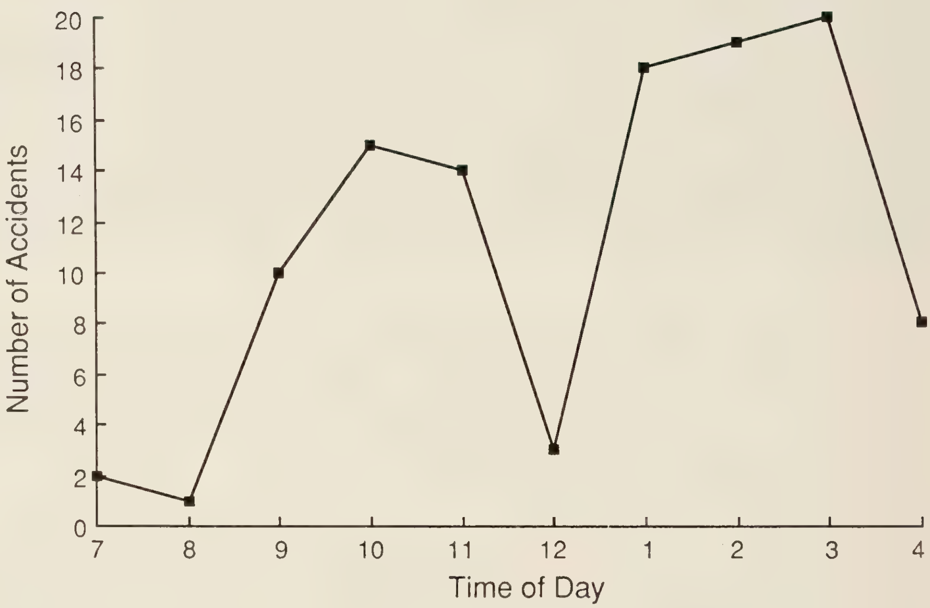


Figure 1.—Number of accidents by time of day.

Time of month. The summer and fall months experienced the largest number of accidents as shown in figure 2, probably due to the increased number of motorists. Fewer accidents were reported in the winter and spring months, presumably due to a decrease in mowing activity.

Type of mower. The most widely involved type of mower was the rotary bat-wing type. The second largest group consisted of 30 different flex-wing mowers. Figure 3 shows the types of mowers involved in MTO accidents in Texas.

Vehicle region struck. Windshields were hit in over 39 percent of the reported accidents; the second most vulnerable place was the right side of the vehicle, which had 33 hits. The left side was hit 19 times. There were a few incidents of personal injury. Although most of the damage was caused by rocks, other debris—including concrete, metal, wood, and an armadillo—also was thrown (see figure 4).

Direction of travel. Five directions were used to classify the positional relationships between the mowers and the cars, as shown in figure 5. The largest number of accidents (39) occurred when the mower and the damaged vehicle were traveling in the same direction and the car was to the left of the mower. The second largest group also consisted of vehicles traveling in the same direction as the mowers but to the right of the mowers. Twelve vehicles were struck while traveling in the opposite direction of and to the right of the mower. Six accidents occurred when the mower and car were perpendicular to each other. The remaining records did not list vehicle position.

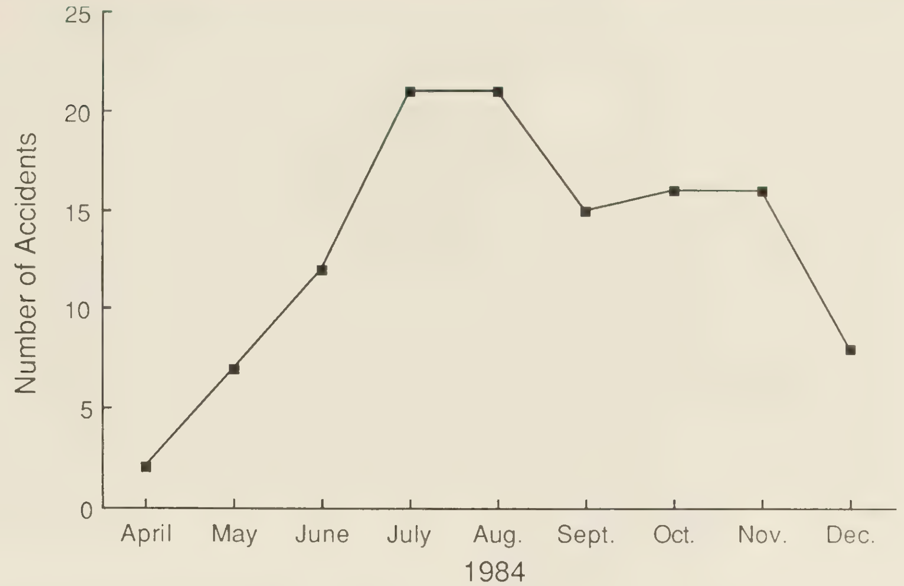


Figure 2.—Number of accidents by month.

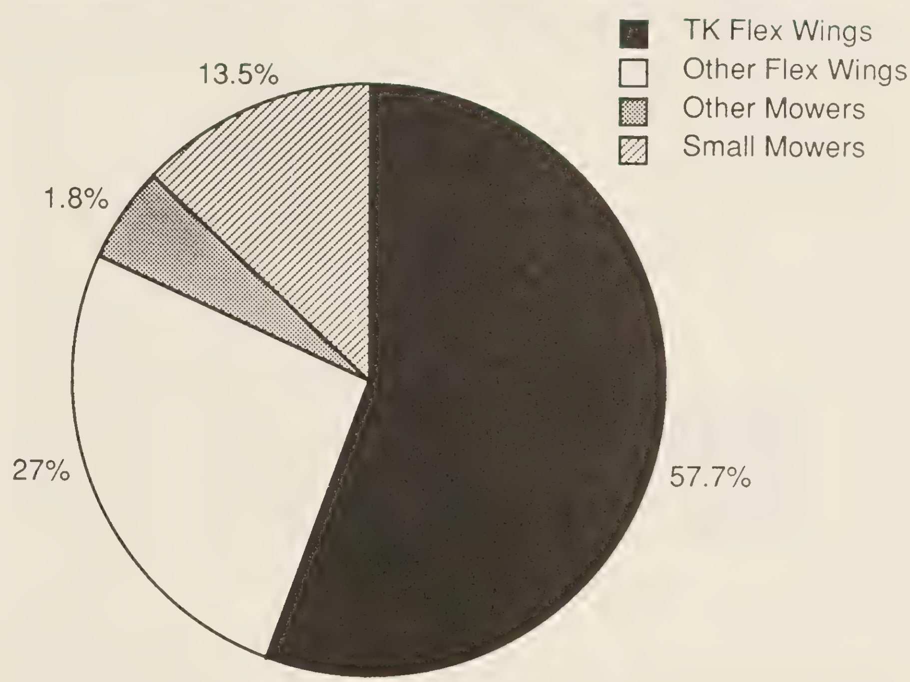


Figure 3.—Mower types involved in MTO accidents.

