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Effect of Roadway Geometrics on Traffic Operations

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CONTENTS

FOREWORD

Traffic operations and traffic safety are influenced by roadway geometry, roadside development, and traffic control devices. These interrelationships are discussed in this RECORD and should be of considerable interest to traffic safety and operations authorities.

Agent and Deen analyzed accident experience on different roadway types in Kentucky and found the highest rates on four-lane undivided roads and the lowest rates on toll roads. Their study of accident severity showed relationships to types of accidents, types of highways, traffic control, and safety belt use. Accidents involving pedestrians were the most severe, and single-vehicle accidents ranked next highest.

Using the Maine Facility, an electronically instrumented two-lane road, Rosenbaum, Basham, Byington, and Young studied speeds in a rural school zone as affected by several types of traffic control devices, including a dynamic speed violation sign. The dynamic signing, activated by speed measurements, warned individual drivers when they were in violation and was more effective in reducing speeds. None of the sets of devices, however, influenced drivers to obey the 15-mph (24-km/h) limit; the best set yielded average speeds of 34 mph (54 km/h).

After discussing the nature of traffic operations at freeway lane drop locations, Goodwin presents several design principles that should be considered when such sites are constructed or reconstructed. These principles include visibility, location, taper and escape lane characteristics, and traffic control device requirements. A before and after case study is used to show application of the principles in evaluating control device changes.

The obstruction of sight distance at urban intersections by physical objects on private property has been a problem as long as there have been intersections. Moore and Humphreys surveyed current practices in state, county, and city governments and suggest a methodology for dealing with specific cases of sight distance obstruction. Sample letters, a model ordinance, and other supportive elements are described.

Traffic-induced vibration probably came to us with the first wheel. Chilton, Friesz, and Chen examine the knowledge about such vibration and try to put it into a succinct form useful to highway and transportation engineers. Human response frequently will classify vibration as unacceptable before structural damage is possible; careful maintenance is suggested as the most effective preventive.

Gupta and Jain studied accident occurrence for relationships to roadway width, horizontal curvature, vertical clearance, and restricted sight distance. They concluded that the vertical clearance had no effect on accident rates but that restricted sight distance and horizontal curvature probably did have some effect. Other uncontrolled variables influenced the ability of the researchers to draw firm conclusions about the variables studied.

RELATIONSHIPS BETWEEN ROADWAY GEOMETRICS AND ACCIDENTS

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Statewide average and critical rates of accidents were determined from 1970, 1971, and 1972 Kentucky accident records for each type of rural highway. Accident data, obtained from state police computer tapes, were summarized to give the number of accidents on each highway type as well as information on accident severity, road surface conditions, light conditions, road character, and type of traffic control. Four-lane undivided highways had the highest average accident rate, and parkways (toll roads) had the lowest rate. The severity of accidents was related to types of accidents, highways, and traffic control and to safety belt use. Accidents involving pedestrians were the most severe, and single-vehicle accidents ranked next highest in severity. Excluding accidents at railroad crossings, accidents that occurred on curves had the highest severity index. The use of safety belts was associated with reduced severity.

•CRITERIA now used in Kentucky to identify high-accident locations are not specific with respect to the type of highway. Intuitively, one knows that differences in accident histories should exist; it should be possible to statistically identify or define relationships between the geometrics and the accident history of a location. If differences are noted in accident experiences of highway types, benefits realized from a particular change in geometrics could be assessed.

Several high-accident location identification procedures use average or critical accident rates (1, 2). A critical rate is determined, and rates higher than the critical indicate that a location is hazardous. Through the use of volume and accident data, critical rates for various types of highways can be calculated and used for determining high-accident sites.

Findings in this paper resulted from a study of accident experience on different highway types encompassing the rural highway system in Kentucky.

PROCEDURE

Accident and traffic volume data were collected for 1970, 1971, and 1972. The accident data were obtained from computer tapes containing all accidents reported by the state police. Kentucky only recently enacted a uniform accident reporting law; therefore the state police reports studied were almost exclusively for rural areas, and only rural accidents were considered. Rural accidents include all accidents occurring in cities with less than 2,500 population. Jefferson, Fayette, Campbell, Kenton, and Boone Counties were excluded inasmuch as local police investigate the vast majority of all accidents within those counties.

The volume data were collected from two sources. First, a computer printout was obtained that summarized the number of vehicle miles (kilometers) of travel on different highway types in rural areas. Second, volumes were taken from Kentucky traffic flow maps for those locations that were omitted in the first source.

The rural highway system was divided into the following types of highways:

1. Two-lane,
2. Three-lane,
3. Four-lane undivided,
4. Four-lane divided (no access control), and
5. Interstate and parkway.

The Interstate and parkway division was separated into two separate categories for some comparisons.

The accident and volume computer printouts yielded satisfactory information for the two-lane and Interstate and parkway categories. For the remaining categories, errors were found in the computer information. This necessitated manual determination of accident locations. The limited mileage of these highways permitted long-hand manipulation. When the mileposts were assigned, a computer program was written to obtain accident information. Volumes were obtained from traffic flow maps.

The accident data tape enabled preparation of rather detailed summaries. Accident severity information was obtained as well as information on type of accident, road surface condition, light conditions, road character, and type of traffic control. The information was then summarized by highway type. Also, types of accidents were summarized according to traffic control. Accident severity associated with safety belt use was studied.

Average critical accident rates per 100 million vehicle miles (MVM) [160 million vehicle km (MVK)] were calculated for each highway type. The following formula was used (3):

$$A_c = A_a + K\sqrt{A_a/M} + \frac{1}{2}M$$

where

A_c = critical accident rate,
A_a = average accident rate,
K = constant related to level of statistical significance selected (for $P = 0.95$, $K = 1.645$; for $P = 0.995$, $K = 2.576$), and
M = annual 100 MVM (160 MVK) traveled on a particular highway type.

Critical rates were determined for two probability levels to show the effect the choice of probability level has on critical rates. Critical accident rates in terms of accidents per mile (kilometer) were determined by multiplying the critical rate by the annual volume.

Each accident was classified according to one of the following types:

1. Head-on collision or opposite-direction sideswipe,
2. Rear-end collision or same-direction sideswipe,
3. Angle,
4. Pedestrian,
5. Other collision,
6. Single vehicle,
7. Fixed object, or
8. Other.

Most of the accident types are self-explanatory. Other collision refers to collisions with a nonmotor vehicle (train, bicycle, and parked car) as well as nonintersection accidents, whose directional analysis was not stated. The other category refers to accidents involving single vehicles for which the circumstances were not stated.

In some severity comparisons, a term called the severity index (SI) (4) was used. SI was calculated by the following formula:

$$SI = EPDO/N_t$$

where

N_t = total number of accidents,
EPDO = 9.5 (K + A) + 3.5 (B + C) + PDO,
K = number of fatal accidents,
A = number of type A injury accidents (accidents where type A injury was the most severe injury sustained),
B = number of type B injury accidents,
C = number of type C injury accidents, and
PDO = number of property-damage-only accidents.

FINDINGS

The average accident rates by type of highway are given in Table 1. The fatality rates appear high, but this results from including only rural accidents. Four-lane undivided highways had the highest accident, injury, and fatality rates. This was not surprising since that type of highway is frequently a high-volume road with a large number of conflict points. When the number of conflict points is reduced by dividing the roadway, the accident rate exhibits a sharp reduction, and the injury and fatality rates decline. Volumes on this highway type and the four-lane undivided highway are similar. When access control and at-grade intersections are eliminated on Interstates and parkways, the accident rate reaches a minimum. The effect of volume on accident rate can be seen in the difference between Interstate and parkway rates. Interstates have much higher volumes and higher accident rates.

The critical accident rates by type of highway are given in Table 2. Because of low volumes, two-lane highways have the highest critical rate in terms of accidents per 100 MVM (160 MVK). In terms of accidents per mile (1.6 km) per year, four-lane undivided highways have the highest critical rate. If the accident rate for a particular section of highway exceeds the critical accident rate for that highway type, the section may be considered hazardous. The critical accident rates cited were derived from statewide averages for rural highways. In practice, each roadway section would have its own critical rate based on its volume. A graph can be drawn for each highway type to relate the critical rate to the average daily volume (5). As the volume increases, the critical rate will decrease and finally become nearly constant. The graph would also give critical accident rates for various section lengths.

The percentage of accident types occurring on various highways is shown in Figure 1. Rear-end or same-direction sideswipe accidents were the most frequent types of accidents for all highways as a group. For three-lane, four-lane divided, and four-lane undivided highways, the rear-end accident was the most common. Single-vehicle and rear-end accidents were the most common on two-lane roads. Single-vehicle accidents were the most frequent on Interstates and parkways, and there was a significant percentage of rear-end accidents. Two-lane and three-lane highways had a significant percentage of head-on or opposite-direction sideswipe accidents, but four-lane divided and undivided highways had a significant percentage of angle accidents. The percentage of fixed-object accidents appears low. This could have resulted from classifying some fixed-object accidents as single-vehicle accidents.

As volumes increase on Interstate highways, the percentage of rear-end accidents increases and the percentage of single-vehicle accidents decreases (6). This was found to be the case in a comparison of the percentages of these accidents occurring on Interstates (high-volume roads) and on parkways (low-volume roads). On parkways, 22 percent were rear-end or same-direction sideswipe accidents, and 73 percent were single-vehicle accidents (including fixed-object and other accidents). On Interstates, 33 percent were rear-end accidents and 59 percent were single-vehicle accidents. This relationship should be similar for other types of highways, but accident data were not sufficiently stratified by volume to permit comparisons. Accident rates for each type

Table 1. Average accident rates.

Type of Highway	Accident Rate		Injury Rate		Fatality Rate	
	Per 100 MVM	Per Mile per Year	Per 100 MVM	Per Mile per year	Per 100 MVM	Per Mile per Year
Two-lane	239	0.90	154	0.58	9.3	0.04
Three-lane	244	3.47	197	2.79	11.0	0.16
Four-lane, undivided	313	9.35	202	5.97	24.6	0.73
Four-lane, divided[a]	156	5.48	100	3.51	4.7	0.16
Interstate	85	3.72	60	2.61	3.1	0.13
Parkway	80	0.82	54	0.55	4.6	0.05
Interstate and parkway	84	2.37	59	1.65	3.3	0.09
Mean (all roads)	204	1.00	132	0.65	7.9	0.04

Note: 1 mile = 1.6 km.

[a]No access control.

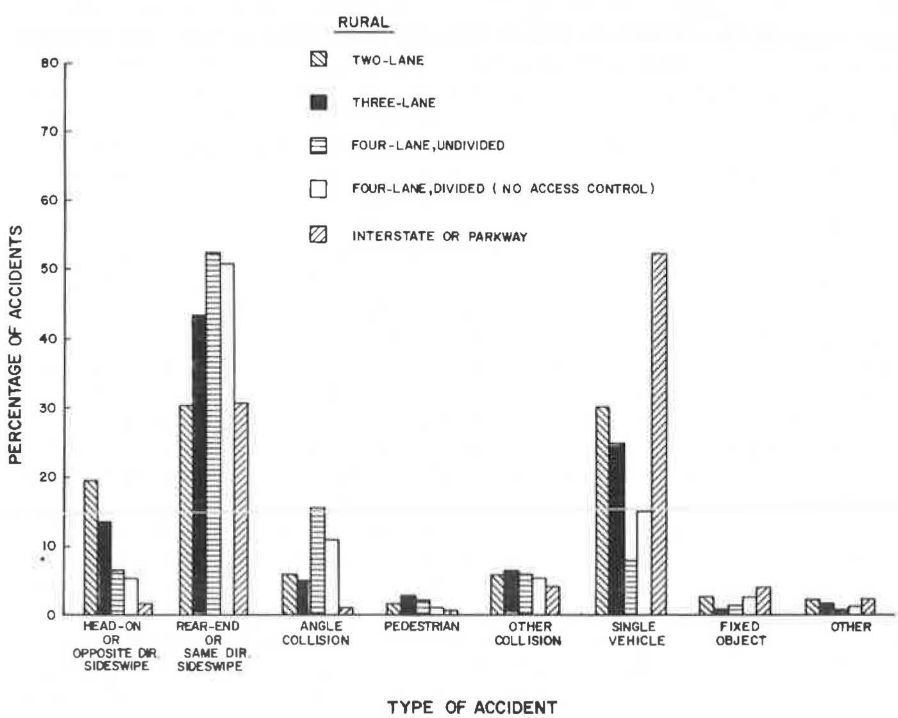
Table 2. Critical accident rates.

Type of Highway	Mean AADT	Accidents per 100 MVM (1-mile section)		Accidents per Mile per Year	
		P = 0.95	P = 0.995	P = 0.95	P = 0.995
Two-lane	1,036	785	1,019	3.0	3.9
Three-lane	5,510	450	553	9.0	11.1
Four-lane, undivided	8,189	498	593	14.9	17.7
Four-lane, divided[a]	9,628	280	342	9.8	12.0
Interstate	11,957	169	210	7.4	9.2
Parkway	2,808	279	360	2.8	3.7
Interstate and parkway	7,703	192	243	5.4	6.8

Note: 1 mile = 1.6 km.

[a]No access control.

Figure 1. Percentage of accident types on various types of highways.



of accident on each type of highway are given in Table 3.

Percentages of accident types for a given traffic control device are given in Table 4. The data provide a general idea of the effects a change in traffic control would have on the type of accident occurring. For example, changing from a stop sign to a signal may reduce angle accidents but increase rear-end accidents. When percentages of the types of accidents occurring at a given location are compared to the statewide averages, an abnormal number of a particular type of accident may be detected.

Table 5 gives the relationship between the SI and types of accidents, highways, and traffic controls. Pedestrian accidents had a much higher SI than any other type of accident; single-vehicle accidents also exhibited a high SI.

Four-lane divided highways had the lowest SI of any highway type, and parkway accidents had the highest SI. This may be attributed to the high percentage of single-vehicle accidents as well as high speeds. The data further show that, when a stop sign is replaced by a signal, the severity of the accidents may be decreased because angle types of accidents (which are more severe) usually decrease, but rear-end types increase. The relatively low severity of rear-end accidents was shown by noting that the yield sign, which is associated with a very high percentage of rear-end accidents, had the lowest severity index of any traffic control. Accidents at railroad crossings had the highest severity index. Accidents on curves were also severe.

Safety belts have been strongly recommended as a means to reduce severity of traffic accidents. The following are SIs associated with safety belt use.

Safety Belt Use	Severity Index
Safety belts used	1.66
Safety belts not used	2.44
No safety belts in vehicle	3.00
Vehicle equipped with safety belts	1.95

The SI formula was modified so that values could be calculated for occupants rather than for accidents:

$$SI = [9.5 (K + A) + 3.5 (B + C) + O]/N_t$$

where

N_t = total occupants involved in state police-reported accidents, which had safety belt use indicated,
K = total fatalities,
A = total type A injuries,
B = total type B injuries,
C = total type C injuries, and
O = total occupants who sustained no injuries.

The SI was much lower for occupants who used safety belts than for those who did not use safety belts. This adds further credence to the supposition that safety belt use can greatly reduce the severity of most accidents. The difference between the SI of vehicles without safety belts and the SI of vehicles equipped with safety belts (which were not used) was larger than would be anticipated. A higher SI for occupants in vehicles not equipped with safety belts may be expected since the older vehicles tend to be in worse mechanical condition than the newer cars. Some safety features have been added to the newer cars; still, the large difference was surprising.

Of the total vehicle occupants, 6 percent used safety belts. Eleven percent of the

Table 3. Accident rates by type of highway and type of accident.

Type of Highway	Head-On or Opposite Direction Sideswipe	Rear-End or Same Direction Sideswipe	Angle Collision	Pedestrian	Other Collision	Single Vehicle	Fixed Object	Other
Accidents per 100 MVM								
Two-lane	46	73	15	3	15	73	8	6
Three-lane	32	106	12	5	18	62	3	6
Four-lane, undivided	20	164	50	6	20	43	7	3
Four-lane, divided[a]	8	80	18	1	9	32	6	2
Interstate	1	28	0	1	5	44	4	2
Parkway	1	18	1	1	2	45	5	7
Interstate and parkway	1	26	1	1	4	44	4	3
Accidents per mile								
Two-lane	0.17	0.28	0.06	0.01	0.06	0.28	0.03	0.01
Three-lane	0.46	1.50	0.18	0.07	0.25	0.88	0.05	0.08
Four-lane, undivided	0.61	4.89	1.49	0.19	0.59	1.27	0.21	0.10
Four-lane, divided[a]	0.28	2.79	0.62	0.04	0.34	1.13	0.20	0.08
Interstate	0.07	1.21	0.01	0.02	0.21	1.92	0.18	0.10
Parkway	0.01	0.18	0.01	0.01	0.01	0.47	0.06	0.07
Interstate and parkway	0.04	0.73	0.01	0.02	0.12	1.25	0.12	0.08

Note: 1 mile = 1.6 km.
[a]No access control.