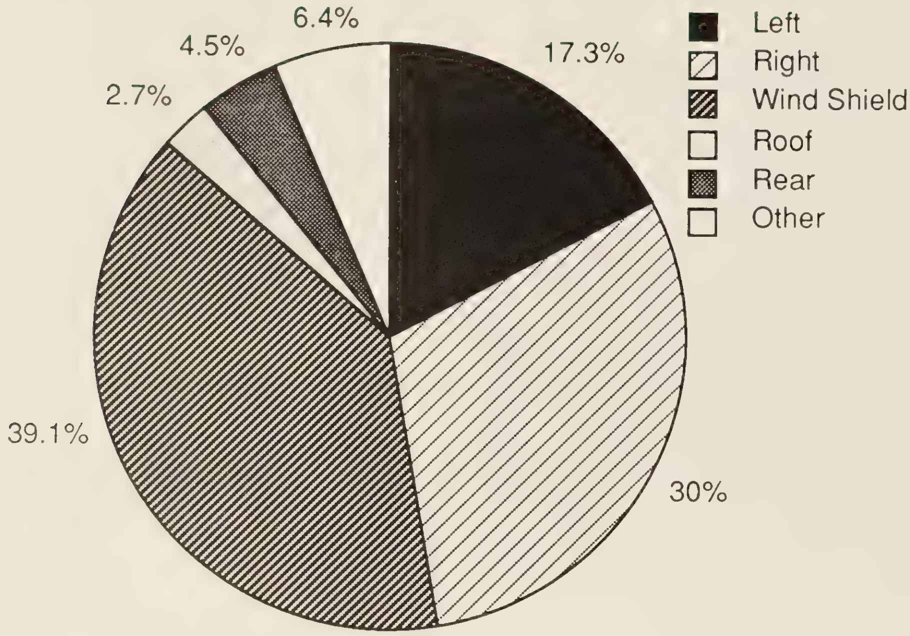


Figure 4.—Vehicle regions of impact.

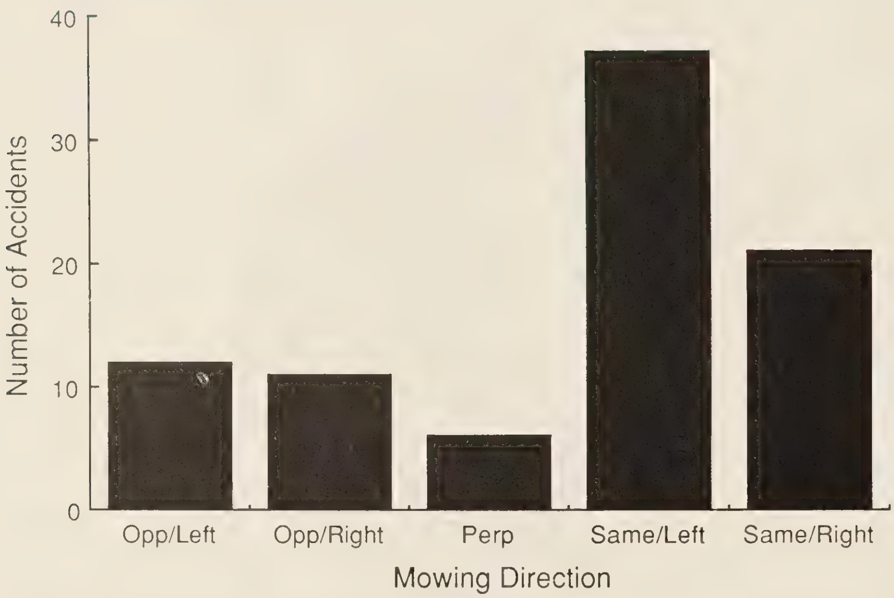


Figure 5.—Number of accidents vs mowing direction.

Field Experiments

Experiments were conducted to determine the types of objects hit by bat-winged mowers and the effects of this hit on the objects. These variables were considered:

- Object size.
- Object mass.
- Location of object entry into mower.
- Direction of mowing (forward, backward).
- Chain and cable guards (with, without).

Preliminary testing indicated that two types of objects should be used: 4-in pressure-treated wooden cubes and 3- to 5-in limestone rip-rap. A bat-wing mower with pivoted lift blades and a 15-ft cutting span was used in the experiments. The effectiveness of three different safety devices was evaluated. They are:

(1) Mowing with chains and cables.

(2) Mowing with chains but without cables.

(3) Mowing without chains and without cables.

A testing method was developed for a 400- by 600-ft testing site. Mowing was performed both forward and backward, and wooden blocks and limestone rip-rap were placed at predetermined locations. The tests were repeated under various conditions: with and without chains and cables; forward and backward; and over level and uneven terrain. Average distance of thrown objects was calculated for four trials and for each of the 15 stations.

All testing done with rocks and blocks showed that the operation of the mower without chains produced the longest object travel. However, the distinction between using cables during operation and not using them is not as clear. For block testing, the results from maximum distances and the distance distribution indicate that there was virtually no difference between using and not using cables; there was, however, a slight increase in average distance when the cables were not used. For rock testing, average distances and maximum distances were slightly greater in testing without cables. The distance distribution also supports the conclusion that rocks travel slightly farther without cables.

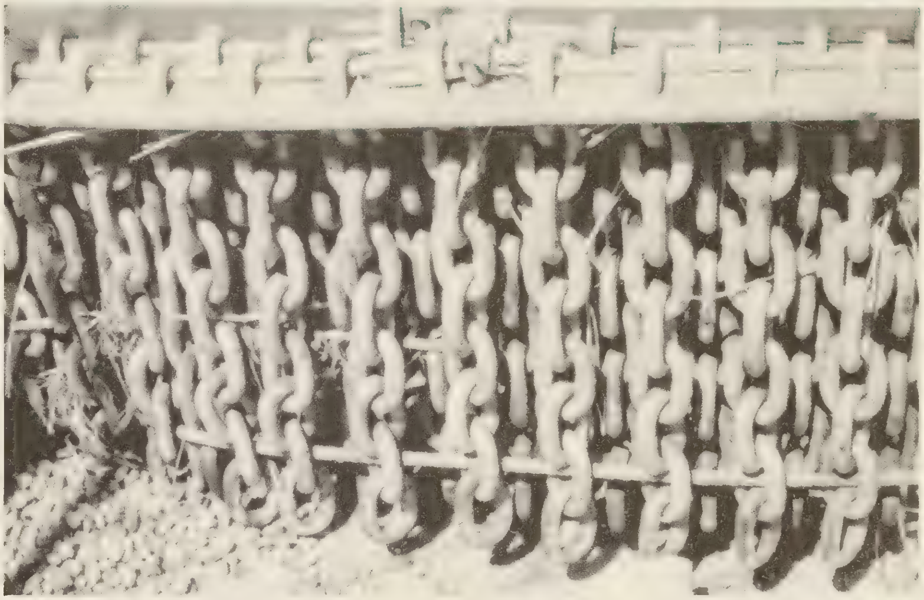
Discussion of Results

Test results show that the safety devices on current mowers (chains, cables, skirts, etc.) are effective in normal use: When used properly and with care, the mower is relatively safe. These safety devices, however, cannot stop every object from being thrown from the mower—under certain conditions, the mower is likely to throw an object.

When used in a forward direction, the mower tended to throw objects out to the back of the mower. This was mainly due to the way in which the cutting height was set for the mower. The height of the mower's rear was set 1 in higher than the front. The resulting angle tended to force the objects that were hit forward, and down slightly so that the chains were more effective in deflecting them to the ground. Also, objects hit forward could be hit again and finally exit the back of the mower.

When objects were thrown forward by one of the blades, the chain guards tended to either deflect them down or backward into the mower. The chain guards were solid down to about the level of the blades; the chains were attached below this point. A comparison of the tests performed with and without chains shows that without both chains and chain guards, many objects were thrown forward. Also, the objects thrown in these tests were very large. Sometimes the entire rock or block was thrown. This shows the effectiveness of the front chain guards and chains in preventing objects from exiting this area.

Bat-winged mower in operation.



Mower with chains and cables.

Canvas skirt used as a safety device.

One of the safety devices used on mowers involved cables through a lower link in the chains. The test results did not show a significant effect in reducing the distance a lighter weight object (e.g., wood) is thrown. The cables did seem effective in reducing the distance a heavy object (e.g., rock) was thrown. The cables helped the chains act as a curtain.

Finally, the tests showed that objects were thrown farther when the mower was used in a backward direction than when it was pulled forward. Objects that entered the mower from the back tended to exit the mower immediately after being hit. This was because the back was higher than the front, and thus provided less resistance to the object's flight (figures 6 and 7).

Conclusion

Most of the States participating in this study regard the height of the cut as a major contributing factor to MTO accidents. Therefore, restricting the height of cut to 6 in will reduce MTO accidents.

Since field experiments with a batwing rotary mower showed that most debris exited the right side rear of the mower, tractor/mower drivers should be made aware of this danger zone so they can avoid placing coworkers or others in this area. In addition, mowers should move against traffic since statistics show that this is the safest way to mow. In this configuration, the motorist and any MTO's are traveling in the same direction, and the impact velocity from the MTO is lessened.

Field experiments showed that mowing without safety chains was significantly more dangerous than mowing with them, and that mowing without the cables that were strung through safety chains was slightly more dangerous than mowing with the strung cables.

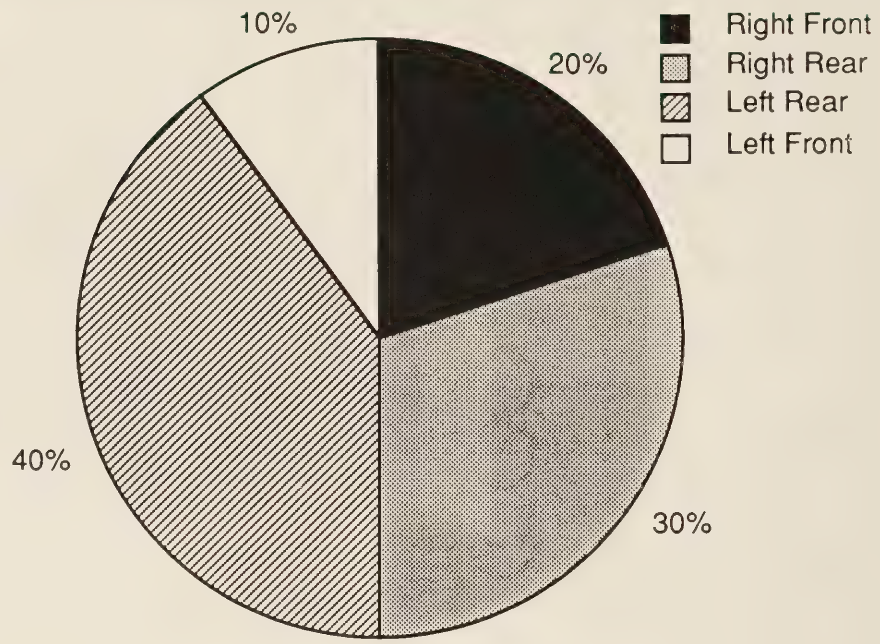


Figure 6.—Percentage of rock exiting the mower in each direction for testing with safety devices and mowing in forward direction.

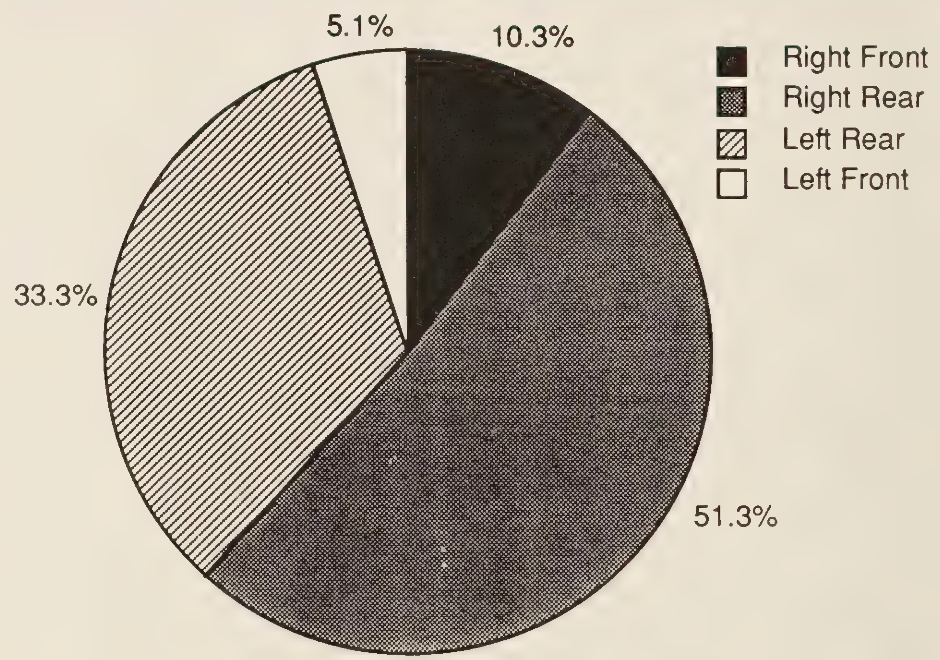


Figure 7.—Percentage of blocks exiting the mower in each direction for testing with safety devices and mowing in forward direction.

Recent Research Reports You Should Know About

The following are brief descriptions of selected reports recently published by the Federal Highway Administration, Office of Research, Development, and Technology (RD&T). The Office of Engineering and Highway Operations Research and Development (R&D) includes the Structures Division, Pavements Division, and Materials Division. The Office of Safety and Traffic Operations R&D includes the Traffic Systems Division, Safety Design Division, and Traffic Safety Research Division. All reports are available from the National Technical Information Service (NTIS). In some cases limited copies of reports are available from the RD&T Report Center.