Table 4. Percentages of various types of accidents for types of traffic controls.

Traffic Control	Head-On or Opposite Direction Sideswipe	Rear-End or Same Direction Sideswipe	Angle Collision	Pedestrian	Other Collision	Single Vehicle	Fixed Object	Other
Stop sign	4.1	29.6	51.9	0.2	1.2	12.0	0.7	0.3
Signal	6.2	55.9	28.6	0.3	2.2	5.0	2.0	0.2
Yield sign	4.0	56.2	22.5	0	3.6	12.0	0	1.6
Flashing beacon	5.8	51.9	14.9	1.6	7.7	13.3	5.0	0.5
No passing zone	25.1	28.0	3.9	1.6	8.9	29.7	1.2	1.5
Curve sign	29.1	9.0	1.9	0.5	4.8	52.5	1.4	0.7
Speed limit zone	17.3	29.9	5.0	1.7	15.6	27.5	1.1	1.9
Advisory speed sign	11.6	29.6	3.3	1.3	11.9	38.2	2.8	1.2
Railroad gates or signals	8.7	18.9	3.1	1.0	46.4	18.9	2.6	0.5
Centerline	12.8	35.7	2.7	1.4	7.8	35.3	1.4	3.0
Officer or watchman	4.4	62.4	1.7	1.7	16.6	9.6	3.1	0.4
Other	37.4	16.8	2.7	1.4	11.4	27.1	1.3	1.9

Table 5. Severity indexes for various types of accidents, highways, and traffic controls.

Item	Type	Severity Index
Accident	Head-on or opposite direction sideswipe	2.84
	Rear-end or same direction sideswipe	2.10
	Angle collision	2.60
	Pedestrian	7.60
	Other collision	2.59
	Single vehicle	3.58
	Fixed object	2.70
	Other	1.99
Highway	Two-lane	2.85
	Three-lane	2.96
	Four-lane, undivided	2.84
	Four-lane, divided[a]	2.75
	Interstate	2.82
	Parkway	3.07
	Interstate and parkway	2.86
	Mean (all roads)	2.84
Traffic control	Stop sign	2.70
	Signal	2.27
	Yield sign	2.03
	Flashing beacon	2.45
	No passing zone	2.72
	Curve sign	3.13
	Speed limit zone	2.66
	Advisory speed sign	2.80
	Railroad gates or signals	3.81
	Centerline	2.94
	Officer or watchman	2.21
	Other	2.62

[a]No access control.

occupants of vehicles equipped with safety belts were wearing them. This percentage did not change significantly from 1970 to 1972. Forty-four percent of the occupants were in vehicles not equipped with safety belts, but 50 percent of the occupants were in vehicles that had safety belts that were not used.

The percentage of vehicle occupants injured or killed in relation to safety belt use further illustrates the effectiveness of safety belts. Of the occupants who used safety belts, 17 percent received a nonfatal injury, and 0.4 percent were fatalities. In contrast, of the occupants who did not use a safety belt, 30 percent were nonfatally injured and 1.7 percent were killed. It should be noted that these percentages pertain to vehicle occupants whose safety belt use was coded on the accident tape. The percentages show that a person who does not wear a safety belt has approximately twice the probability of being injured and four times the probability of being killed compared to a person who does wear a safety belt.

The average SIs of all rural accidents were as follows: 2.91 in 1970, 2.85 in 1971, and 2.78 in 1972. This decrease in severity may be attributable to new vehicle safety features or increased traffic volumes that result in lower speeds and less severe accidents.

Figure 2 shows the percentage of intersection-related accidents versus type of highway. Four-lane divided and undivided (no access control) highways had the highest percentage of intersection-related accidents. The percentage drops drastically on Interstates or parkways, where there are no at-grade intersections.

Figure 3 shows road surface conditions versus accidents. Between 20 and 30 percent of the total accidents occurred during wet-weather conditions. Therefore, if this percentage is greatly exceeded, a remedy such as improved drainage or resurfacing may be necessary. Interstates and parkways had the highest percentage of accidents during snowy or icy conditions. Higher traffic speeds may be a contributing factor.

The percentages of accidents that occurred during daylight and darkness are shown in Figure 4. The percentages during darkness varied from 27 to 35 percent. If the percentage on a particular road section significantly exceeds these percentages, lighting may be advisable.

The percentages of accidents on each highway type involving curvature and grade are shown in Figures 5 and 6 respectively. Two-lane highways had the highest percentage of accidents that involved curvature. Three-lane highways had the highest percentage of accidents involving grade. This is logical inasmuch as most three-lane highway sections are built to provide a passing lane on long grades. Table 6 gives the percentage of accidents for various highway types versus type of traffic control.

IMPLEMENTATION

The tables that give rural statewide average accident rates for the various highway types are a means of assessing whether a particular section of roadway is hazardous. More accurate judgments can be made by using graphs that relate critical accident rate, volume for each type of highway, section length, and probabilities (5).

The tables and figures that relate type of highway, accident, and traffic control and SI are a means of determining whether a certain location or section of roadway deviates greatly from the average and of estimating the effect of a change in traffic control or geometrics. The figures that relate the percentage of accidents to road surface and light condition provide only a set of references for judging normalcy or abnormalcy in other or more specific data sets. The tables and figures presented here are intended to show rural statewide average conditions that can be useful for comparative purposes. Deviations from the averages can provide indications of the need for remedial action.

Finally, the section of the study dealing with safety belt use provides quantitative results about the benefits of using safety belts. The numbers given are an effective means of illustrating the results of using safety belts.

Figure 2. Percentage of intersection-related accidents on various types of highways.

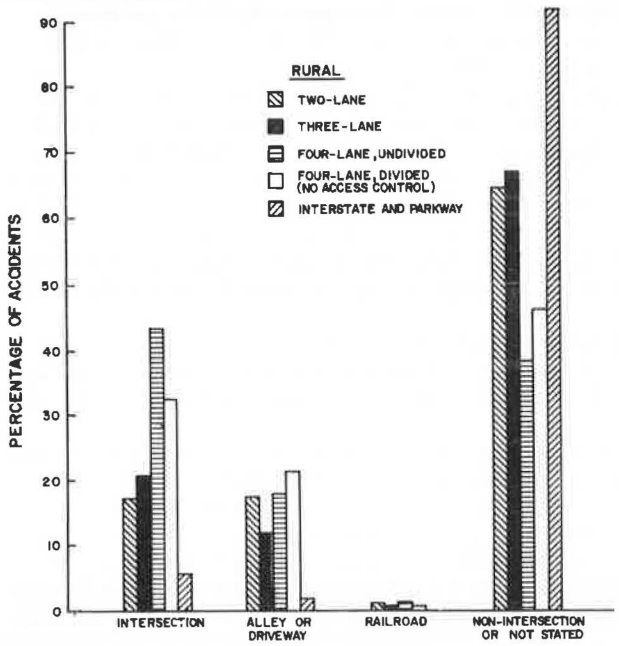


Figure 3. Percentage of accidents versus road surface conditions on various types of highways.

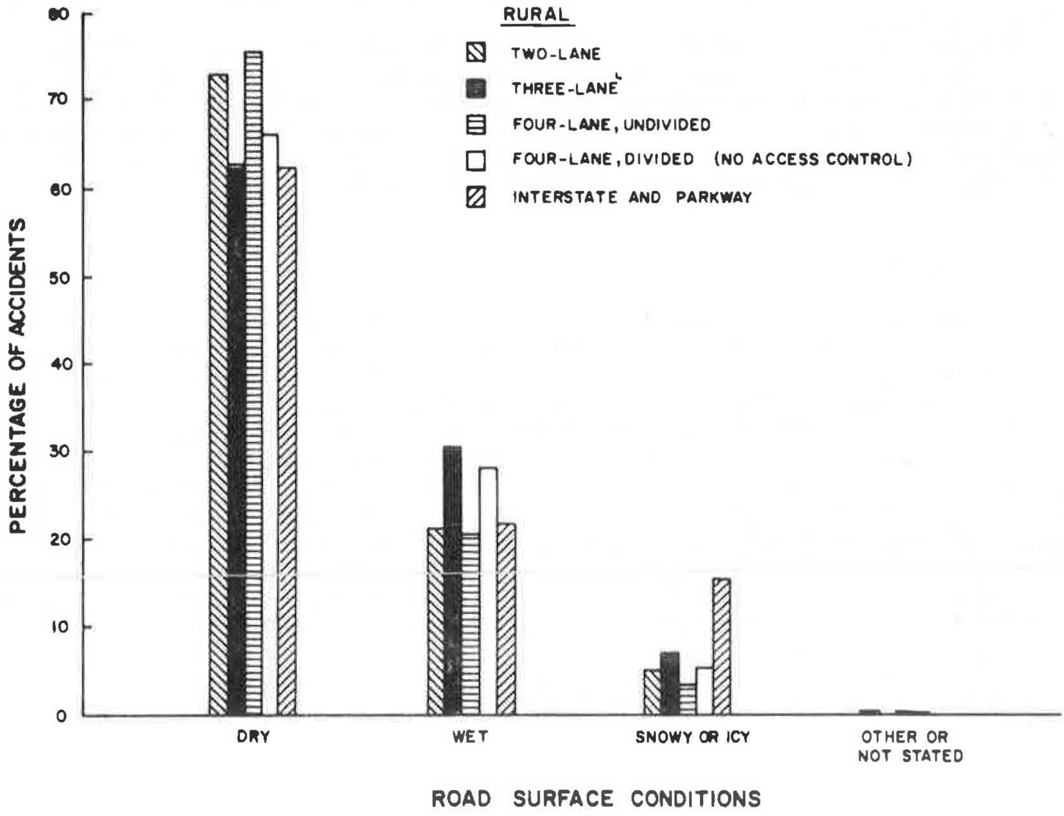


Figure 4. Percentage of accidents versus lighting conditions on various types of highways.

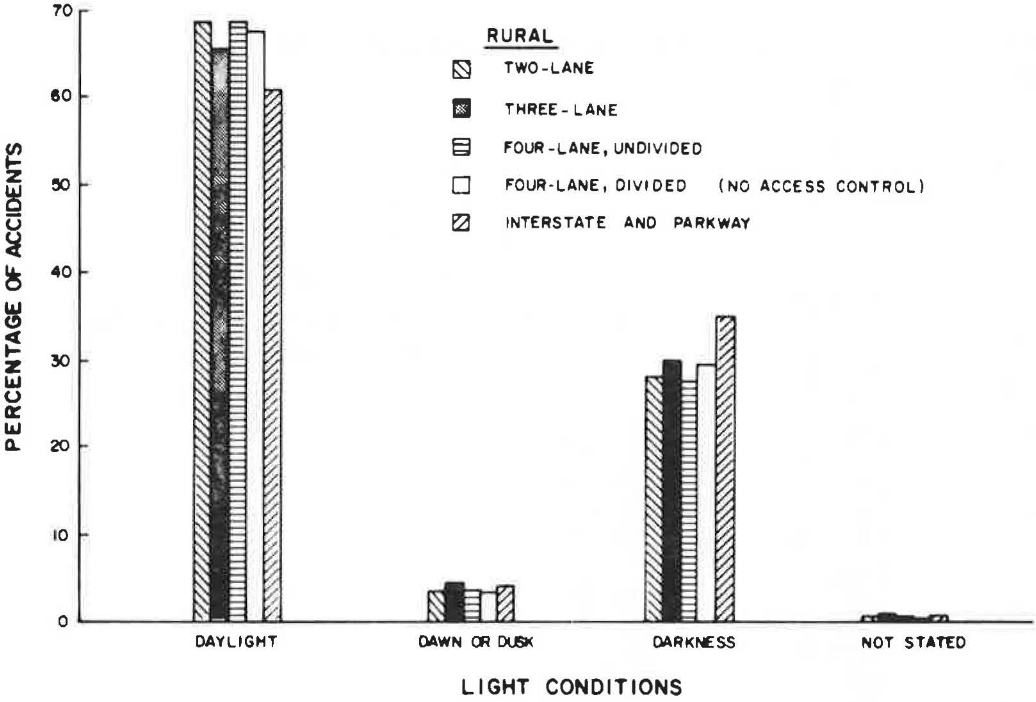


Figure 5. Percentage of accidents versus horizontal alignment on various types of highways.

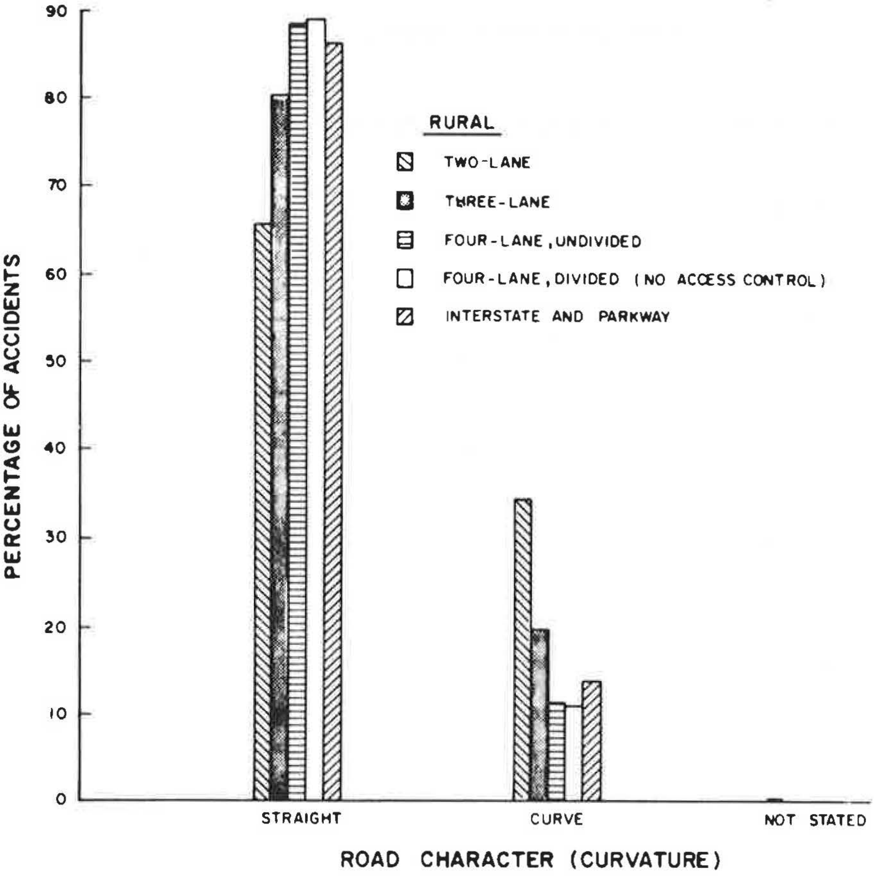


Figure 6. Percentage of accidents versus vertical alignment on various types of highways.

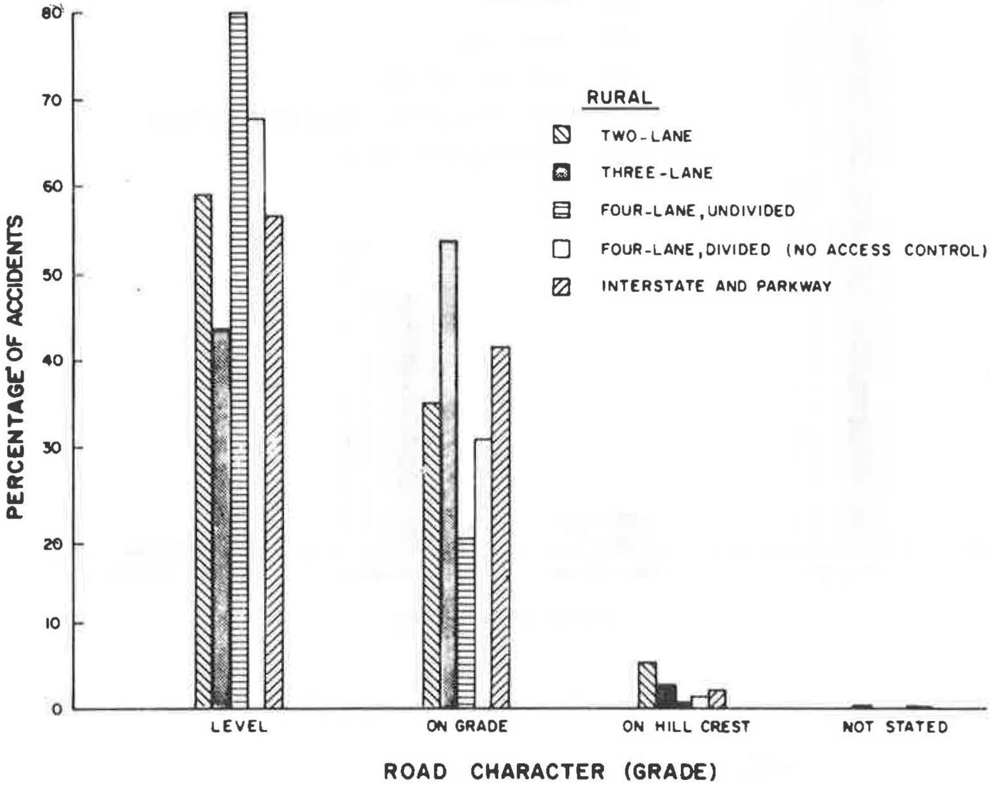


Table 6. Percentages of rural highway accidents for type of highway and type of traffic control.

	Type of Highway				
			Four-Lane		Interstate and
Traffic Control	Two-Lane	Three-Lane	Undivided	Divided[a]	Parkway
Stop sign	5.9	3.9	12.5	8.2	1.3
Signal	0.5	4.5	13.4	6.0	0.3
Yield sign	0.3	0	1.2	1.3	0.9
Flashing beacon	0.5	0.6	1.2	1.9	0.6
No passing zone	3.7	2.3	1.0	0.4	0.4
Curve sign	1.9	0.6	0.2	0.3	0.5
Speed limit zone	3.6	2.5	2.2	2.2	4.1
Advisory speed sign	0.7	1.7	0.3	0.7	3.5
Railroad gates or signal	0.3	0.3	0.4	0.1	0
Centerline	63.0	79.3	62.8	76.0	83.8
Officer or watchman	0.3	0.6	0.1	0.7	0.8
Other	19.3	3.7	4.7	2.2	3.8

[a]No access control.

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SPEED CONTROL IN RURAL SCHOOL ZONES

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Initial results are presented of a comprehensive experiment dealing with speed control in a rural school zone on a high-speed, two-lane highway. Data were collected in a school zone located on the Maine Facility, an electronically instrumented roadway where a 15-mph (24-km/h) speed limit is in effect during certain times of the school day. The experiment was to determine the effects on drivers of the Manual on Uniform Traffic Control Devices mandatory and advisory school zone signs, including beacon flashers, and the effect of a new, dynamic speed violation sign. Speeds for automobiles and large vehicles were measured for one dynamic and four passive sign conditions when the 15-mph (24-km/h) speed limit both was and was not in effect. No enforcement was used during the experiment. Results showed that (a) vehicle velocities at the school were less when the driver was advised by flashing beacons that the 15-mph (24-km/h) speed limit was in effect, (b) the average vehicle velocity was relatively constant at the school when the speed limit was not in effect, and (c) the lowest average speeds at the school [34 mph (55 km/h)] were obtained when the dynamic speed violation sign was used.

•WIDE noncompliance with state statutes covering speed limits in school zones is believed to be due to drivers either not seeing speed zone signing or not understanding the statute and thus not obeying the sign message. The effects of five school speed zone signs on driver behavior were examined to determine the most desirable speed limit for rural school zones and the most effective signing required to achieve driver compliance.

EXPERIMENTAL SITUATION

All experiments were conducted on the Maine Facility located along US-2 between Newport and Canaan. This facility is electronically instrumented to detect vehicles, track their positions as they travel along sections of the two-lane road, and store the collected vehicle information on magnetic tape for subsequent off-line data reduction (1). The site of the experiments, shown in Figure 1, was adjacent to the Palmyra Consolidated School, bounded on the north by US-2 and on the west by a state road. The driveway and parking lot for school buses and staff vehicles are located at the intersection of the two roads. A minor local road also intersects US-2 from the north.

At the start of the experiments in January 1973, the test site was instrumented with 10 vehicle detector stations. Two more stations were added during the experiments.

Although data were collected on all vehicles passing through the test site, only data collected on eastbound nonturning vehicles were used in the analysis. Drivers heading east on US-2 entered the school zone from a 60-mph (96-km/h) speed zone, which began 1.2 miles (1.93 km) west of the school. The legal vehicle speed limit through the school zone at any time of day during the school session was either 15 mph (24 km/h) or 60 mph (96 km/h) depending on school activity. The Maine statute (2) pertaining to speed reduction in school zones states:

> Speed in excess of 15 miles per hour when passing a school during a recess or where children are going to or leaving school during opening or closing hours shall be unlawful.

A preliminary survey indicated that well over 95 percent of the drivers did not comply with the statute.

Between 7:15 a.m. and 3:45 p.m., the 15-mph (24-km/h) speed limit was in effect during seven time periods at Palmyra Consolidated School as given in Table 1. Traffic volumes on US-2 at the school during the experiments varied from 600 to 800 vehicles for the 8½-hour school day. The school had 164 students, aged 5 to 12, 7 teachers, and 5 additional staff. All students (except one family's, who walked) arrived and left by school bus. Four buses served the school, entering or leaving the school entrance 22 times during the school day. The buses also discharged and picked up students requiring transfer transportation to and from other schools in the area.

SIGN CONDITIONS

Five sign conditions, based on the school zone signs and flashing beacons in the Manual on Uniform Traffic Control Devices (MUTCD), were selected to determine driver compliance with the 15-mph (24-km/h) speed zone adjacent to the rural school and the effects of a dynamic speed violation sign. The five sign conditions used are shown in Figure 2 and are as follows:

1. Existing school signing, which conformed with the 1961 MUTCD;
2. The 1971 MUTCD mandatory school sign and the permitted speed limit sign with beacons;
3. Sign condition 2 and an advisory advance school zone sign;
4. Sign condition 3 and an advisory speed zone sign with beacons; and
5. Sign condition 4 and a speed violation sign with beacons.

For sign condition 2, the 1971 MUTCD states (3) that "the School Speed Limit sign shall be used to indicate the speed limit where a reduced speed zone for a school area... is specified for such areas by statute." (Shall, as used in the MUTCD, means mandatory, but should and may mean advisory and permissive respectively.) Since the Maine statute specifies speed limits for school zones, the school speed limit sign was used in sign condition 2. Speed limit signs with beacons and the words WHEN FLASHING, as permitted in the MUTCD, were activated by a time clock for those time periods when the 15-mph (24-km/h) limit was in effect. A 60-mph (96-km/h) speed limit sign was placed at the end of the school speed zone to show the speed limit for the next section of highway.

The 1971 MUTCD recommends a symbolic school advance sign for use before locations where school buildings or grounds are adjacent to the highway (3). The sign was used in sign condition 3. Since this sign was new to drivers at the test site, the word SCHOOL was used as well.

For sign condition 4, an MUTCD advance advisory sign for reduced speed ahead was added, which "... should be used in rural areas to inform the motorist of a reduced speed zone when an advance notice is needed to comply with the speed limit posted ahead" (3). Speed limit signs with beacons were also used to indicate when the reduced speed limit was in effect.

The fifth sign condition added a new (not covered in the 1971 MUTCD) speed violation sign with beacons to remind the driver who had exceeded the reduced speed limit that it was in effect. This sign flashed when a driver was electronically detected exceeding 20 mph (32 km/h) during the times that the speed limit signs with beacons were flashing.

The same sign conditions were installed for eastbound and westbound traffic concurrently at appropriate distances from the school zone for sign conditions 1 through 4. The dynamic speed violation sign was not used for westbound traffic. The size, color, and legend of each of the signs used are described in Figure 3.

Figure 1. Experiment test site and eastbound signs for sign condition 4.

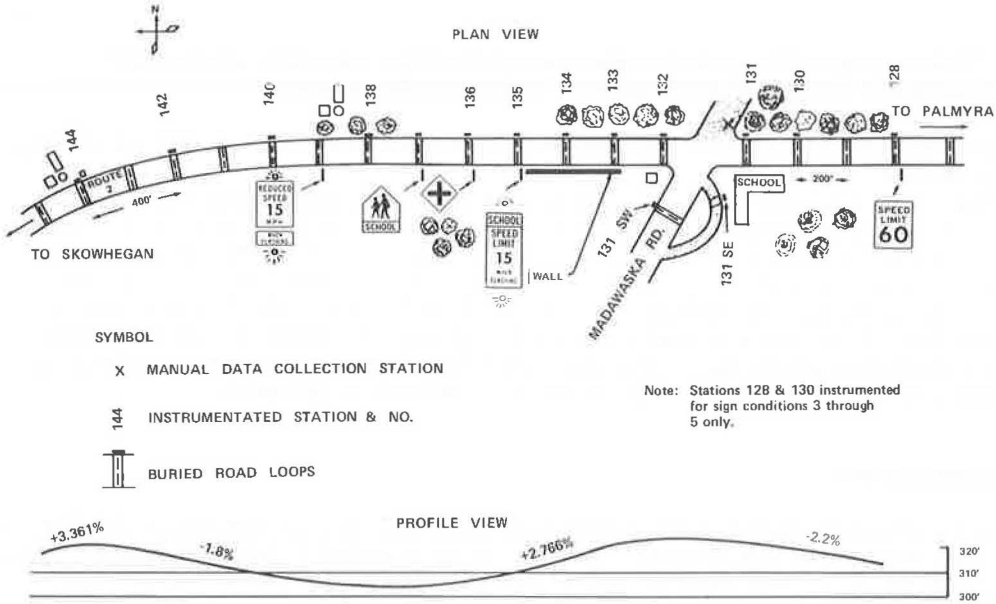
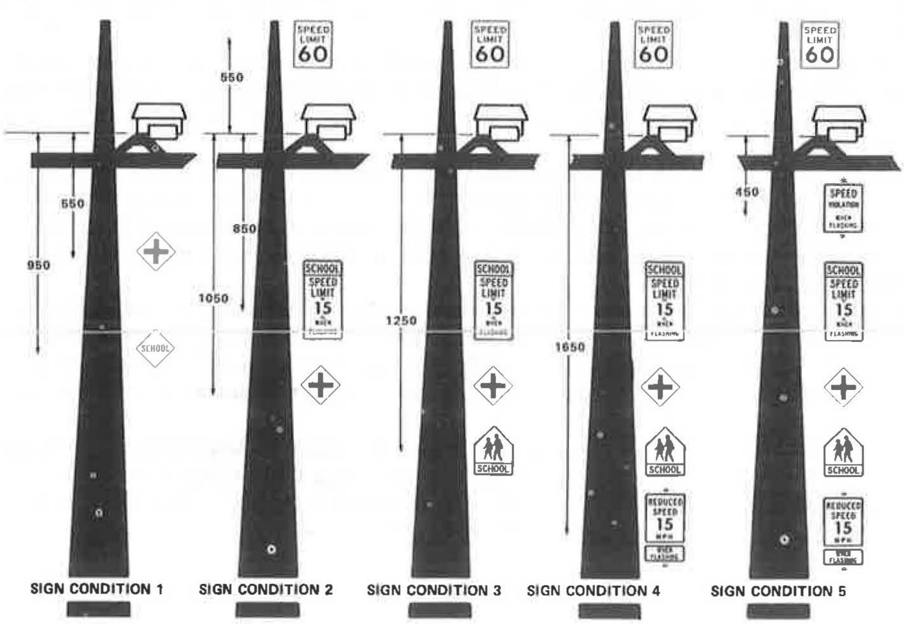


Table 1. Time periods during which Maine school zone speed statute in effect and not in effect.

Time Period	In Effect	Not in Effect
1		12 midnight to 7:15 a.m.
2	7:15 to 8:00 a.m.	
3	8:00 to 8:45 a.m.	
4		8:45 to 10:00 a.m.
5	10:00 to 10:25 a.m.	
6		10:25 to 11:00 a.m.
7	11:00 to 11:25 a.m.	
8		11:25 a.m. to 12 noon
9	12 noon to 1:15 p.m.	
10		1:15 to 2:00 p.m.
11		2:00 to 2:30 p.m.
12	2:30 to 2:50 p.m.	
13		2:50 to 3:15 p.m.
14	3:15 to 3:45 p.m.	
15		3:45 p.m. to 12 midnight

Figure 2. Sign conditions 1 through 5 for eastbound traffic.



EXPERIMENTAL VARIABLES

The primary objective of the experiments was to evaluate driver response and voluntary compliance with each of the five sign conditions. [No enforcement of the 15-mph (24-km/h) speed limit was used during the entire experiment.] As drivers traveled through the school zone test site, dependent and independent variables were measured and recorded either electronically by the Maine Facility system or manually by field observers.

The dependent variables used in the experiments were average speed, speed reduction, and variance between each pair of instrumented sensors for eastbound traffic [between sensors 144 and 131 for sign conditions 1 and 2 and between sensors 144 and 128 for sign conditions 3, 4, and 5 (Figure 1)].

Independent variables controlled or accounted for in the experiments are given in Table 2. The effects of only three independent variables—vehicle type, sign location, and sign and statute condition—on the dependent variables are discussed in this paper. Measured traffic volumes did not vary significantly during the hours dependent variables were measured.

EXPERIMENTS

Two categories of experiments were conducted at the Maine Facility school test site: driver speed reduction characteristics for the various sign conditions were analyzed, and different vehicle interactions were examined. The experiments were to answer the following questions:

1. Were vehicle types (automobiles and others) affected differently by various sign conditions?
2. Was there an adverse effect on drivers caused by certain sign conditions when the Maine school statute was not in effect [speed limit 60 mph (96 km/h)]? Did certain sign conditions cause drivers to drive at speeds lower than the posted speed limit?
3. If a significant number of drivers did not decrease their speed to 15 mph (24 km/h) for any of the sign conditions, what was the minimum velocity that these drivers deemed reasonable for passing through the school speed zone?
4. Where on the road did the speed reductions take place with respect to particular signs?
5. Did certain signs cause drivers to decelerate more rapidly than others?

Subsequent analyses will deal with other questions relating to this experiment.

Data Collection

Data were collected from January 5 through June 8, 1973, when school was in session. Daily data collection (1 to 6 hours) was planned to ensure sample sizes sufficient for data analysis. Testing under each sign condition was scheduled to last for 4 weeks to allow drivers to become accustomed to the given sign conditions. This phenomenon is commonly known as the learning curve effect. At the conclusion of each 4 weeks of testing, the next sign condition was to have been installed. However, because of equipment failures at the site, data were not recorded on each school day. Thus, number of days for data collection and driver exposure under each experimental sign condition were not equally balanced. Treatment for this uncontrollable situation was handled during the data analysis and is discussed later. The schedule for data collection is given in Table 3. Hours during the day when data were collected are the same as those listed in Table 1.

During the experiments, all of the flasher beacons (Figure 2) were operated at all appropriate times even though data were not always being collected.

During selected time periods, both computer and manual data were collected. Maine

Figure 3. Experiment signs.

	MUTCD Year	MUTCD No.	Size (IN)	Remarks
	1961	W9-1	30x30	Black letters on yellow background. Data collected using this sign served as the base from which improvement or degradation of traffic performance with other signs was measured
	1971	-	24x48	"School" black letters on yellow background. Remainder black letters on white background. Speed Limit Sign Beacons employed with sign to inform driver when Maine School Statute was in effect
	1971	S-1 S4-3	36x36 36x12	Black legends on yellow background. Used in advance of locations where school buildings or grounds were adjacent to the highway
	1971	R2-5 S4-4	24x30 24x10	Black letters on white background. Beacons, when flashing, informed drivers that a school zone speed limit lay ahead.
	-	-	36x36	Black letters on white background. Special design "reminder" sign. Beacons flashed when Maine School Statute was in effect and Maine Facility computer detected, in real time, a vehicle speed of 20 MPH or over.

Table 2. Experimental independent variables.