When ordering from the NTIS, include the PB number (or the report number) and the report title. Address requests to

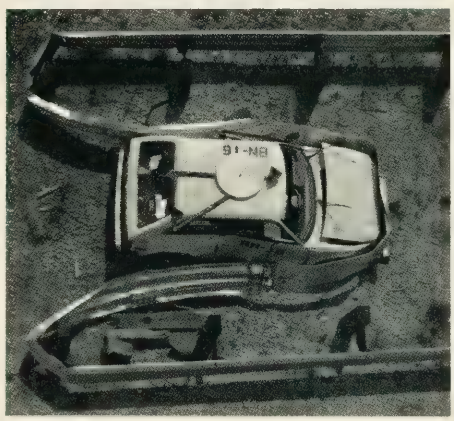
National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

Requests for items available from the RD&T Report Center should be addressed to

Federal Highway Administration
RD&T Report Center, HRD–11
6300 Georgetown Pike
McLean, Virginia 22101–2296
Telephone: (703) 285–2144

Median Barrier Terminals and Median Treatments, Vol. I, Research and Appendix A, Publication No. FHWA–RD–88–004, Vol. II, Appendixes B and C, Publication No. FHWA–RD–88–005

by Safety Design Division



These reports present the details of the bullnose median treatment development. The system is based on the modified thrie-beam guardrail system with a flat plate nose element. The thrie beam makes this bullnose system more effective in capturing a wide variety of vehicles because it is 30 percent deeper than the standard w-beam. This deeper cross section minimizes those cases where the vehicle either becomes wedged under the rail or vaults over the system. Sixteen full-scale developmental crash tests, using the bullnose median terminal concept, were conducted based on NCHRP Report 230 guidelines. Although several of the Report 230 tests were not performed, the final design was shown to provide a higher degree of protection than many currently used median barrier terminal treatments.

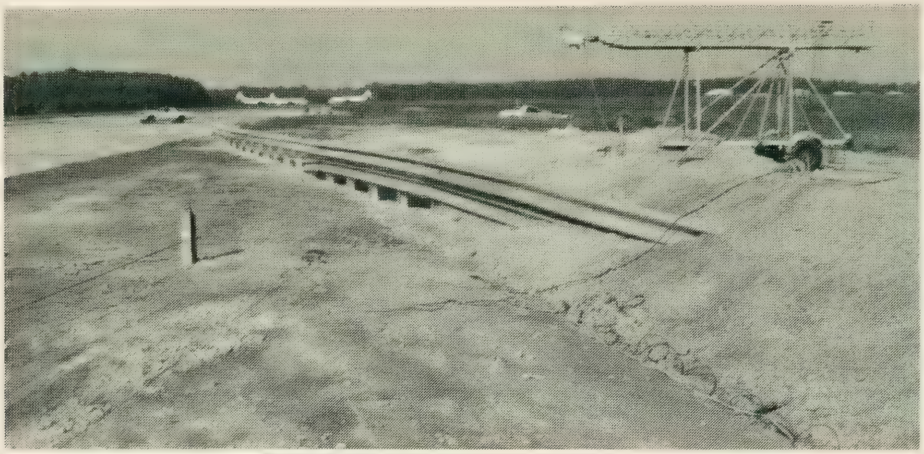
These reports may only be purchased from the NTIS: (Vol. II, PB No. 88–142344/AS, Price code: A02; Vol. II, PB No. 88–142351/AS, Price code: A16).

Evaluation of Cathodic Protection Criteria for the Rehabilitation of Bridge Decks, Publication No. FHWA–RD–88–141

by Structures Division

This report describes the installation of a cathodic protection (CP) system to a salvaged bridge deck section removed during the replacement of a bridge deck on the George Washington Memorial Parkway in Northern Virginia. The CP system consisted of grooves, cut into the deck surface on 1-ft centers, and filled with an electrically-conductive grout to distribute impressed current to the underlying steel. Various current and potential levels were tried in an attempt to establish the necessary criteria to stop the corrosion of reinforced steel embedded in salt-contaminated concrete. The results of this research are of primary interest to corrosion engineers, although design and maintenance engineers, contractors, and others will have an interest in the construction of such CP systems to extend the life of bridge structures through the application of cathodic protection.

This report may only be purchased from the NTIS: PB No. 89–116461/AS, Price code: A05).



Test and Evaluation of Guardrail Terminals Buried-in-Backslopes, Publication No. FHWA–RD–88–142

by Safety Design Division

This report documents the results of six full-scale crash tests that were conducted to evaluate two types of buried-in-backslope terminal designs. The first design was constructed in accordance with FHWA and AASHTO design guidelines. After one modification this rail was successfully full-scale crashed tested. The second design, which was representative of a typical installation failed the acceptance criteria. The report also presents a survey of several State practices and a design and cost analysis of select designs.

Limited copies of this publication are available from the RD&T Report Center. This publication also may be purchased from the NTIS: (PB No. 88–217385/AS, Price code: A05).

Reliability of System Detector Data in Replicating Field Conditions for the Integrated Motorist Information System, Publication No. FHWA–RD–88–192

by Traffic Systems Division

This report describes the results of a study performed under FHWA's Graduate Research Fellowship (GRF) program which investigated the feasibility of using data collected by loop detectors in a typical freeway surveillance and control system as a substitute for speed and travel time data collected through traditional travel time and delay field studies. Several relationships between field and system data collected at an existing freeway surveillance and control system were developed. With some calibration, these relationships should be applicable to other systems.

The report may only be purchased from the NTIS: (PB No. 89–117691/AS, Price code: A06).

Development of Fuel Consumption and Vehicle Emissions Relationships for Congested Freeway Flow Conditions, Publication No. FHWA–RD–88–205

by Traffic Systems Division

This report describes the results of an FHWA staff study that examined several types of relationships between fuel consumption, vehicle emissions, and various operating parameters, and tested them using real-world vehicle trajectories from congested freeway segments. The most practical of these relationships uses total distance traveled and total travel time as independent variables. These relationships are very highly correlated with the test data for both total fuel consumed and total emissions of the three major types of pollutants. A computational example of the potential usefulness of the relationships developed is given.

The report may only be purchased from the NTIS: (PB No. 89–117683/AS, Price code: A06).

Bridge Rail Designs and Performance Standards, Report No. FHWA/RD–87/049

by Safety Design Division

This report contains information of interest to engineers who select and design bridge rails. All of the State standard bridge rails were reviewed and the "best" designs were selected for crash testing. Findings indicated that some of the bridge rail designs did not perform very well when tested with 1,800-lb cars at 60 mi/h and 20 degrees, or with 4,500-lb cars at 60 mi/h and 25 degrees. Therefore, safer designs were developed. The report contains drawings of the recommended designs and new bridge railing geometric criteria that will be helpful to designers. A performance level approach for selecting bridge rails is proposed.

Limited copies of this report are available from the RD&T Report Center. Copies of this report also may be purchased from the NTIS: (PB No. 89–122576/AS; Price code: A08).