Name	Code	Description
Vehicle type	1	Automobiles and pickup trucks, or vehicle length = 5 to 20 ft
	2	Other, or vehicle length >20 ft (e.g., trucks and buses)
Sign location	1 to 10	Sign conditions 1 and 2 (see Figure 1)
	1 to 12	Sign conditions 3, 4, and 5 (see Figure 1)
Vehicle direction	1	Eastbound through vehicles on US-2
	2	Westbound through vehicles on US-2
	3	Vehicles turning onto or off of Madawaska Road (adjacent to school)
Conflict	1	Conflict, or vehicle headway at school ≤5 sec
	2	No conflict, or vehicle headway at school >5 sec[a]
Driver type	1	Drivers of vehicles with Maine license plate
	2	Drivers of vehicles with out-of-state license plate
Maine school	1	Times Maine school zone statute in effect
	2	Times Maine school zone statute not in effect
Sign condition	1 to 5	See Figure 2
Weather	1	Good—Visibility[b] and/or skid condition[c] met
	2	Bad—Visibility and/or skid condition not met
Week of test	1 to 4	Week of test when data collected
Day of test	1 to 5	Day of test (Monday through Friday) when data collected
Time of day	1 to 15	15 data collection time periods given in Table 1

Note: 1 ft = 0.3048 m. 1 mph = 1.6 km/h.

[a]Cause of vehicle deceleration, presence of school sign or proximity of leading vehicle, should be known.

[b]When observer at school could see traffic sign at 500 ft (152 m).

[c]If test vehicle did not skid when brakes were applied at 20 mph (32 km/h).

Table 3. Data collection periods for sign conditions.

Sign Condition	Data Collection Period	Days Data Collected	Days Data Analyzed	Weeks of Exposure[b]
1	January 15 to February 5	15	3	3
2	February 7 to March 13[a]	21½	3	6
3	March 13[a] to April 19	15½	4	5
4	May 7 to 18	9	9	2
5	May 25 to June 8	9	5	3
Total		70	24	19

[a]Half days. [b]Time during which drivers traveling on US-2 could have observed indicated sign condition.

Department of Transportation observers were stationed north of the school intersection (X, Figure 1) in an unnoticeable position to drivers on US-2. The observers recorded (a) time vehicle was observed, (b) vehicle direction, (c) vehicle type (e.g., automobile, bus, truck), (d) Maine or out-of-state registration, and (e) turning movements.

Data Reduction

The raw data tapes were run through a data reduction program that recognized vehicles; tracked vehicles through the test site; calculated vehicle parameters such as velocity, headway, and length of vehicle; and stored the reduced data on computer tape in a format for data analysis. The manually collected data were correlated and combined with the reduced data.

Data Analysis

Data from 24 days (Table 3) were selected for analysis to balance the exposure of drivers to the experimental signs, the time-of-day exposure, and the scheduled time periods of data collection. The specific days, the number of weeks that drivers could be exposed to each sign condition, and the proportion of the drivers of the 2,418 vehicles exposed to each sign condition are given in Table 4.

Table 5 gives the number of vehicles whose drivers were exposed to the sign conditions when the school zone speed statute was and was not in effect. Included are vehicles that could be tracked through most instrumented sensors (10 for sign conditions 1 and 2 and 12 for sign conditions 3, 4, and 5).

Data collected during nonschool hours (3:45 p.m. to 7:15 a.m.) were not used because it was felt that these data, taken during time periods when the speed statute was obviously not in effect, would bias the results. Only data for vehicles traveling in the eastbound direction under clear visibility and not impeded by leading vehicles or turning vehicles from either direction were used.

RESULTS

Table 6 gives the standard deviation SD (in mph), sample size N, and calculated average speeds $\overline{V}$ (in mph) for each sign and statute condition by distance from the school intersection. The instrumented station locations have been transformed into distances to the school for ease of discussion and illustration. All of the data in Table 6 are for the selected 24 data analysis days.

Speed Profiles

Average speed profiles from Table 6 are shown in Figures 4, 5, 6, 7, and 8. Each figure shows profiles by a specific sign condition for both statute conditions. At the top of each figure, the experimental sign condition is shown. Average speeds for automobiles are plotted separately from other vehicles, which include trucks and buses.

When the speed reduction statute is in effect, the slope of these profiles markedly increases from about 1,200 ft (368 m) from the school as experimental sign conditions are made more dynamic. The slight grades of the highway correlate with the upward and downward slopes of the profiles when no speed reduction statute was in effect. However, the experimental signs also appear to influence the slopes of the profiles for the no-speed-reduction-statute condition.

The following observations can be made from the comparison in Figure 9 of the five automobile speed profiles for the time the school speed statute was in effect.

1. The flashing school zone speed limit sign (1971 MUTCD) is much more effective

Table 4. Analysis data.

Sign Condition	Days Selected	Weeks of Exposure	Sample Represented (percent)
1	January 18, 26; February 1	1, 2, 3	15
2	February 27, 28; March 2	4	20
3	March 29, 30; April 3, 13	2, 3, 4	21
4	May 7 to 11, 14, 16 to 18	1, 2	28
5	May 31; June 1, 4, 5, 6	2, 3	16

Table 5. Number of vehicles used.

Sign Condition	Statute in Effect			Statute Not in Effect		
	Automobile	Other	Total	Automobile	Other	Total
1	167	26	193	138	40	178
2	216	43	259	172	49	221
3	178	50	228	220	55	275
4	239	49	288	325	72	397
5	140	40	180	154	45	199
Total	940	208	1,148	1,009	261	1,270

Table 6. Average speed, sample size, and standard deviation.

Item	Distance to School (ft)	Sign Condition 1			Sign Condition 2			Sign Condition 3			Sign Condition 4			Sign Condition 5		
		$\overline{V}$ (mph)	N	SD (mph)	$\overline{V}$ (mph)	N	SD (mph)	$\overline{V}$ (mph)	N	SD (mph)	$\overline{V}$ (mph)	N	SD (mph)	$\overline{V}$ (mph)	N	SD (mph)
Automobiles																
Statute in effect	2,600	55.01	159	8.29	54.58	213	8.19	55.90	175	8.30	54.65	240	7.75	54.84	138	7.03
	2,200	56.57	168	8.62	55.80	217	7.99	56.87	177	6.11	54.20	242	7.65	52.84	145	8.58
	1,700	56.55	167	10.48	55.73	218	9.01	57.04	177	8.83	51.43	237	8.78	49.58	141	9.11
	1,300	57.36	167	9.54	54.98	216	8.98	55.93	178	9.34	47.58	241	10.57	46.86	142	10.65
	1,100	56.82	166	8.90	52.08	215	9.98	52.83	180	9.33	44.92	235	10.97	44.30	141	10.70
	900	56.46	169	8.18	49.02	216	10.89	49.45	179	9.99	42.43	241	11.40	41.64	139	11.20
	700	55.40	168	8.29	45.58	217	11.28	45.44	178	11.07	39.94	240	11.23	38.49	137	11.39
	400	54.47	169	7.86	42.71	217	11.59	42.27	181	11.99	37.83	240	11.04	35.03	141	11.33
	200	53.41	168	7.79	40.68	216	11.90	40.29	178	12.08	36.54	241	10.93	34.23	139	10.46
	0							41.33	178	12.05	37.95	234	10.71	35.55	138	10.13
	-200							43.93	176	10.98	40.96	234	9.19	39.01	134	8.94
Statute not in effect	2,600	56.63	134	8.56	55.16	172	8.40	56.04	220	8.16	55.88	321	8.73	54.01	154	8.88
	2,200	57.38	137	9.09	56.80	173	8.85	57.21	223	8.76	57.24	327	8.40	55.78	154	8.74
	1,700	57.89	140	9.37	57.49	172	9.59	58.32	221	8.03	56.83	326	8.49	55.26	155	9.33
	1,300	58.06	136	8.78	57.77	172	8.96	58.37	221	7.94	56.08	326	9.19	54.38	155	10.19
	1,100	57.96	140	8.34	56.90	172	9.11	57.35	221	8.54	55.32	327	9.58	52.93	155	10.42
	900	57.29	138	8.46	55.59	172	9.07	56.09	220	8.43	54.23	326	9.87	51.66	154	10.18
	700	56.05	139	8.25	54.08	171	9.45	54.19	220	8.79	52.91	326	10.14	49.90	154	10.56
	400	54.73	139	8.15	52.58	171	9.89	52.46	221	9.04	51.33	328	10.61	47.80	155	11.29
	200	53.81	140	8.42	51.45	171	9.84	51.26	221	9.07	50.51	327	10.55	46.77	154	11.23
	0							52.44	218	9.16	51.61	325	10.30	48.26	152	11.06
	-200							52.92	215	8.72	52.57	317	9.19	49.30	153	10.20
Other vehicles																
Statute in effect	2,600	48.77	25	10.52	49.38	43	8.51	51.35	49	11.22	48.83	51	8.92	48.22	38	7.42
	2,200	49.69	27	10.91	51.71	43	8.04	54.26	48	8.06	50.16	50	7.12	49.37	39	6.67
	1,700	52.73	26	10.37	52.89	43	7.45	55.08	50	7.49	48.71	50	6.39	47.07	38	8.74
	1,300	53.06	27	9.57	52.83	43	7.44	53.41	51	7.59	47.27	49	6.64	45.63	40	9.47
	1,100	52.36	27	9.63	49.95	43	7.33	49.31	51	8.99	44.90	49	7.14	43.09	40	9.83
	900	51.76	27	9.97	46.96	43	7.97	45.91	51	9.84	43.46	48	7.20	40.87	41	9.90
	700	49.57	26	10.39	42.62	43	8.24	41.88	51	9.89	40.58	49	8.04	38.26	39	10.25
	400	48.54	27	11.11	39.02	43	9.03	38.99	51	10.32	39.19	48	8.01	35.16	41	10.69
	200	47.72	27	10.99	36.37	43	9.58	37.08	51	10.24	37.83	48	8.46	34.39	40	10.38
	0							38.46	49	10.36	39.16	47	8.35	35.22	40	10.72
	-200							41.22	48	8.88	40.49	46	7.84	37.70	39	8.80
Statute not in effect	2,600	49.38	39	9.70	47.77	47	9.02	51.08	54	8.14	49.12	67	9.68	51.11	47	8.10
	2,200	52.78	40	7.79	50.28	49	8.47	53.74	56	7.71	51.91	71	8.64	53.09	47	8.02
	1,700	54.65	40	7.29	52.37	49	7.63	55.18	56	7.21	53.01	72	7.81	52.76	47	8.51
	1,300	55.01	40	6.90	52.88	49	6.97	55.43	56	7.16	53.11	72	8.17	52.67	46	8.96
	1,100	54.62	39	6.60	52.33	49	6.87	54.61	56	7.40	52.42	72	8.49	51.18	46	9.25
	900	53.62	40	6.86	51.41	49	6.83	53.40	56	7.94	51.55	72	8.56	50.22	45	10.14
	700	52.25	39	6.87	49.86	49	6.59	51.91	56	8.44	49.68	72	8.90	48.46	45	10.29
	400	51.18	40	7.09	48.46	49	6.72	50.81	56	8.67	48.05	73	9.18	46.94	45	10.97
	200	50.31	40	6.73	47.28	49	6.76	49.88	56	8.51	47.17	73	9.46	45.93	45	10.81
	0							51.63	55	8.78	48.32	73	9.42	48.00	44	10.96
	-200							51.91	54	7.80	49.23	71	8.49	48.51	43	10.14

Note: 1 mph = 1.6 km/h. 1 ft = 0.3048 m.

Figure 4. Sign condition 1 speed profiles.

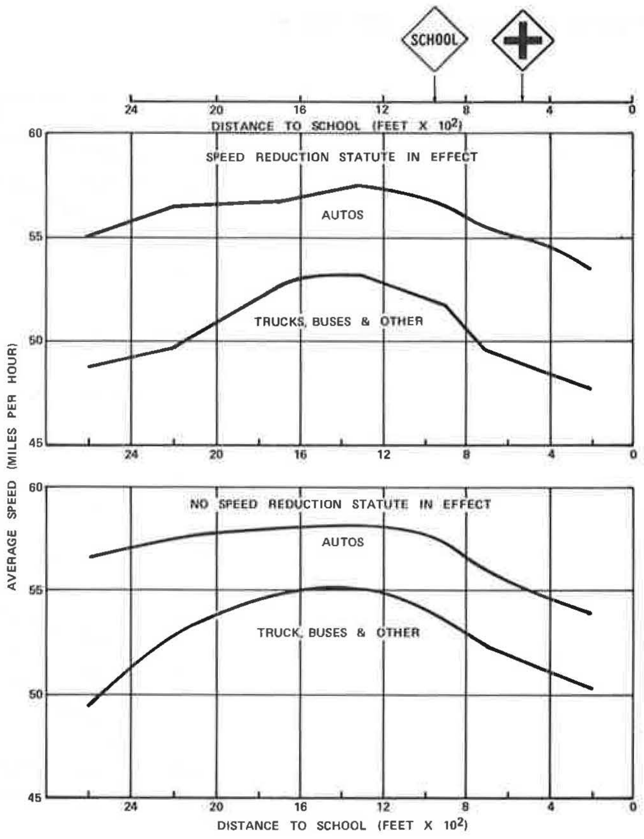


Figure 5. Sign condition 2 speed profiles.

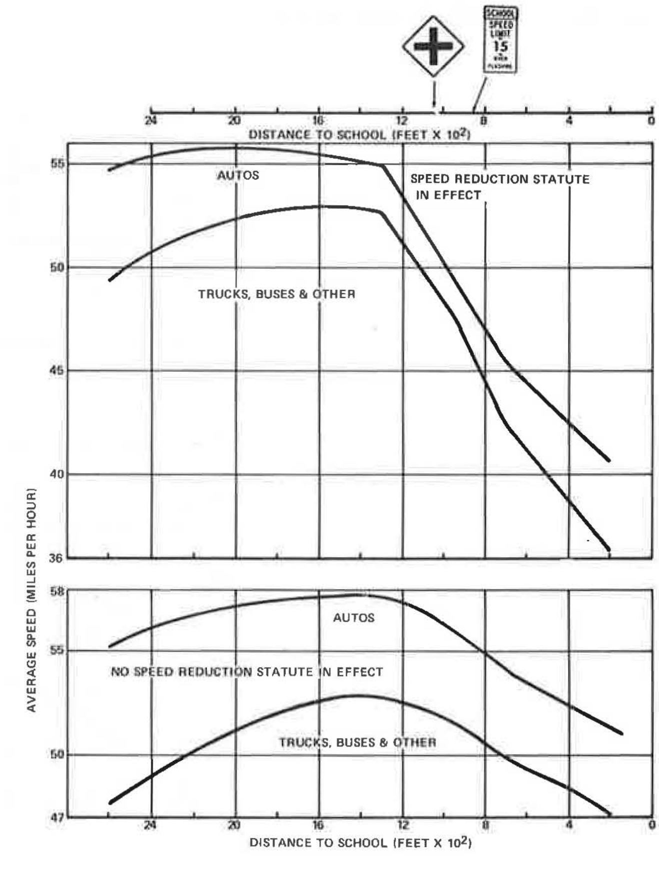


Figure 6. Sign condition 3 speed profiles.

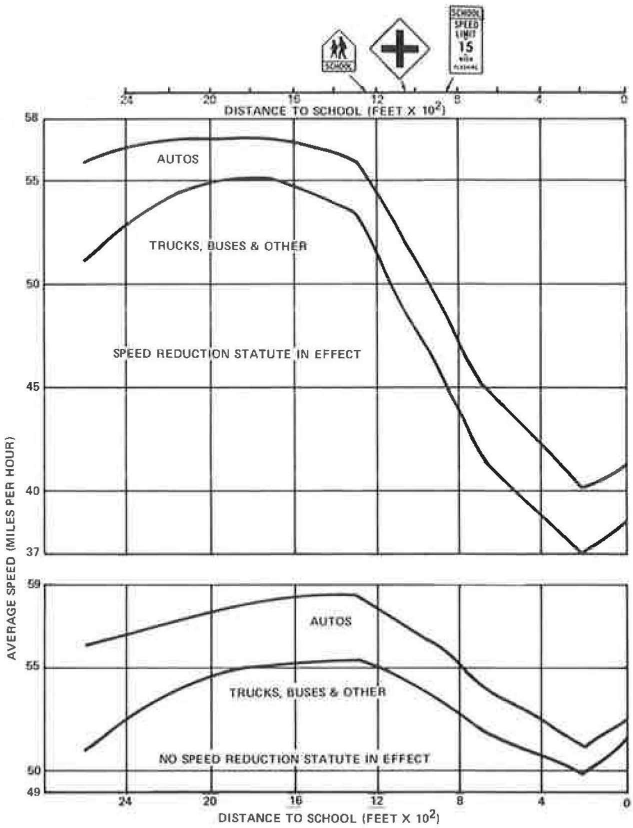


Figure 7. Sign condition 4 speed profiles.

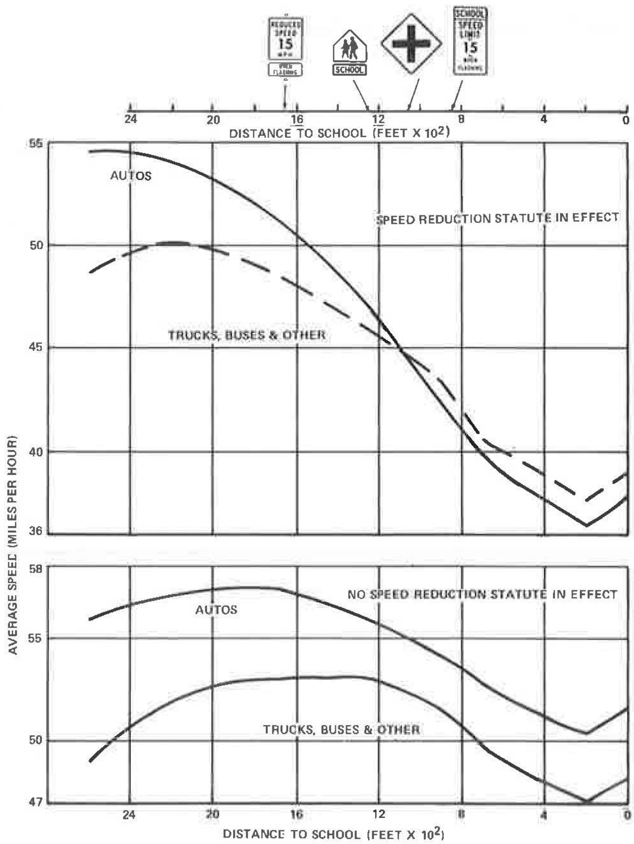


Figure 8. Sign condition 5 speed profiles.

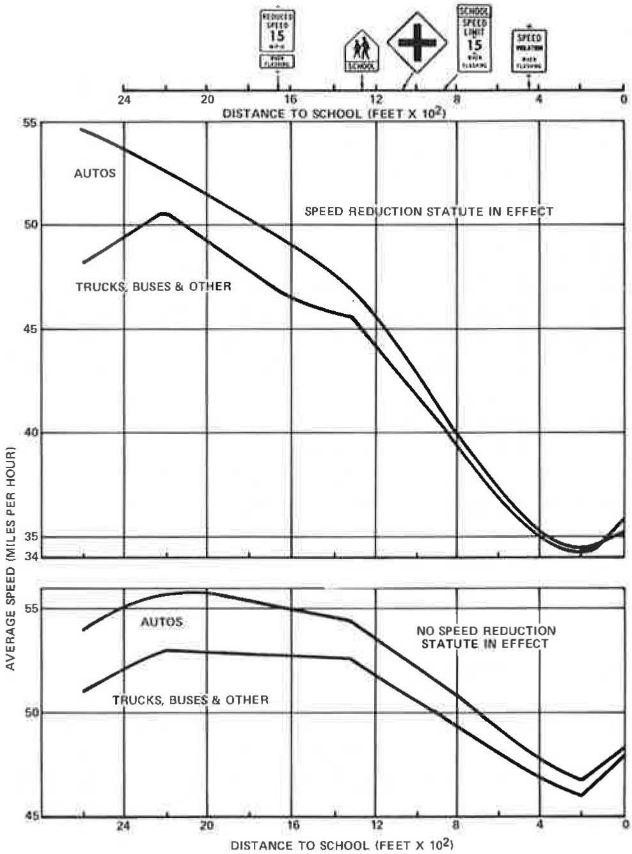
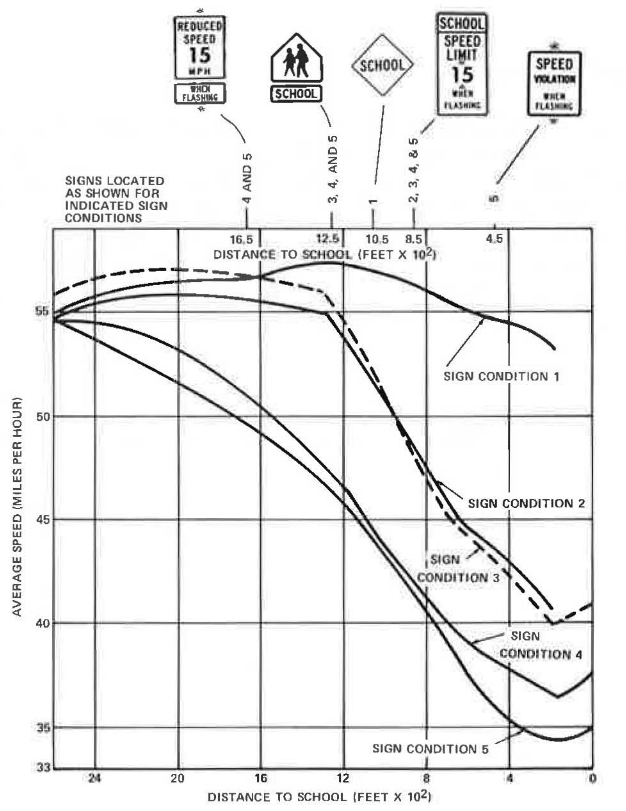


Figure 9. Automobile speed profiles when statute in effect.



than the passive, diamond-shaped school sign (W9-1, 1961 MUTCD). Drivers start to reduce their speed sharply at about 400 ft (122 m) in advance of the sign when it is the only dynamic sign present.

2. The symbol type of school advance sign does not cause drivers to further alter their speed when it is used with the flashing speed limit sign.

3. The rate of speed reduction effected by sign conditions 2, 3, 4, and 5 is approximately 1.25 ft/sec^2 (0.38 m/s^2), which is approximately the deceleration rate achieved with the engine engaged and without brakes used (4).

4. The flashing reduced speed ahead sign causes drivers to begin to reduce their speed as much as 800 ft (244 m) before the sign. When this sign was located 800 ft (244 m) in advance of the flashing school zone speed limit sign and the drivers decelerated at 1.25 ft/sec^2 (0.38 m/s^2), 3- to 5-mph (4.8- to 8.0-km/h) lower average speeds were experienced at the school intersection.

5. The flashing speed violation sign produced an additional 2-mph (3.2-km/h) lower average speed at the school intersection than the sign for the combined flashing reduced speed ahead and school zone speed limit signs.

A more detailed examination of where significant speed changes occurred for each sign condition is discussed below.

Speed Reductions

Table 7 gives the average absolute speed reduction for each sign condition as measured from 2,600 ft (793 m) to 200 ft (61 m) from the school intersection. Experimental signs 2, 3, 4, and 5 produced lower speeds for both speed statute conditions and for all vehicles. None of the signs produced the posted speed of 15 mph (24 km/h) when the speed statute was in effect. The lowest speed, approximately 34 mph (54 km/h), and the greatest amount of speed reduction, approximately 20 mph (32 km/h), occurred when the most dynamic sign condition was used.

Speed Variance

In Table 6, a trend can be seen toward increases in SD as sign conditions were made more dynamic under both statute conditions. Although most of the vehicles in the data analysis sample were operating under unimpeded conditions, this increased variance in speed and decrease in average speed must be related to the possible critical conditions that could arise under more congested traffic conditions.

Table 7 gives overall average speeds (average for all vehicles in a classification group over all instrumented stations) and speed variance for each vehicle type under each sign and statute condition. The overall average speed performances were tested

Table 7. Speed reduction, overall average speeds, and speed variance by sign condition.

Speed Statute	Sign Condition	Speed Reduction (mph)		Average Speed (mph)		Speed Variance (mph)	
		Automobiles	Other	Automobiles	Other	Automobiles	Other
In effect	1	1.6	1.1	55.8	50.5	8.8	10.4
	2	13.9	13.0	50.1	46.9	11.5	9.9
	3	15.6	14.3	49.2	46.1	12.1	11.4
	4	18.1	11.0	44.2	43.8	11.9	8.7
	5	20.6	13.8	43.0	41.3	12.2	10.8
Not in effect	1	1.8	-0.9	56.6	52.6	8.7	7.5
	2	3.7	0.5	55.3	50.3	9.5	7.5
	3	4.8	1.2	55.2	52.7	8.9	8.1
	4	5.4	1.9	54.1	50.3	9.8	8.9
	5	7.2	5.2	51.5	49.9	10.6	9.9

Note: 1 mph = 1.6 km/h.

to determine whether automobile drivers differed significantly ($\alpha = 0.05$) from truck, bus, and other vehicle drivers. The test was made for both statute conditions. The results show that the average performance of automobile and other vehicle drivers differed for all but sign condition 4 when the statute was in effect. This is a curious result. However, the exposure of drivers to sign condition 4 was the least and may not reflect the longer term effects of that sign condition. The opposite condition may be true; i.e., sign condition 4 may lead to the more uniform average speed performance of the two classes of vehicle drivers.

Differences in speed variability were also tested by using an F-test ($\alpha = 0.05$) to compare sign conditions. Sign conditions were compared for each vehicle type when the speed statute was in effect. The results in Table 7 show that the performance of automobile drivers differed with regard to variability for sign conditions 3, 4, and 5. There is no reason to infer differences in performance variability among sign conditions 3, 4, and 5. Performance of truck, bus, and other vehicle drivers differed with regard to variability for sign conditions 1 and 2 when compared with sign conditions 3 and 4. Performance of drivers did not show significant differences in variability for sign condition 5 compared with all other sign conditions.

Vehicle Location

A one-way analysis of variance was run with vehicle location as the treatment factor (the vehicle was over the instrumented station). The F-tests showed significant differences among the effects of vehicle location on average speed for all sign condition, vehicle type, and statute status combinations except for the combination of sign condition 1; trucks, buses, and other vehicles; and the statute in effect. It is not clear why these vehicles operating with only sign condition 1 were unaffected by their location along the roadway except that the old diamond-shaped school sign had no effect on the drivers of such vehicles. The number of vehicles in this combination was only 26, a much smaller sample size than for other combinations (Table 5).

Statistical t-tests ($\alpha = 0.05$) were conducted next to determine the exact locations at which changes in the average speeds became significant within each sign condition when the speed statute was in effect. For each sign condition, no significant differences in average speed changes occurred closer than 700 ft (214 m) to the school for either automobiles or other vehicles.

Further t-tests ($\alpha = 0.05$) were run to compare the vehicles' average speeds under differing experimental sign conditions on an instrumented station basis; i.e., speeds at the same location were compared across sign conditions. As is shown in Figure 9, significant differences in average speed were found at all locations except for the instrumented station farthest from the school. The speed response of drivers to sign conditions 2 and 3 was statistically the same. Significant differences between sign conditions 1 and 2 first occurred 1,300 ft (396 m) from the school for automobiles and 900 ft (313 m) before the school for other vehicles. Significant differences between sign conditions 1 and 3 first occurred 1,100 ft (335 m) from the school for all type vehicles. At the school, the automobile driver response to sign condition 3 was statistically different from that to sign conditions 4 and 5, but the response to sign condition 4 was significantly different from the response to sign condition 5 for all vehicle drivers. Sign conditions 4 and 5 differed statistically from sign conditions 1, 2, and 3 for automobiles up to 200 ft (61 m) from the school and for other vehicles up to 900 ft (274 m) from the school.

Finally, statistical tests for significant differences ($\alpha = 0.05$) were conducted to determine the points at which the vehicles differed in average speed when the statute was both in effect and not in effect. The results are given in Table 8. These results show a high correlation between the location of the first sign that the driver sees in a sign condition and the point at which significant differences occur. Such correlation is encouraging in that drivers are reacting to the signs at the proper time; i.e., they obey them when the statute is in effect and ignore them when the statute is not in effect.

Table 8. Statistically significant speed differences for various sign conditions.

Vehicle	Sign Condition	Location of First Sign (ft from school)	Significant Differences (α = 0.05)
Automobiles	1	1,100	None
	2	1,100	Significant from 1,300 ft to school
	3	1,300	Significant from 1,300 ft to school
	4	1,700	Significant from 2,200 ft to school
	5	1,700	Significant from 2,200 ft to school
Other	1	1,100	None
	2	1,100	Significant from 900 ft to school
	3	1,300	Significant from 1,100 ft to school
	4	1,700	Significant from 1,700 ft to school
	5	1,700	Significant from 2,200 ft to school

Note: 1 ft = 0.3048 m.

SUMMARY AND CONCLUSIONS

This paper has focused on the effectiveness of five rural school zone signing conditions in achieving driver compliance with a 15-mph (24-km/h) school zone speed limit. Although the total objectives of the experiments must await further analysis and refinement of the data, a number of useful conclusions can be made now.

1. The 1961 MUTCD school signing (sign condition 1) is inadequate for informing drivers of existing school zone speed limits.
2. The 1971 MUTCD mandatory school signing when combined with beacons and the words WHEN FLASHING (sign condition 2) made the drivers reduce their speeds but only to about 40 mph (64 km/h), which they may have felt was reasonable and proper for the observed condition.
3. The addition of the MUTCD advance school zone sign (sign condition 3) with both the symbol and the word SCHOOL included had no significant additional effect on speed reduction over that experienced with the speed limit sign as given above.
4. An advance sign advising drivers of the reduced speed limit ahead (sign condition 4) did cause an earlier and somewhat more gradual speed reduction when compared with the abrupt reduction obtained by using the school speed limit sign with beacons and the words WHEN FLASHING (sign condition 2) or with the advance school zone sign (sign condition 3). The average speed was reduced to approximately 37 mph (59 km/h) near the school with the advance reduced speed limit sign.
5. The addition of a dynamic speed violation sign resulted in an average speed of 34 mph (55 km/h), a further speed decrease of about 3 mph (4.8 km/h).

By reviewing the effects of the five sign conditions discussed above, we can further conclude that the speed limit sign introduced in sign condition 2 produced a consistent average speed reduction and profile that indicated the sign, reinforced by the flashing beacons, was being recognized by the drivers. It also appears, from the speed reduction achieved, that the drivers did not recognize the need for a speed limit of 15 mph (24 km/h), but were willing to slow down to what seemed to them to be a reasonable speed [35 to 40 mph (56 to 64 km/h)] for the road and surrounding conditions as they saw them.

The effect of the introduction of the school zone symbol sign on drivers could not be interpreted. Drivers may have thought that it was advisory only and that no additional action was required. The speed limit sign with flashing beacons had the same effect with and without the symbol sign. Further experimentation would be necessary to determine the need for and efficacy of the symbol sign.

The advance sign advising drivers of the reduced speed of 15 mph (24 km/h) ahead caused an earlier reaction by the drivers. Although traveling at an average speed of 55 mph (88 km/h) 800 ft (244 m) in advance of the sign, they had reduced their speed

to about 50 mph (80 km/h) at the sign and further reduced their speed to about 42 mph (67 km/h) as they passed the speed limit sign. The combined effect of the two signs was significant and appears to indicate that the maximum speed reduction was achieved on a voluntary basis through an understanding of the signs. However, it should be noted that this sign condition was observed only over a 2-week period.

The ultimate value of the dynamic speed violation sign could not be determined from this analysis. Although the average speed achieved was the lowest, down to 34 mph (55 km/h), this sign was used during the last 2 weeks of the school session (May 25 to June 8, 1974), and the extent of the learning process is not known, i.e., how much lower speed might have been obtained.

Finally, it now appears that

1. The 1961 MUTCD school sign was not adequate.
2. The 1971 MUTCD school speed limit sign when combined with beacons and the words WHEN FLASHING is effective in achieving a reasonable speed reduction.
3. The advance school zone signs, with the symbol and with the word SCHOOL, may not be of sufficient value for use at all locations. Further study may show that it could be effectively combined with speed advisory information to form one sign.
4. The advance reduced speed advisory sign with beacons caused drivers to reduce their speeds more in advance of the intersection.
5. The dynamic speed violation sign will require further study before a decision can be reached about its total effectiveness.

A speed of 15 mph (24 km/h) for rural school zones where there are very few children walking to the school area and where adjacent posted speed limits are 50 to 60 mph (80 to 96 km/h) cannot be achieved by the MUTCD signing and the auxiliary signing used for the experiments. The most desirable speed limit for such zones, based on these data, is 35 mph (56 km/h).

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OPERATIONAL EFFECTS OF GEOMETRIC DESIGN AT FREEWAY LANE DROPS

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ABRIDGMENT

Traffic operations at freeway lane drops suffer when geometric design or traffic control devices provide insufficient or misleading information to drivers. This paper discusses the nature of traffic operation problems at freeway lane drop locations and presents eight design principles that should be considered when a lane drop is constructed or updated. These principles include recommendations for planning visibility, location, taper and escape lane characteristics, and traffic control device requirements. A before and after study conducted at a lane drop site in metropolitan Los Angeles illustrates a method for using the design principles to evaluate the effectiveness of a change in traffic control devices at the site.