Malfunction Management System, Report No. FHWA/RD–87/054, Vol. I, Functional Specifications, and Vol. II, Final Report, Report No. FHWA/RD–87/055

by Traffic Systems Division

This study examines the cost-effectiveness of various malfunction management techniques and concludes that a fast digital device could be installed in most intersection controller cabinets to test load switches, signal lamps, loop amplifiers, flashers, and the conflict monitor. A message can be dispatched if out-of-specification operation of any component is detected and redundant load switches, flashers, and loop amplifiers switched in, if needed. If the controller itself fails, the device would take over operation of the intersection in a simple pre-timed mode. No modification to the controller would be required. All functions have been demonstrated in a laboratory environment.

Volume I of this report describes the functions that the contractor believes would be cost-effective. Volume II, Final Report, describes the conduct of the research and the reasoning that lead to the functional specifications in Volume I.

Limited copies of this report are available from the RD&T Report Center. These reports also may be purchased from the NTIS: (Vol. I, PB No. 89–100689/AS, Price code: A03; Vol. II, PB No. 89–100697/AS, Price code: A07).

Luminaire Supports Capability Test Program, Publication Nos. FHWA–RD–88–226 through FHWA–RD–88–266

by Safety Design Division

A series of tests recently was completed to determine the capability of currently accepted luminaire support devices to pass the new (1985) AASHTO proposed criteria. These criteria are currently under consideration by FHWA for use on Federal-aid highways. A total of 44 devices was evaluated, 41 at the Federal Outdoor Impact Laboratory (FOIL) and 3 at Mobility Systems and Equipment Company. The FOIL test program included 63 experiments, all utilizing the bogie vehicle. The luminaire supports were all provided by the manufacturers at no cost to the government, and the tests were performed at no cost to the manufacturers. This cooperative arrangement was negotiated to provide the necessary data base to determine the adequacy of the new proposed AASHTO criteria. The tests at the FOIL included 45 at 20 mi/h (8.9 m/s) and 18 at 60 mi/h (26.8). Fewer high-speed tests were conducted because many of the devices had a very high change in velocity at low speed, and could possibly have caused damage to the bogie at high speed.

Three additional devices were evaluated by Mobility Systems and Equipment Company using full-scale automobiles. Five tests were conducted; three at 20 mi/h (8.9 m/s), and two at 60 mi/h (26.8 m/s).

A separate test report was prepared for each device evaluated at the FOIL, providing details of each experiment.

These reports may only be purchased from the NTIS:

Report No.	Luminaire Supports Capability Test: Program Test Nos.	NTIS No./Price Code
FHWA–RD–88–226	86F0666	PB89–108252/AS (A03)
FHWA–RD–88–227	86F067/86068	PB89–108260/AS (A03)
FHWA–RD–88–228	86F069/86070	PB89–108278/AS (A03)
FHWA–RD–88–229	86F071	PB89–108286/AS (A03)
FHWA–RD–88–230	86F072/86073	PB89–108294/AS (A03)
FHWA–RD–88–231	86F074	PB89–108302/AS (A03)
FHWA–RD–88–232	86F075/86079	PB89–108310/AS (A03)
FHWA–RD–88–233	86F077	PB89–108328/AS (A03)
FHWA–RD–88–234	86F076/86078	PB89–108336/AS (A03)
FHWA–RD–88–235	86F087	PB89–108344/AS (A03)
FHWA–RD–88–236	86F085/86086	PB89–108351/AS (A03)
FHWA–RD–88–237	86F088	PB89–108369AS (A03)
FHWA–RD–88–238	86F091	PB89–108377/AS (A03)
FHWA–RD–88–239	86F083/86084	PB89–108385/AS (A03)
FHWA–RD–88–240	86F081/86082	PB89–108393/AS (A03)

FHWA–RD–88–241	86F080	PB89–108401/AS (A03)
FHWA–RD–88–242	86F089/86090	PB89–108419/AS (A03)
FHWA–RD–88–243	87F001	PB89–108427/AS (A03)
FHWA–RD–88–244	87F002/86003	PB89–108435/AS (A03)
FHWA–RD–88–245	87F004	PB89–108443/AS (A03)
FHWA–RD–88–246	87F012	PB89–108450/AS (A03)
FHWA–RD–88–247	87F013	PB89–108468/AS (A03)
FHWA–RD–88–248	87F014	PB89–108476/AS (A03)
FHWA–RD–88–249	87F020	PB89–108484/AS (A03)
FHWA–RD–88–250	87F021	PB89–108492/AS (A03)
FHWA–RD–88–251	87F022	PB89–108500/AS (A03)
FHWA–RD–88–252	87F023	PB89–108518/AS (A03)
FHWA–RD–88–253	87F033/87034	PB89–108526/AS (A03)
FHWA–RD–88–254	87F051	PB89–108534/AS (A03)
FHWA–RD–88–255	87F053/87054/87F072	PB89–108542/AS (A04)
FHWA–RD–88–256	87F054/87055	PB89–108559/AS (A03)
FHWA–RD–88–257	87F068/86070	PB89–108567/AS (A03)
FHWA–RD–88–258	87F069/87071	PB89–108575/AS (A03)
FHWA–RD–88–259	87F173/87F074	PB89–108583/AS (A03)
FHWA–RD–88–260	87F075/87076	PB89–108591/AS (A03)
FHWA–RD–88–261	87F115	PB89–108609/AS (A03)
FHWA–RD–88–262	87F116	PB89–108617/AS (A03)
FHWA–RD–88–263	87F117	PB89–108625/AS (A03)
FHWA–RD–88–264	87F111/87F113/87118	PB89–108633/AS (A03)
FHWA–RD–88–265	87F112/87114	PB89–108641/AS (A03)
FHWA–RD–88–266	87F119/87120	PB89–108658/AS (A03)

A summary report, No. FHWA/RD–87/104, has been prepared and will be available from the NTIS later this year.

Automated Imaging System for Bridge Inspection, Vol. II, Report No. FHWA/RD–87/090

by Structures Division

This report describes the design, operation, and capabilities of the ultrasonic imaging system developed for the FHWA. The system uses computerized data acquisition and a lightweight scanner to obtain color coded images of defects in metal bridge components. Several types of images are obtained, including holographic reconstruction of defects. Defect size, location, and type can be obtained from these images.

This volume is the second in the series. Limited copies are available from the RD&T Report Center and also may be purchased from the NTIS: (No. ADA-198844; Price code: A05) Volume I, Executive, Summary, Report No. FHWA/RD—87/089 may only be purchased from the NTIS: (PB No. 89-134571/AS; Price Code: A03.)

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

The following are brief descriptions of selected items that have been completed recently by State and Federal highway units in cooperation with the Office of Implementation, Offices of Research, Development, and Technology (RD&T), Federal Highway Administration. Some items by others are included when the items are of special interest to highway agencies. All reports are available from the National Technical Information Service (NTIS). In some cases limited copies of reports are available from the RD&T Report Center.