•OPERATIONAL problems stemming from a reduction in the number of traffic lanes on a freeway are frequent and sometimes severe. A project (1) was undertaken to define the nature and extent of the operational problems of freeway lane drops so that operational improvement of existing lane drop locations and guidelines for future site construction could be recommended. Field observations at 65 lane drop sites throughout the United States were made, and interviews with representatives of over 20 transportation agencies were conducted.

The results of the study pinpoint two basic types of operational problems: those attributed to an excessive demand on the system and those attributed to insufficient information available for the driver to respond effectively to the lane drop situation.

Although not easy to accomplish, the solution to operational problems caused by demand exceeding downstream capacity is fairly straightforward. Two solutions for existing problem locations are (a) extend the lane until demand is reduced to a level below lane reduction capacity and (b) reduce upstream demand. A Policy on Geometric Design of Rural Highways (2) indicates a design capacity of 1,200 vehicles per hour (vph) on suburban freeways and 1,500 vph on urban freeways. If the demand predictions hold true, then a lane can be dropped, and a geometric bottleneck will not be created.

Operational problems associated with the inability of drivers to perceive, interpret, and react properly to a lane drop situation are much more subtle and more difficult to analyze.

By definition, an operational problem exists if a significant number of drivers make erratic maneuvers in the area of the lane drop. Erratic maneuvers include sudden speed changes; abrupt lane changes; and lane changes that require driving through a ramp gore area, an escape lane, or a lane drop taper. Some of these erratic maneuvers may result in unsafe conditions or even accidents; many may result in increased driver anxiety.

The requirements for negotiating a lane drop are an awareness of an impending lane drop, a knowledge of the location of the lane drop, and an ability to decide on an appropriate maneuver and to execute that maneuver. When drivers are in the vicinity of a lane drop, the longer information regarding these requirements is withheld from them, the fewer options they have for making smooth transitions through the area. Therefore, lack of important information necessary for negotiating the lane drop may be seen as the source of driver-behavior operational problems at lane drop locations.

The analysis of observed traffic operations at many differently configured lane drop

locations has yielded eight design principles that should be considered in the construction or remedial treatment of freeway lane drops.

PROVIDE CONTINUOUS VISIBILITY

The lane drop should be placed where the surface of the roadway remains continuously visible for a significant amount of time. A lane drop that is located just over the crest of a grade or just beyond a horizontal curve is not desirable since such placement results in a loss of valuable visual cues. Conversely, lane drops located at the end of a sagging vertical curve or on an upgrade may operate effectively even without good advance signing because the driver can see such drops in time to take appropriate action.

MINIMIZE ATTENTION-DIVIDING CONDITIONS

The lane drop should be placed away from attention-dividing conditions, such as ramps or complicated directional signing. The driver should have to make only one decision at a time. This does not mean that a lane drop should never be built at an exit ramp. It does mean that, if additional ramps or traffic control devices not directly pertaining to the lane drop exit ramp are nearby, then chances of drivers missing the cues associated with the lane drop are increased.

PROVIDE ADEQUATE TRANSITION CUES

The lane drop taper should allow for a smooth transition for a lane change in the taper area and should provide adequate visual cues that inform the driver that the lane is ending. A taper that is too short will cause drivers to make panic lane changes or speed changes, even though it produces a dramatic visual lane-ending cue to the driver. A lane drop taper that is too long will allow drivers to make a smooth transition into the through lane, but does little in the way of giving drivers visual cues that the lane is ending. Since a visually observable taper is probably the most reliable cue available for informing drivers of the impending lane drop, its loss can seriously impair the effectiveness of the lane drop site. Therefore, stub-end lane drops should be avoided. Where a stub end is desirable from a construction standpoint, it should be made with an artificial taper by covering upstream pavement with dirt and by providing removable curbing. Further research should be conducted to define the standard length of a lane drop taper.

CREATE LANE DROPS ON BETTER SIDE OF FREEWAY

The lane drop should be placed on the better side of the freeway for given traffic and geometric conditions. Whether a lane drop taper should be built on the left or the right has been the subject of considerable discussion. Based on this study, there seems to be no definitive answer to this question. One argument states that the left drop is advantageous because (a) there is usually less traffic in the left two lanes, (b) the left lanes are away from the influence of ramp turbulence on the right, and (c) vehicles generally flow at a more uniform speed in the left lanes since there are few slower commercial vehicles. Another argument states that the right drop is advantageous because (a) drivers are accustomed to having lanes end (i.e., acceleration lanes) on the right and can merge better from right to left than left to right, (b) traffic is generally slower in the right lanes and therefore there will be a slower speed merge, and (c) there is generally less traffic in the right lanes.

To help determine which lane to drop from a freeway, the following factors should be considered:

1. What type of lane distribution is expected? It would be preferable to merge the two most lightly traveled lanes.
2. What type of traffic composition is expected? When a large percentage of heavy trucks or recreational vehicles is expected, consideration should be given to merging the two left lanes.
3. What other geometric features, such as ramps, are nearby? Lane drops generally work better away from the influence of ramp turbulence.
4. Will the sight distance be significantly better on one side than the other? Sight distance is always critical.
5. Will it be more difficult to sign a lane drop on one side than the other? Appropriate signing can significantly improve a bad situation.

By examining these factors, the engineer can then make a reasonable judgment concerning which side of the freeway should have the lane drop.

COORDINATE VISUAL AND OPERATIONAL DROP

The lane should appear to physically end on the same side of the freeway as the operational lane drop. In some cases it is physically advantageous, yet not operationally desirable, to drop a lane on a particular side of the freeway. This may occur when a lane is dropped but there is a high probability of a future continuation. From a construction viewpoint, it is desirable to drop the left lane by stubbing the pavement off. However, from an operation view, this treatment of a lane drop may be far from optimum. This situation is usually corrected by merging the right two lanes by striping and signing. Theoretically, this will solve the problem; practically, the results of such situations have been less than optimum. Such treatment sets up a right-of-way problem for two drivers who arrive simultaneously at the lane drop and results in the loss of valuable information cues. A practical solution to this problem should be researched further. Generally, however, the operational merge should be accomplished by disguising the operational drop lane upstream of the physical drop so that it appears to be physically dropped. Figure 1 shows a plan and two perspective views of this situation. This may mean that, as in the case above in which a lane is dropped and future continuation is intended, some pavement may temporarily be unused by traffic so that better operational characteristics can be afforded.

PROVIDE ADEQUATE ESCAPE AREA

When a lane ends at an exit ramp, an escape area of adequate dimensions should be provided to allow for a smooth transition into through lanes. The escape area should be just that: an area for merging into the through lane after the driver is too close to the exit gore to make a normal lane change. The lane drop gore should be plainly visible to the approaching driver. Since the driver is probably traveling at or near freeway speed, a full acceleration lane is not needed, and a full lane width plus shoulder width may confuse the driver by providing too wide an area. Figure 2 shows perspective and plan views of an exit ramp lane drop.

NOTIFY DRIVERS THAT LANE IS NOT CONTINUOUS

When a lane is added at an on-ramp and dropped at a nearby off-ramp, the entering drivers should be notified that the lane they are traveling in is not a continuous lane for through travel. Normal lane lines should not be used as delineators in this situation. The lane should be designed as a special lane through the use of traffic control devices such as contrasting pavement color; overhead signs; or short, wide skip striping.

Figure 1. Plan and perspective views of opposite taper lane drop.

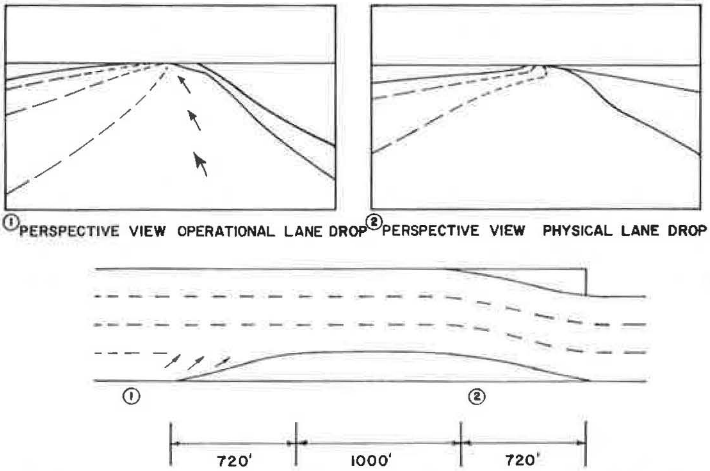
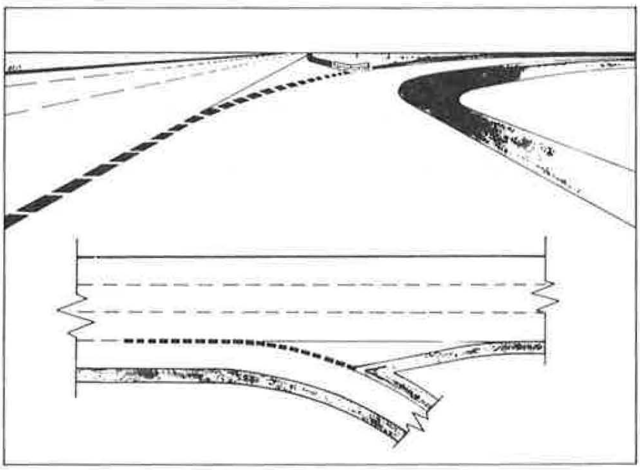


Figure 2. Plan and perspective view of an exit ramp lane drop.



USE ADEQUATE TRAFFIC CONTROL DEVICES

Consistent and appropriate traffic control devices should be used in advance of a lane drop. At many sites, incomplete or misleading information is given to the drivers. Drivers may be told to merge left, but in actuality the other lanes may move into their lane, such as where a lane is operationally dropped on the opposite side of the freeway from the physical drop. Occasionally missing information can be detrimental to lane drop performance. For example, a simple sign that reads ROAD NARROWS does not inform drivers of two important facts: (a) where the road narrows and (b) whether they are supposed to change lanes. Good traffic control devices will tell drivers what is going to happen, where it is going to happen, and what should be done about it. Traffic control devices should not confuse drivers with information not related to the task of traversing the lane drop section.

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SIGHT DISTANCE OBSTRUCTIONS ON PRIVATE PROPERTY AT URBAN INTERSECTIONS

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This paper discusses a study of current procedures used to correct sight distance obstruction on private property at urban intersections. The purpose of the paper is to identify the problems encountered in the removal of the obstruction; to determine the current laws, ordinances, and practices used by government agencies in removing obstructions; and to make recommendations for improving the laws, ordinances, and current methods of removal. A questionnaire mailed to state, county, and municipal traffic engineers throughout the United States was used to gather data for the study. Based on responses, recommendations are made for improving the level of voluntary compliance by the property owner. A model ordinance and a drawing showing how one city deals with this problem are included.

•PAST RESEARCH has shown that a high percentage of all traffic accidents occur at roadway intersections. The National Safety Council (1) recently reported that 41 percent of all accidents in urban areas and 27 percent of all accidents in rural areas occurred at intersections. Accident research in Tennessee shows that 54 percent of all accidents reported to the Department of Safety in 1973 occurred at intersections.

This study was to investigate the problem of obstructions such as shrubbery, trees, and signs that limit motorists' sight distance at roadway intersections and thus increase the accident potential at this point on the road. Sight obstructions are a major factor in the safe operation of an intersection. This is particularly true in urban areas where there is a great deal of land development adjacent to the roadway.

Disque (2) described the problem as follows:

> Sight distance at street intersections in urban areas is another phase of traffic safety on which much that is critical and very little that is commendable can be said. It can be stated, probably without contradiction, that in every community in the land there are street crossings where trees and shrubs have been planted within the street right-of-way and permitted to grow there until they approach, and perhaps overhang, the curb. At such a crossing, the cautious driver must creep his vehicle slowly forward to a position beyond the verdant obstruction where he can glance to the right and left down the intersecting street and judge when he can cross or turn. Statistics reveal that a very great number of accidents occur at street and highway intersections, where highway and vehicle conditions and circumstances, together with driver behavior, result in experiences that are costly, painful and often tragic.

Unfortunately, the problem of sight obstructions at intersections does not limit itself to the public right-of-way. In many cases, the obstruction is located on private property behind the right-of-way line. Because of the limited public street right-of-way, especially in cities, the government agency must cope with the problem of eliminating obstructions on private property in the interest of public safety. The accident rate at most intersections will generally decrease if and when problem sight obstructions are removed. A recent before and after study in Concord, California, illustrates this point. In this study (3), Mitchell stated:

An intersection sight distance study and a stop sign visibility check led to the trimming or removal of vegetation in the public right-of-way. Intersections where trimming would be required periodically were noted and reported to the Park Department. Where trimming on private property was needed, the owners were contacted by letters citing the requirements of the municipal code. With few exceptions, the response was excellent.

The sight distance at five intersections was improved during the study in Concord. After these obstructions were eliminated, total accidents at these intersections dropped from 39 in the year before to 13 in the year after obstruction removal, a 67 percent reduction. In the same study, many other intersections at other locations in Concord were improved by use of signal installation or modification, delineation striping, improved pavement markings, and increased police enforcement. However, although all these intersection improvements resulted in a reduction in accidents, the greatest percentage of reduction was experienced at the intersections where the sight distance was improved (3).

Although the sample size in Concord was small, the study reveals the potential reduction in accidents that could be obtained if this type of obstruction removal program were implemented nationwide.

To determine the significance of this problem nationwide and to obtain the necessary data to evaluate this problem area, a questionnaire was prepared and submitted to 202 government officials. The questionnaire was sent to state government officials in 48 states, city government officials in 138 cities from all 50 states, and 16 county government officials from 13 states. The questionnaire was basically designed to identify the problems associated with sight obstructions at intersections and to determine the methods used by the different levels of government in attempting to solve this problem. It was assumed that all government agencies had the authority to remove sight obstructions located on public rights-of-way; however, the officials were urged to send copies of state laws and city or county ordinances that were directly related to the removal of sight obstructions located on private property.

A total of 77 percent of the questionnaires was returned. State governments had 81 percent returned; city governments, 76 percent; and county governments, 69 percent. In addition, over 57 agencies returned copies of actual laws or ordinances that were evaluated in this study. All of the questionnaire data and the selected literature were used to answer the following questions:

1. What is considered to be adequate sight distance at an intersection?
2. What are the major problems experienced by government officials in obtaining adequate sight distance at intersections?
3. What changes should be made in the present method used to obtain removal, and can a model law or ordinance be developed that if adopted would help solve this problem without requiring expensive legal battles and a lot of engineering time?

An analysis of these questions follows.

SIGHT DISTANCE AT INTERSECTIONS

To recommend a size for a sight distance triangle at intersections required that the minimum value be determined. This was accomplished by evaluating two types of intersection control. Case 1 included intersections at which no traffic control existed and the basic right-of-way rule controlled the entering traffic. Case 2 included intersections where stop control had been placed on the minor street approaches and the major street was assigned the right-of-way. The AASHO procedure (4) was used to evaluate two specific intersection conditions that were relevant to our minimum sight triangle investigation.

Case 1 involved an intersection with no traffic control devices on any of the approaches. This condition is sometimes desirable in urban or suburban areas for

intersections of local streets where the total entering average daily traffic is 1,500 vehicles or fewer [accident history indicates fewer than three right-angle accidents per year and adequate safe stopping sight distance exists (5)]. In the evaluation of case 1, a design speed of 30 mph (48.3 km/h) for both local streets and a roadway right-of-way width of 60 ft (18.3 m) were assumed (6). This condition is shown in Figure 1. Based on these given roadway conditions, the safe stopping distance was calculated. A perception reaction and brake lag time of 1.0 sec was assumed (7). It was also assumed that the pavement was wet and that the coefficient of friction for a 30-mph (48.3-km/h) approach speed was 0.36 (4). A safe stopping distance of 127 ft (38.7 m) was calculated for case 1, and this distance was used to evaluate several different sight distance triangles. From these trials, it was concluded that a sight distance triangle with legs equal to 50 ft (15.2 m) extended along the property lines was the minimum triangle that would basically satisfy the stopping sight distance requirement. When this triangle is used, approximately 110 ft (33.5 m) of sight distance is provided for driver perception and reaction to a vehicle approaching on the cross street.