When ordering from the NTIS, include the PB number (or the report number) and the report title. Address requests to

National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

Requests for items available from the RD&T Report Center should be addressed to

Federal Highway Administration
RD&T Report Center, HRD–11
6300 Georgetown Pike
McLean, Virginia 22101–2296
Telephone: (703) 285–2144

Traffic Conflict Techniques for Safety and Operations, Engineers Guide, Publication No. FHWA–IP–88–026

by Office of Implementation

This guide provides basic background information and the methodology for using traffic conflict studies to analyze safety and operational problems at signalized and unsignalized intersections. The guide was prepared for engineers and supervisors who have the responsibility for analyzing conflict data and making decisions and recommendations for operational improvements.

The Traffic Conflict Techniques (TCT) have been packaged into an engineers guide. TCT studies can be used to diagnose specific unsafe traffic conditions, select corrective treatments and evaluate effectiveness of countermeasures without having to wait for the long periods of time normally required to develop an accident history.

This publication may only be purchased from the NTIS: (PB No. 89–116164/AS, Price Code: A06).

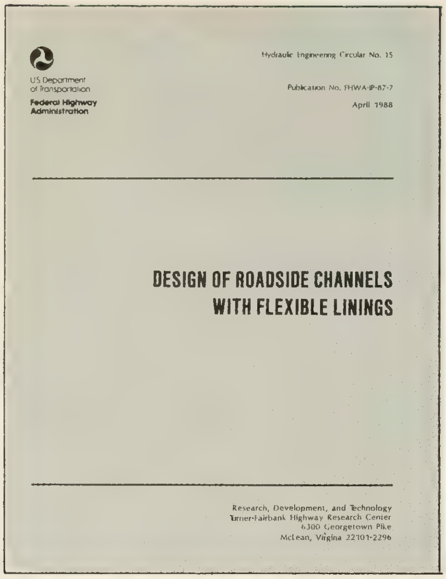
Heavy Vehicle Median Barrier, Publication No. FHWA–TS–88–024

by Office of Implementation

This publication discusses the performance of the Heavy Vehicle Median Barrier (HVMB) and presents criteria for identifying situations where this barrier should be used. The HVMB is a modified (42-in high) New Jersey Safety Shape Median Barrier capable of redirecting heavy vehicles such as buses and van-type tractor-trailers with low centers of gravity. The barrier was originally developed to deter trucks from crossing the median and colliding with oncoming vehicles.

This publication may only be purchased from the NTIS: (PB No. 89–117675/AS, Price code: A04).

Design of Roadside Channels with Flexible Linings, (Hydraulic Engineering Circular No. 15), Publication No. FHWA-IP-87-7



by Office of Implementation

This Implementation Package provides guidance for the design of stable conveyance channels using flexible linings. Flexible linings are able to conform to changes in channel shape while maintaining the overall lining integrity.

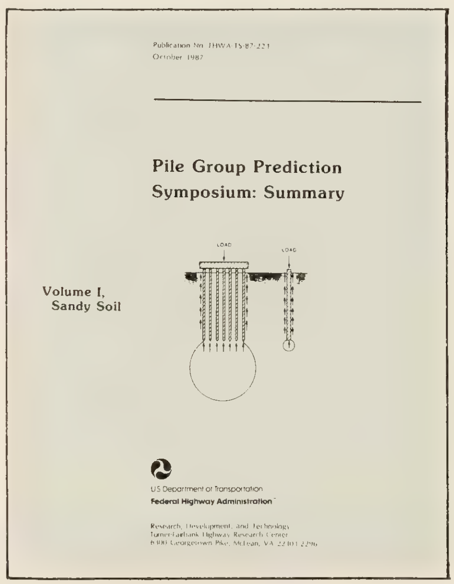
Design procedures are given for rock riprap, wire-enclosed riprap, woven paper net, synthetic mat, and others. Special procedures are presented for composite channels and channels with steep gradients.

Limited copies of the publication are available from the RD&T Report Center. Copies also may be purchased from the NTIS: PB No. 89–122584/AS, Price code: A07).

Pile Group Prediction Symposium: Summary, Vol. I, Sandy Soil, Report No. FHWA–TS–87–221 and Vol. II, Clay Soil, Report No. FHWA–TS–87–222

by Office of Implementation

These reports document the results of two separate symposiums that presented various methods for estimating the load-carrying capacity of pile groups in sandy soils and clay soils, respectively. In each case, 11 experts presented their methods and the results of their evaluations of the load capacity of the pile group. The summary reports describe each method used and the load capacity prediction resulting from each method. The reports also provide a comparison of the predicted results with the results of load tests conducted on each pile group.



Limited copies of these reports are available from the RD&T Report Center. Copies also may be purchased from the NTIS: (Vol. I, PB No. 88–170378, Price code: A08; Vol. II, PB No. 88–170386, Price code: A04).

Asphalt Seal Coats, Report No. WA–RD 136.1

by Washington State Department of Transportation

This Highway Planning and Research study was conducted by the Washington State Department of Transportation. This manual is written for those who direct or physically construct asphalt seal coats and is based on field experiences. The manual describes various types of seal coats, elaborates on the reasons for seal coating, and places particular emphasis on the factors which can affect obtaining consistently good seal coats.

Some of the factors addressed include weather, type of asphalt, choice of cover rock, and uniform distribution and application.

The information contained in this manual will be used in training courses presented by the National Highway Institute and has been reprinted by the FHWA for this purpose.

Limited copies of the report are available from the RD&T Report Center. Copies also may be purchased from the NTIS: (PB No. 89–126155/AS, Price code: A03).

New Research in Progress

The following new research studies reported by FHWA's Office of Research, Development, and Technology are sponsored in whole or in part with Federal highway funds. For further details on a particular study, please note the kind of study at the end of each description and contact the following: Staff and administrative contract research—*Public Roads* magazine; Highway Planning and Research (HP&R)—performing State highway or transportation department; National Cooperative Highway Research Program (NCHRP)—Program Director, National Cooperative Highway Research Program, Transportation Research Board, 2101 Constitution Avenue, NW., Washington, DC 20418.

NCP Category A—Highway Safety

NCP Program A.1: Traffic Control for Safety

Title: Speed Control Methods in Work Zones. (NCP No. 4A1E0242)
Objective: Review literature and examine agency procedures to identify promising speed control techniques. Field test selected techniques to determine their effectiveness and conduct statistical analyses to quantify the speed reduction achieved by each method.
Performing Organization: University of Illinois, Urbana, IL 61801
Funding Agency: Illinois Department of Transportation
Expected Completion Date: September 1990
Estimated Cost: $190,000 (HP&R)

Title: Design Process for Workzone Speed Control and Traffic Control Guidelines for Urban Arterial Street Work Zones. (NCP No. 4A1E0252)
Objective: Develop a process for selecting appropriate speed control techniques for work zones and guidelines for work zone traffic control on urban arterials. Review literature and survey district experience. Test new devices and techniques. Catalog work zone speed control measures. Develop and pilot test a design process. Study urban work sites to document and evaluate traffic control plans. Develop guidelines for work zone traffic control on urban arterials.
Performing Organization: Texas Transportation Institute, College Station, TX 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1991
Estimated Cost: $392,000 (HP&R)