Although 60 ft (18.3 m) is a frequently recommended minimum right-of-way width for a local street (6), many existing roadways do not meet this criterion. When this condition occurs and an adequate sight distance triangle cannot be obtained, installing some form of traffic control device such as a yield or stop sign is often necessary. Installation of a traffic control device is also usually required at (a) the intersection of a county road, city street, or township road with a state road or (b) any street that enters a through highway (5).

In case 2, one of the two intersecting streets is controlled by a traffic control device (Figure 2). Since most state highways have ample right-of-way width, especially in rural areas, an urban intersection of a local street was evaluated with another through street having a limited right-of-way width of 40 ft (12.2 m). The through street could be classified as another local street, a collector street, or even possibly a minor, old state highway. It was necessary to determine the minimum sight distance required for the stopped vehicle to safely cross the through roadway. Based on the conditions shown in Figure 2 and a through roadway speed of 30 mph (48.3 km/h), 285 ft (86.7 m) of clear sight distance along the through highway was required for the driver of a passenger car design vehicle to safely cross the through highway (4). After several trials, it was determined that a 30-ft (9.1-m) sight distance triangle along the property lines at this intersection provided a sight distance of 285 to 350 ft (86.7 to 106.7 m) depending on the position of the stopped vehicle. The front of the vehicle could be 10 ft (3 m) behind the near edge of pavement and still have adequate crossing sight distance. Therefore, the 30-ft (9.1-m) sight triangle measured along the property line provided adequate sight distance for a safe crossing at this intersection if the controlled vehicle stopped within 10 ft (3 m) of the intersecting street. In this evaluation, only passenger cars were used; additional sight distance is required for larger vehicles. The required sight distance for a WB-50 design vehicle (the maximum case), for example, is approximately 650 ft (198.1 m). However, drivers of WB-50s are often compensated for their

Figure 1. Case 1.

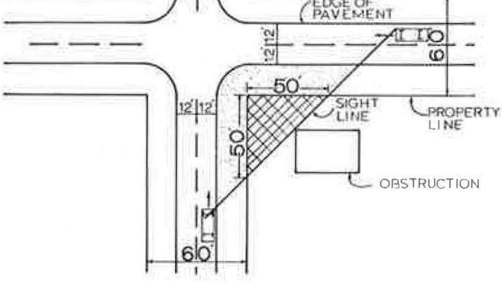
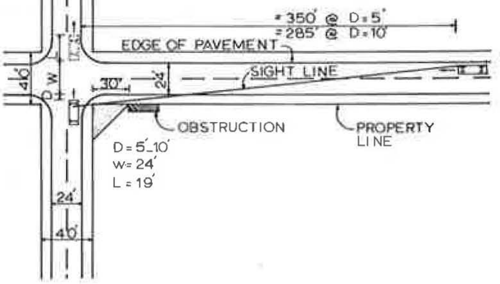


Figure 2. Case 2.



larger vehicles by higher sight levels [6.0 ft (1.8 m) compared to 3.75 ft (1.1 m) for passenger vehicles] and by the 285-ft (86.7-m) sight distance that is provided under these conditions. This sight distance is over two times greater than the safe stopping sight distance required for the vehicle on the through roadway to come to a complete stop before reaching the intersection. In addition, the 40-ft (12.2-m) right-of-way width used in this example is the absolute minimum for this type of intersection and is rarely designed today.

Thus, based on cases 1 and 2, a sight distance triangle with 30-ft (9.1-m) legs, measured along the property line, was necessary to provide the minimum sight distance required for most urban or suburban intersections. A 30-ft (9.1-m) triangle would accommodate vehicles in case 1 up to 25 mph (40.2 km/h); this would include most urban intersections.

To determine the existing use nationally of this recommended 30-ft (9.1-m) sight triangle required that the existing laws or ordinances that were obtained from the questionnaire be evaluated. Only 57 percent or 86 of the agencies returning the questionnaire had an existing law or ordinance that covered the problem of sight obstructions at intersections. Of these 86 agencies, only 57 returned a copy of their actual laws and ordinances. Only 40 of the laws and ordinances listed a specific sight distance triangle, and these were divided into two groups: (a) laws and ordinances prohibiting sight obstruction in a sight triangle by using the property line as reference and (b) laws and ordinances prohibiting sight obstructions in a sight triangle by using the curb line as reference. Only 8 percent of the agencies returning the questionnaire had a law or ordinance that equaled or exceeded the recommended 30-ft (9.1-m) sight triangle.

Since it is not realistic to expect that all objects can be removed from the sight distance triangle, two other factors must be considered when its effectiveness is evaluated: (a) the maximum height of an object, such as a hedge, a shrub, or a fence, and (b) the minimum clearance of an object, such as tree limbs, or the bottom of a sign, that are allowed in the sight distance triangle. The average for all 40 laws and ordinances was 2.74 ft (0.8 m) for the height of an object in the sight distance triangle. The average of the 24 laws or ordinances was 8.95 ft (2.7 m) for minimum clearance heights for objects such as tree limbs and signs in the sight distance triangle.

The many possible combinations of roadway grades made it impossible to satisfactorily evaluate the maximum allowed height of low obstructions and the minimum allowed height of high obstructions. However, several roadway grade combinations were tested, and within the recommended sight triangle at intersections [that triangular area between the property line and a diagonal line joining points on the property line 30 ft (9.1 m) from the point of their intersection] no object that impairs sight distance should be allowed to remain between 2.5 and 8 ft (0.8 and 2.4 m) above the level of the adjacent roadway. This recommended sight triangle should provide adequate sight distance for the safe operation of most intersections throughout the country.

PROBLEMS IN OBTAINING ADEQUATE SIGHT DISTANCE AT INTERSECTIONS

After minimum sight distance values at intersections were determined, attention shifted to the problem of obtaining this value in the field. Eight questions were designed to obtain information on this problem.

Of those who returned the questionnaire, 97 percent of the city, 100 percent of the county, and 89 percent of the state officials replied that sight obstructions at intersections presented problems for their agencies. So that the major problem in removing these obstructions could be ascertained, the officials were asked to indicate their problems. A lack of voluntary removal of the obstruction by the property owner was a more major problem in obtaining good sight distance than the problem of having no existing law or ordinance in effect.

Having no ordinance or law in effect received its highest rating with state officials, who indicated this condition on 50 percent of the returns. This was expected, however,

since the returns also revealed that 71 percent of the states have no applicable law that covers this problem area. A number of states indicated that the problem of removing sight obstructions was basically urban because the right-of-way was usually adequate to provide sufficient sight distance in rural areas. In only 19 percent of the returns, city officials reported that having no applicable ordinance presented problems; however, 27 percent of the cities have no ordinance. The number of replies from the county officials was so small that the results were of questionable reliability; thus, they were not considered in the evaluation of problem areas.

The other two possible problems on the questionnaire were (a) lack of engineering personnel to investigate problem areas and (b) no administrative backing for enforcement of existing laws or ordinances. Lack of engineering personnel was a problem for 29 percent of the cities and 21 percent of the states. Surprisingly, only 14 percent of the city officials and 4 percent of the state officials gave no administrative backing as a problem area. From these replies, it was obvious that an effective method should be developed whereby affected property owners would voluntarily remove, or allow the government agency to remove, existing obstructions in the sight distance triangle.

Before any method can be successful, local backing is needed in the form of a law or ordinance; however, the total solution to this problem cannot rely on this. Of the cities replying, 73 percent had existing ordinances, but 97 percent were having problems removing obstructions. Thus, in an effort to identify other problem areas, an analysis of the method of obstruction removal, the degree of agency enforcement, and the number of locations investigated each year was conducted. Since only 18 percent of the 39 states returning questionnaires have existing laws allowing obstruction removal from private property, this analysis was limited to the returns from city agencies.

In this analysis, the method of obstruction removal was explored. Of the cities with an ordinance, 96 percent indicated that the property owner was required to remove the obstruction at his own expense. However, in 26 percent of the cities, the obstruction could be removed by city forces and the cost billed to the property owner. In 56 percent of the cities, the city would remove the obstruction only when the property owner refused to do so. In most of these cases, the cost of the removal was charged to the property owner. Some degree of flexibility should be provided regarding the method of obstruction removal; however, in the interest of public safety, the city should have authority to enter private property and remove obstructions if the property owner refuses to do so.

The replies showed that existing ordinances were never enforced by 4 percent of the cities, seldom enforced by 30 percent, usually enforced by 38 percent, and very frequently enforced by 28 percent. The disturbing fact is that 34 percent of the cities seldom or never enforced existing ordinances. Since only 14 percent of the cities cited no administrative backing as a major problem area, it can only be concluded that enforcement officials feel that this law is not important enough to enforce. There appears to be no clear solution to this problem, although it is hoped that, through reports such as this, the importance of obtaining a good sight triangle at intersections will be conveyed to the affected enforcement officials.

A place on the questionnaire was provided for all cities, whether or not they had obstruction ordinances, to indicate the yearly number of cases investigated that concerned problems of sight obstructions at intersections. The replies indicated that, each year, 10 percent investigated 0 to 5 cases, 7 percent investigated 6 to 10 cases, 17 percent investigated 11 to 25 cases, 23 percent investigated 26 to 50 cases, and 30 percent investigated over 50 cases. One official reported investigating over 600 cases a year.

RECOMMENDATIONS FOR CHANGE

There are 3 important questions regarding sight distance obstructions:

1. What is the adequate size of a sight triangle at intersections?
2. What is an adequate law or ordinance controlling sight obstructions at

intersections, and how are elected officials to establish it?

3. How can the ordinance be effectively enforced with a minimum amount of engineering time and legal expense?

Sight Triangle

A 50-ft (15.2-m) sight triangle is desirable for intersections with no traffic control. At intersections where one street is regulated by a traffic control device, a 30-ft (9.1-m) sight triangle is required. In application, the 50-ft (15.2-m) triangle, although certainly desirable, is probably unrealistic because of its size. This triangle requires 1,250 ft^2 (116 m^2) of land if the lot property lines intersect at right angles. In comparison, the 30-ft (9.1-m) sight triangle requires only 450 ft^2 (42 m^2), 64 percent less land at the intersection. In addition, few of the existing zoning setback regulations in cities meet or exceed requirements for a 50-ft (15.2-m) triangle, even in low-density residential areas. Therefore, a 30-ft (9.1-m) sight triangle is recommended.

Model Ordinance

After a sight distance triangle has been established, the next step is to include it in a model ordinance. Zoning setback regulations play an important role in an obstruction ordinance. The zoning setback requirements should be written so that the sight triangle can be obtained in all residential and local business areas. Obviously, however, this same value cannot be obtained in the central business district and possibly other areas of high commercial development. Because of this limited CBD factor, it is recommended that the area within the 30-ft (9.1-m) triangle that encroaches within the interior of the setback lines established by the local zoning laws be exempted from compliance with this requirement. The validity of such an exception relies to a great extent on the zoning laws of the city, and a complete review of these laws is recommended before such a regulation is adopted. However, if reasonable zoning laws exist, this exception will in most cases provide drivers with some usable sight distance at all intersections. In addition to the exemptions made of areas encroaching within the interior of zoning setback lines the following exemptions are also recommended:

1. Small trees that are not more that 12 in. (30.5 cm) wide and that are planted so as to leave a clear and unobstructed cross-view;
2. Existing permanent buildings;
3. Existing grades that, by reason of natural topography, are more than 30 in. (76.2 cm) above the center of the adjacent intersection; and
4. Fire hydrants, public utility poles, street markers, and traffic control devices.

Buildings and existing grades are exempted because the removal of these obstructions would place an unreasonable financial burden on the property owner. It is recommended that during roadway design consideration be given to purchasing adequate right-of-way to provide the required sight distance. All of the objects installed to serve the general public do not usually cause a sight distance problem. Small trees, properly trimmed and planted, will not create significant sight distance problems for motorists.

It is also recommended that failure to remove obstructions in this specified area within 10 days of notification be classified as a misdemeanor committed by the property owner. The recommended fine for conviction of this offense is not less than $50 nor more than $100, and each day that the violation continues constitutes a separate offense.

Since the ultimate goal of this ordinance is to remove obstructions and not to engage in lengthy and costly legal battles, the city should be given authority to enter private property as required, to remove any obstructions in the specified sight distance triangle, and to charge the cost of such action by the city to the property owner in the

form of a lien against the property from which such obstruction is removed. This clause will permit quick and correct removal of the sight obstruction.

Based on the information given above, the following model city ordinance is proposed.

SECTION 01-001. Obstructions to Visibility at Intersections—Visibility Area Defined.

It shall be a misdemeanor for any person or persons or corporations owning real property at intersecting streets to install, set out, or maintain or to allow the installation, setting out, or maintenance of any sign, hedge, fence, shrubbery, natural growth, or other obstruction to the view, whether movable or stationary, higher than 30 in. (76.2 cm) above the level of the adjacent intersection.

1. The obstruction shall not be placed in that triangular area between the property line and a diagonal line joining points on the property line, 30 ft (9.1 m) from the point of their intersection.
2. In the case of rounded property corners, that triangular area shall be between the property lines extended and a diagonal line joining points on the property lines, 30 ft (9.1 m) from the point of their intersection.
3. In both 1 and 2 above, such area within the said triangle that encroaches within the interior of the setback lines applicable to any lot or parcel of real property by and through the zoning laws of this city as fully set forth in this code shall be exempted from the application of this section and shall not be deemed a part of the visibility area.
4. Sections 1, 2, and 3 above shall also apply to the intersection of a public street right-of-way and a railroad right-of-way.

SECTION 01-002. Obstructions to Visibility at Driveways—Visibility Area Defined.

It shall be a misdemeanor for any person or persons or corporations owning real property to install, set out, or maintain or to allow the installation, setting out, or maintenance of any sign, hedge, fence, shrubbery, natural growth, or other obstruction to the view, whether movable or stationary, higher than 30 in. (76.2 cm) above the level of the adjacent roadway on any lot where a private drive enters a street within the triangular area formed by the street property line, the private drive-edge line, and a line connecting them at 10 ft (3 m) from their intersection.

SECTION 01-003. Obstructions to Visibility at Intersections and Driveways—Exceptions.

Sections 01-001 and 01-002 shall not apply to small trees that are not more than 12 in. (30.5 cm) in diameter (trimmed to the trunk), that are at least 8 ft (2.4 m) above the level of the intersection, and that are planted so as to leave a clear and unobstructed cross-view. Sections 01-001 and 01-002 also shall not apply to fire hydrants; public utility poles; street markers; traffic control devices; existing permanent buildings; existing grades, which by reason of natural topography exceed 30 in. (76.2 cm) above the center of the adjacent intersection; and signs mounted 8 ft (2.4 m) or more above the ground and whose supports do not constitute an obstruction as defined in section 01-002.

SECTION 01-004. Obstructions to Visibility at Intersections and Driveways—Existing Obstructions.

No obstruction to cross-visibility shall be excepted from the application of this article because of its being in existence at the time of the adoption hereof.

SECTION 01-005. Obstructions to Visibility at Intersections and Driveways—Penalty.

Any person or persons or corporations violating sections 01-001 through 01-004 of this code shall be guilty of a misdemeanor and on conviction shall be fined any sum not less than $50 nor more than $100, and each day that the violation shall continue shall constitute a separate offense.

SECTION 01-006. Obstructions to Visibility at Intersections and Driveways—Removal of Obstructions by City.

In the event of any violation of sections 01-001 through 01-004, in addition to the fine mentioned in section 01-005, the city, at the direction of the director of traffic engineering, is authorized to go on said real property and to take any usual and necessary action to effect full compliance with the provisions of these sections. The cost thereof shall be a charge against the person or persons or corporation responsible and shall be a lien against the property from which such obstruction is removed.

Although this ordinance is written for cities, it can also be used by states by deleting section 01-001(3) and by inserting the word "state" instead of "city." The results of before and after accident studies, such as the one conducted in Concord, California, can be used to stress the importance of this legislation to the elected officials. Studies in the particular city or state should be used to provide a more local application, e.g., locations where voluntary compliance was obtained even though no law or ordinance was in effect. In regard to the legality of this ordinance, only 4 of the 202 agencies stated that their laws or ordinances had been tested in the courts; however, all 4 stated that the laws or ordinances had been upheld. The model ordinance is similar to those that were upheld.

Ordinance Enforcement

The easiest and least expensive method of obstruction removal is for the property owner to voluntarily comply. This eliminates the need for expensive and unpopular legal battles. However, voluntary compliance by the property owner was determined from questionnaire replies as the major problem in removing obstructions at intersections. Therefore, improvements in this area are definitely needed. Many officials indicated that a great deal of voluntary compliance was usually obtained when the affected property owner was personally contacted at the site of the obstruction. However, this procedure is quite expensive because of limited engineering time and personnel. Therefore, a cheaper method that obtains the same compliance is desired.