NCP Program A.4: Special Highway Users

Title: Ramp Signing for Trucks. (NCP No. 3A4A3132)
Objective: Review the effectiveness of existing state practices/policies in speed signing and advance speed warning of troublesome ramps along with the AASHTO green book, MUTCD, and MUTCD Handbook. Review driver perception and performance tasks associated with ramp vehicle control and how speed advisory or other advance systems could effectively alert and modify driver behavior in time to maintain good ramp vehicle control.
Performing Organization: Center for Applied Research, Great Falls, VA 22066
Expected Completion Date: December 1990
Estimated Cost: $145,000 (FHWA Administrative Contract)

NCP Program A.5: Design

Title: Safety Index for Evaluating Low-Volume Rural Roads. (NCP No. 4A5A0302)
Objective: Develop a safety index for evaluating low-volume rural roads. The index will include roadway factors, accident experience, and other safety related data. This safety index will be tested on selected roads.
Performing Organization: Texas Transportation Institute, College Station, TX 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1990
Estimated Cost: $174,000 (HP&R)

NCP Category B—Traffic Operations

NCP Program B.1: Traffic Management Systems

Title: A "Before" and "After" Evaluation of the Committed HOV Transitway Projects. (NCP No. 4B1C0082)
Objective: Perform a comprehensive "before" and "after" evaluation of the HOV projects currently being implemented in the Houston area, with emphasis on the development of guidelines for application in future projects. Monitor the status of other HOV priority treatment projects in Texas.
Performing Organization: Texas Transportation Institute, College Station, TX 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1993
Estimated Cost: $825,000 (HP&R)

NCP Program B.2: Traffic Analysis and Operational Design Aids

Title: Interactive Graphics Intersection Design System. (NCP No. 4B2B2022)
Objective: Develop an interactive graphics intersection design system to aid traffic engineers in the design and modification of "at grade" intersections. Functions of the software system should include intersection geometric design, traffic control including signalization, channelization, capacity analysis, and animated graphics of simulation traffic.
Performing Organization: The University of Texas at Austin, Center for Transportation Research, Austin, TX 78705–2650
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1991
Estimated Cost: $391,300 (HP&R)

NCP Program B.9: Technology Transfer for Traffic Operations

Title: Preparation of a Texas Manual for Planning, Designing, and Operating Streets and Highways with Public Transportation Systems. (NCP No. 4B9B0033)
Objective: Develop guidelines and standards for planning, designing and operating streets and highways that include public transportation systems. Issues to be addressed include: design-related considerations on streets and highways in order to better accommodate public transit systems, and operating policies related to the operation of buses and light rail transit systems.
Performing Organization: Texas Transportation Institute, College Station, TX 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: October 1990
Estimated Cost: $150,000 (HP&R)

NCP Category C—Pavements

NCP Program C.1: Evaluation of Rigid Pavements

Title: Finite-Element Analysis of Bonded Concrete Overlays. (NCP No. 4C1C2072)
Objective: Develop information which would maximize the potential for successful construction and long-term performance of bonded concrete overlays. Work tasks include literature survey, identification and selection of analysis parameters, gathering of finite-element input values, modification/development of finite-element program, finite-element analysis, evaluation of results and a final report.
Performing Organization: Center for Transportation Research, Austin, TX 78705–2650
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1990
Estimated Cost: $210,725 (HP&R)

NCP Program C.2: Evaluation of Flexible Pavements

Title: Effect of Mix Design and Equipment on Workability and Rideability of Asphalt Concrete Pavement. (NCP No. 4C2A2452)
Objective: This study will evaluate the potential to more effectively place high stability (and often harsh mixes) by equipment and construction procedural adjustments. The study will also suggest methods to improve workability and compactibility of asphalt concrete mixtures without sacrificing mix stability.
Performing Organization: Texas Transportation Institute, College Station, TX 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1990
Estimated Cost: $158,000 (HP&R)

NCP Program C.3: Field and Laboratory Testing

Title: Using the Multi-Depth Deflectometer to Study Tire Pressure and Dynamic Load Effects on Pavements. (NCP No. 4C3A1442)
Objective: Study the effects of tire pressure and dynamic loads on pavement response using multi-depth deflectometers (MDD). Instrument in-service pavements near weigh stations with MDD and measure pavement responses for various axle configurations, loads, tire pressures, speeds, and pavement roughnesses. Use the pavement response data for verification of existing theoretical models and to study rutting.
Performing Organization: Texas Transportation Institute, College Station, TX 77843
Funding Agency: Texas State Department of Highways & Public Transportation
Expected Completion Date: August 1991
Estimated Cost: $265,000 (HP&R)

Title: Automatic Photo Interpretation System for the ARAN. (NCP No. 4C3A1472)
Objective: Develop equipment and procedures for automatically processing distress data collected by the automatic road analyzer (ARAN). The scope of work includes: (1) building an image-processing system to interface with the ARAN for video image interpretation, (2) evaluate the system on cracked pavements in Texas, and (3) develop procedures for incorporating automatically processed data into the State's pavement management activities.
Performing Organization: Texas A&M (Texas Transportation Institute) College Station, TX 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1991
Estimated Cost: $316,000 (HP&R)

NCP program C.4: Pavement Management Strategies

Title: Life Cycle Costing of Pavement Systems. (NCP No. 4C4C2062)
Objective: Conduct broad-based study on incorporating life cycle costing (LCC) methodology and techniques into pavement management in Kentucky. Review and summarize technical literature on the spectrum of pavement life cycle activities, associated effectiveness measures, and costs, including user costs. Develop and refine procedures on estimation of remaining life of pavements. Develop microcomputer-based program for LCC analyses and determine maintenance, rehabilitation, and reconstruction alternatives to minimize LCC.
Performing Organization: University of Kentucky, Lexington, KY 40506
Funding Agency: Kentucky Transportation Cabinet
Expected Completion Date: August 1993
Estimated Cost: $300,000 (HP&R)

Title: Effects of Heavy Vehicles on Pavement Performance. (NCP No. 5C4A1112)
Objective: Analyze and evaluate interactions between heavy vehicles and pavements, determine the properties of trucks and pavements most sensitive to deterioration, and develop rules for pavement and truck design.
Performing Organization: University of Michigan, Ann Arbor, MI 48109
Expected Completion Date: September 1990
Estimated Cost: $400,000 (NCHRP)

NCP Category D—Structures

NCP Program D.1: Design

Title: Effect of Improved Bonding of External Tendons and the use of Supplemental Bonded Tendons in External Post-Tensioned Bridges. (NCP No. 4D1A3242)
Objective:

- Determine if supplementary bonded tendons improve structural behavior and whether external tendons bonded at intermediate diaphragms improve utilization of positive moment steel under overloads.
- Determine level of prestress that can be developed at deviators.
- Recommend proven methods for enhancing the strength and ductility of segmental box girder construction with external tendons.
- Recommend limits for the effective tendon stress that can be developed through deviators.

Performing Organization: University of Texas, Austin, TX 78712
Funding Agency: Texas State Department of Highways & Public Transportation
Expected Completion Date: August 1990
Estimated Cost: $200,000 (HP&R)

Title: Influence of Debonding of Strands on Behavior of Composite Prestressed Concrete Bridge Girders. (NCP No. 4D1A3252)
Objective: Develop guidelines for the design of pretensioned prestressed concrete bridge girders utilizing debonded strands.
Performing Organization: University of Texas, Austin, TX 78712
Funding Agency: Texas State Department of Highways & Public Transportation
Expected Completion Date: August 1991
Estimated Cost: $350,800 (HP&R)

Title: Fretting Fatigue in External Post-Tensioned Tendons. (NCP No. 4D1B1102)
Objective: Examine the potential for fretting fatigue in external tendons in concrete box girder bridges; examine effects of various deviator details; explore the effects of various tendon parameters; and develop design and construction recommendations for external tendon deviators and tendons suitable for inclusion within the general AASHTO fatigue design framework.
Performing Organization: University of Texas, Austin, TX 78712
Funding Agency: Texas State Department of Highways & Public Transportation
Expected Completion Date: August 1991
Estimated Cost: $225,000 (HP&R)

NCP Category E—Materials and Operations

NCP Program E.3: Geotechnology

Title: Evaluation of Causes of Excessive Settlements of Pavements Behind Bridge Abatements. (NCP No. 4E3A0622)
Objective: Conduct elevation surveys to obtain settlement data on a few selected bridges in Oklahoma. Conduct sampling and testing of the foundation soils, as well as instrumentation and monitoring of further settlement.
Performing Organization: University of Oklahoma, Norman, OK 73019
Funding Agency: Oklahoma Department of Transportation
Expected Completion Date: September 1991
Estimated Cost: $241,000 (HP&R)

Title: A Study of Bridge Approach Instability. (NCP No. 4E3A0632)
Objective: Identify the causitive factors contributing to pavement roughness at bridge approaches and to determine which of these factors are most significant.
Performing Organization: Texas Transportation Institute, College Station, TX 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: September 1990
Estimated Cost: $151,500 (HP&R)

Title: Field and Laboratory Performance Evaluation of Spread Footings. (NCP No. 4E3A0662)
Objective: Observe the performance of the spread footing foundations of six selected bridges and present the findings in a manner consistent with the data base requirements of FHWA and Ohio Department of Transportation. Examine the validity of empirical design equations for the estimation of bearing capacity and settlement by comparing them with the field measurements and observations.
Performing Organization: Ohio University, Athens, OH 45701
Funding Agency: Ohio Department of Transportation
Expected Completion Date: September 1991
Estimated Cost: $369,000 (HP&R)

Title: Long-Term Strength Properties of Compacted Fills for Embankment Design. (NCP No. 4E3B0552)
Objective: Develop rational procedures for measuring the long-term strength properties of highly plastic clays used for construction of earth slopes. Develop apparatus and test procedures to simulate the degree of cracking and deterioration in soil strength that occurs in the field due to repeated wetting and drying.
Performing Organization: University of Texas, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: September 1990
Estimated Cost: $218,650 (HP&R)

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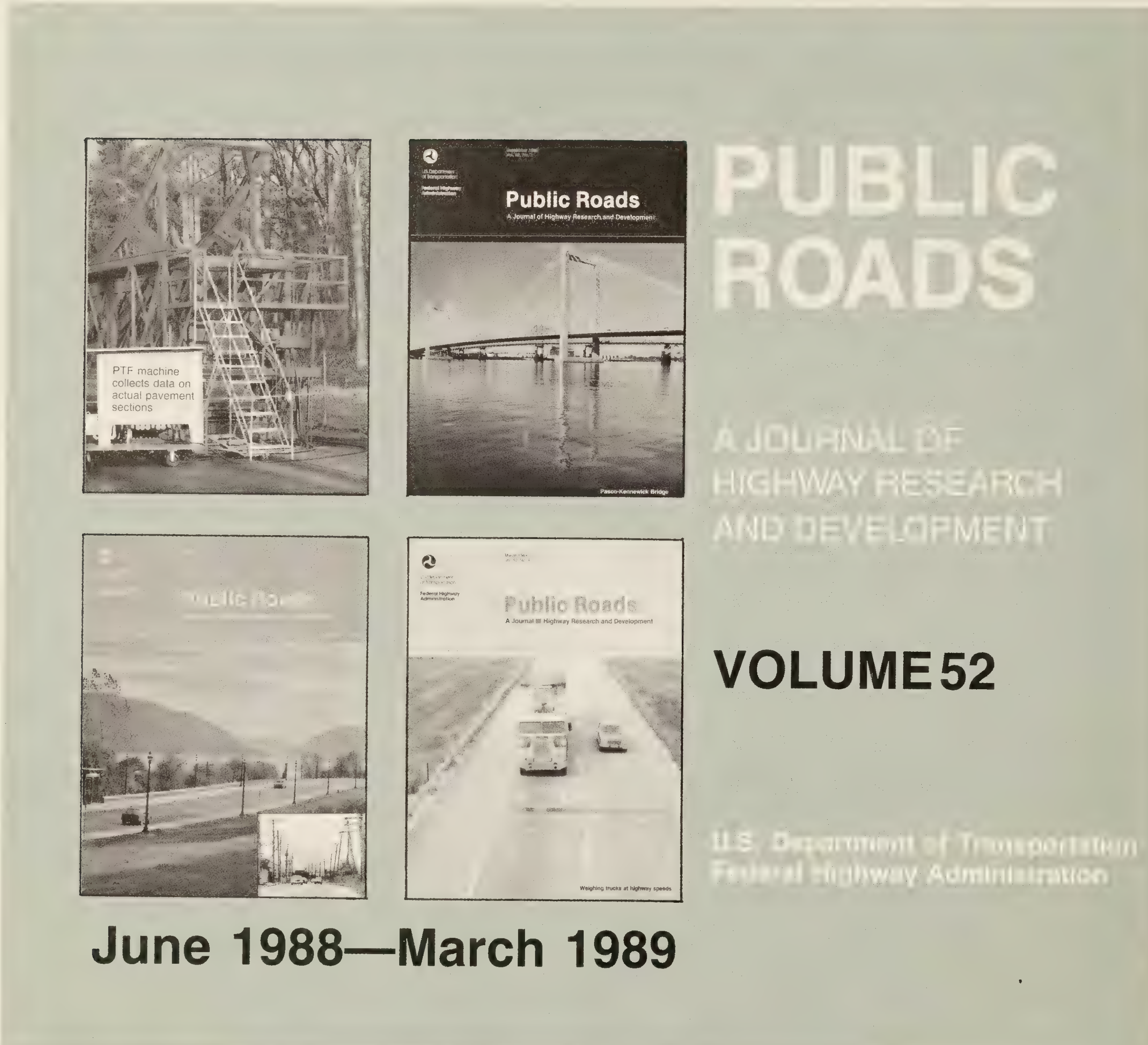

The title sheet for volume 52, June 1988—March 1989, of *Public Roads* is on the inside back cover of this issue. This sheet contains a chronological list of article titles and an alphabetical list of authors' names.

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