One such method, currently used by several cities, involves sending the property owner a letter identifying the problem. In this letter, the problem condition is explained and the appropriate section of the city code that is violated is quoted. It should be supplemented with a typical intersection drawing showing the limits of the obstruction law or ordinance. Figure 3 shows such a drawing used by Louisville, Kentucky. The letter sent to the property owner should also include a method of appeal, for example, the telephone number of an official with whom the problem can be discussed. It is also recommended that the city or state volunteer to remove the obstruction from the property with city or state forces at a fair price to the property owner, if the owner so desires.

If the first letter to the property owner obtains no results, then a second letter should be sent. This letter should point out more strongly that the obstruction is in violation of a local ordinance and that a potential liability on the property owner is present if a traffic accident were to occur in which the obstruction was a contributing factor. One city responded that this remark usually brought about quick action by the property owner.

Figure 3. Intersection sketch sent to property owner.

If this approach also fails, the property owner should be personally contacted at the site of the obstruction and the dangers of the obstruction pointed out. Although this explanation could probably be presented best by a qualified traffic engineer, one city reported good results when the dangers were explained by an off-duty police officer.

If the personal contact fails to obtain action within a reasonable specified period, the city should enter the private property and remove the obstruction, and, at the same time, file legal action against the property owner.

If action is taken voluntarily by the property owner, a letter of appreciation is certainly in order. Such a response by local governments will go a

long way in maintaining good public relations.

This section has focused on the problem of obstruction removal. A better solution to this problem would be to eliminate the obstruction before it appears. This can be accomplished to a certain extent by an effective public relations program and also by contact with the local garden clubs. A few minutes of obstruction explanation before planting could save several hours of obtaining obstruction removal after planting.

CONCLUSION

This paper has dealt with the problem of obstructions on private property that block motorists' sight distance at intersections. The responses to the questionnaire demonstrated that this problem exists in almost all U.S. cities and states. The recommended model ordinance, if established, and the other recommended enforcement changes, if implemented, could significantly help the city or state obtain the removal of the offending sight obstructions. The procedures recommended are aimed at obtaining the desired voluntary compliance by the property owner. If these procedures are used, a high degree of voluntary compliance should be expected. However, if voluntary compliance in removal is not obtained, the city or state should not hesitate to use whatever means available to remove the obstruction because the safety of the motorists is at stake.

ACKNOWLEDGMENTS

We wish to thank the Louisville Department of Traffic Engineering for the use of its intersection drawing shown in Figure 3.

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TRAFFIC-INDUCED VIBRATION

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Vibration generated by highway traffic is a significant form of environmental pollution that has not been studied as comprehensively as noise pollution. Vibration sources and the mechanisms of vibration propagation and attenuation must be better understood before uniform criteria for vibration pollution and corrective measures can be established. The theory of ground-borne vibration provides considerable insight into the nature of traffic-induced vibration. The relevant theory and associated experimental data have not heretofore been put into a form useful to highway engineers and transportation scientists not trained in the problem area. The highway irregularity spectrum is the most important cause of vibration. The Rayleigh wave is of primary importance to traffic-induced vibration assessment. Significant structural damage from traffic-induced vibration is rare. However, human response to vibration is both physiological and psychological, and humans often classify vibration as unacceptable at levels lower than those that cause structural damage. The nature of the long wave lengths of traffic-induced vibrations makes it unlikely that attenuation measures such as trenches will be successful. Indications are that careful maintenance of the highway will be the most effective vibration preventive and that special abatement measures will be used only where complaints have occurred.

•CONCERN for the environment has heightened interest in all forms of pollution. A significant form of pollution, but one for which widely accepted criteria do not yet exist, is vibration. The study of vibration and the effects of vibration on man, equipment, and structures has long been a topic of investigation by physicists, engineers, geophysicists, architects, and human factors specialists. These investigations have considered vibration sources, transmission, propagation, and attenuation; characteristics of vibration received; and criteria relating vibration received to assessment of acceptable vibration limits. The ultimate value of any vibration investigation is the characterization of vibration impacts and the relation of their characteristics to the criteria for acceptable limits. In human response to vibration, the appropriate criteria relate vibration levels and spectra to human levels of perception, irritation, and physical discomfort; in building response, they relate vibration levels and spectra to architectural and structural damage. Concern has been growing over noise and vibration from various transportation sources because of the trend in increasing vehicle use and weight (thus, in increasing vibration) required to transport people and freight in our society. The major source of transportation in the United States is the highway, and, for the sake of convenience, buildings are normally located as close to highways as possible. Thus, vibration from roads and highways has become a growing source of concern, complaints, and litigation.

Although the noise and vibration from transportation systems have long been recognized as having adverse effects on the environment, the past analyses and abatement of environmental vibration have been relatively slight compared with recent noise abatement efforts by government and private organizations. Public interest in the vibration problem, however, already appears quite significant and is increasing. In a survey conducted by the Michigan Department of State Highways (1), vibration near I-75 was cited as bothersome more than two-thirds as often as noise. Public concern is further

reflected by the increasing frequency of litigation associated with environmental vibration [e.g., Tompkins v. State of New York, Pueblo v. Muce (Colorado), Coltin v. Anderdink (California)], despite an absence of federal or state environmental vibration regulations. Local ordinances, however, either have included vibration under tort trespass and general nuisance categories or are in the form of specific statutes dealing with vibration intrusion.

Originally, special issues such as sonic booms and blasting aroused considerable public interest about environmental vibration, which is now most frequently associated with highways because of their expanse and their proximity to the public. Research on vibrations from highways is now being sponsored by the Federal Highway Administration as well as by the governments of Great Britain, Czechoslovakia, Japan, and Norway. This research centers on the physical aspects of vibration generation and propagation for soil-transmitted stresses from vehicle-roadway interaction, airborne infrasonic pressure waves, and the resulting vibration produced in nearby structures. Research pertaining to other areas of the vibration problem has been extensive and plentiful (over 1,500 published studies related to human subjective response to vibration have appeared since 1830) but remains largely inconclusive.

Never before have the following been thoroughly analyzed: (a) traffic flow on highways as a source of vibration; (b) the transmission, propagation, and attenuation behavior of traffic-induced vibrations in relation to the complex geology of roadbeds near buildings; (c) the relationship of vibration levels to structural response, fatigue, and damage; and (d) the relationship of vibration levels and spectra to human perception, irritation, discomfort, and anxiety. The interdependence of these parameters is shown in Figure 1 and is discussed below.

VIBRATION SOURCES

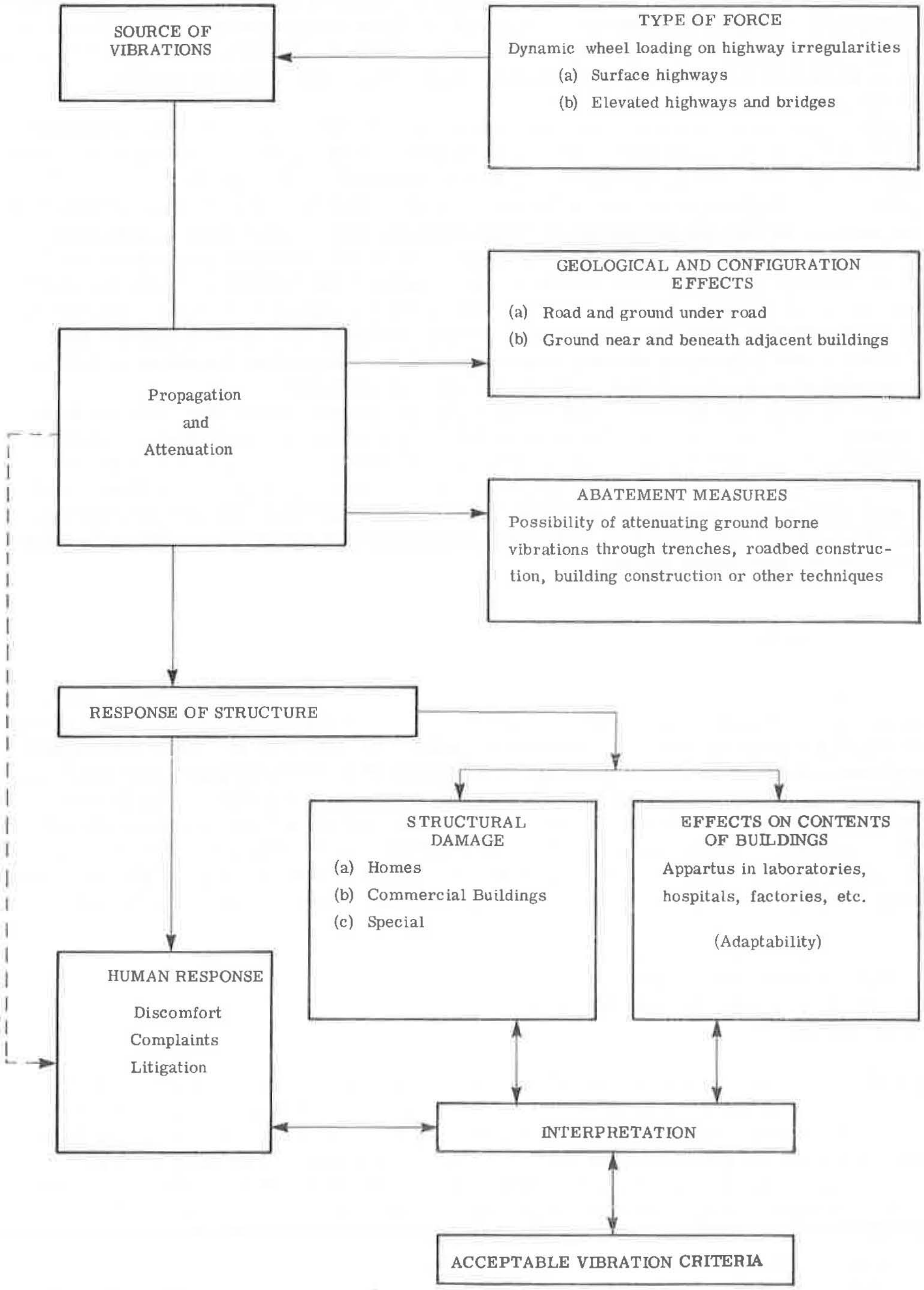
Traffic-induced vibrations have the time-varying forces of the tires of vehicles pressing on the highway as a primary source. The converse problem of the vibration of the vehicle itself due to the spectrum of irregularities in the highway has been well studied. The vibrations resulting from the passage of vehicles of various weights over highway irregularities can presumably be characterized in terms of a spectrum that is the product of the forcing function spectrum from the vehicles times the irregularity spectrum of the highway. A primary concern is to find the proper forcing function spectrum from vehicles as a function of their specific characteristics. An additional source of vibration is infrasonic sound. The following is a breakdown of vibration sources:

1. Irregularities in pavement profile,
2. Internal vehicle vibrations,
3. Changes in roadway impedance, and
4. Infrasonic sound.

The most significant vibration excitations are attributable to the passage of vehicles over irregularities of the pavement profile, commonly resulting from expansion joints, manhole covers, differential settling of pavement slabs, and potholes. The resulting impulsive forces on the pavement, in turn, excite oscillations in the vehicle itself (which, eventually, tend to aggravate the roughness of the pavement). Thus, the variation in forces between the tire and the road after an encounter with an irregularity is a function of the irregularity as well as vehicle speed, mass, and suspension.

Whiffin and Leonard (2) and Frydenlund (3) conducted experiments to measure the vibration generated during the passage of vehicles of various masses and velocities over ≤100-mm-high ramps placed in various pavements and soils. Their results indicate that the size of the irregularity (height of the ramp) as well as vehicle mass had pronounced effects on ground vibration. Parameters such as vehicle speed (tests were conducted at 30 and 50 km/h) and pavement thickness, however, had little effect. Figure 2 shows Frydenlund's results. These results are also substantiated by Sutherland's in situ study (4) of seismic vibrations caused by trolley cars introduced into Winnipeg,

Figure 1. Interdependence of parameters of traffic-induced vibration.



Manitoba, and Bata's study (5) of assorted vehicles traveling on cobblestone roadways near medieval structures of historical interest.

Consequently, it has become important to characterize both the highway pavement irregularities and the frequency responses (i.e., the suspension and damping) of highway vehicles. Various instruments, such as the roughometer and the profilometer, have been developed to characterize roadway irregularities by actual measurement, and the frequency responses for trucks and passenger cars have been determined both analytically and and experimentally. The critical frequencies of highway vehicles are approximately 1.5 Hz for body oscillations, 10 Hz for rear-axle oscillations, and 12 Hz for front-axle oscillations. Other internal vibrations of the vehicle from slightly out-of-balance forces are of secondary importance because of their higher frequencies and efficient attenuation of modern suspension systems. Many other variations in the dynamic forces of vehicles due to acceleration and braking (as evidenced by the distortion of pavement profiles at intersections), tire stiffness, and the negotiation of curves remain to be studied.

A dynamic disturbance is also generated by the motion of a steady vehicle load as it passes over changes in road impedance (i.e., resistance to motion) typically associated with bridges and culverts. This is because, although the induced force is independent of road impedance, the power transmitted into the roadbed increases as the road resistance decreases (and increases as the wheel impedance increases). At the low frequencies pertaining to ground vibration (<20 Hz), the impedance of the roadway is in agreement with the spring constant determined by the subsurface below the pavement and the bending stiffness of the pavement. The dynamic coupling effect of the interaction of vehicles with bridges has been discussed by Popescu (6), who has shown that the commonly used bridge design criteria yield incorrect results when these effects are estimated. Figure 3 shows some of Popescu's results.

Finally, the exhaust pulse (and sometimes the pressure arising from the bow wave of passing vehicles) will transmit significant infrasonic sound to the soil or directly to the structures. Although this type of excitation does not normally produce sufficient pressure, when compared with typical wind pressures, to cause structural damage, the pressure waves impinge on large areas of transduction and cause audible vibrations in windows and frames.

VIBRATION PROPAGATION AND ATTENUATION

The fluctuating dynamic forces applied to the road surface by the wheels of moving vehicles generate stress waves that are propagated through the roadbed construction into the subsoil. (One of the functions of road construction is to spread the wheel loads so that the stresses applied to the soil subgrade are small and are only a fraction of that applied to the road surface). The geological characteristics of the soil, rock, and subterranean structures between the highway and nearby structures determine the paths and intensities of vibration propagation as well as the dispersive and dissipative properties. In general, soil is a nonlinear, thermoviscoelastic medium that can be layered, nonhomogeneous, and anisotropic. Fortunately, a considerable understanding of vibration is possible without a precise theoretical description of the soil. Many soil properties, such as blastability, ripability, scraper loading characteristics, and bearing capacity, are already of concern to highway engineers in the determination of engineering properties.

Excitation of Subsoil

Transmission of vibration to the subsoil is complicated in practice because road construction has a layered configuration and because many of the materials used to build flexible roads are deliberately chosen to be absorptive and have elastic moduli that fall significantly as the road temperature rises. Furthermore, these materials are viscoelastic and have complex moduli that depend on the magnitude of the local stresses and the rate of loading.

Figure 2. Effect of vehicle speed and ramp height on seismic vibrations.

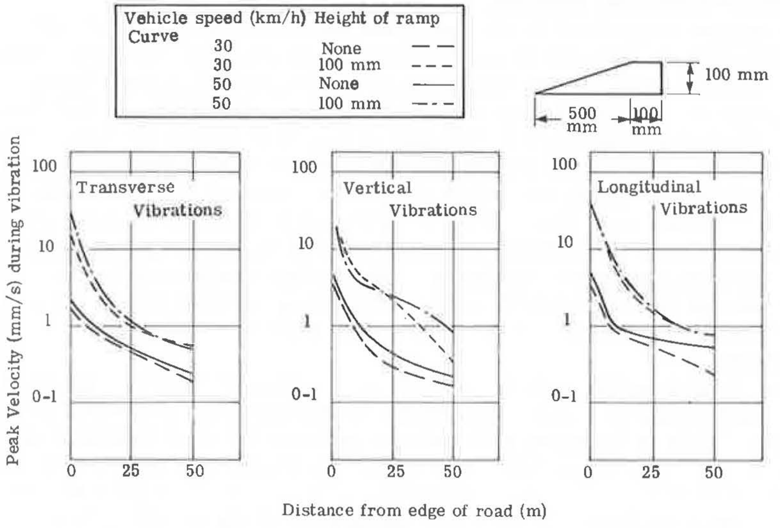
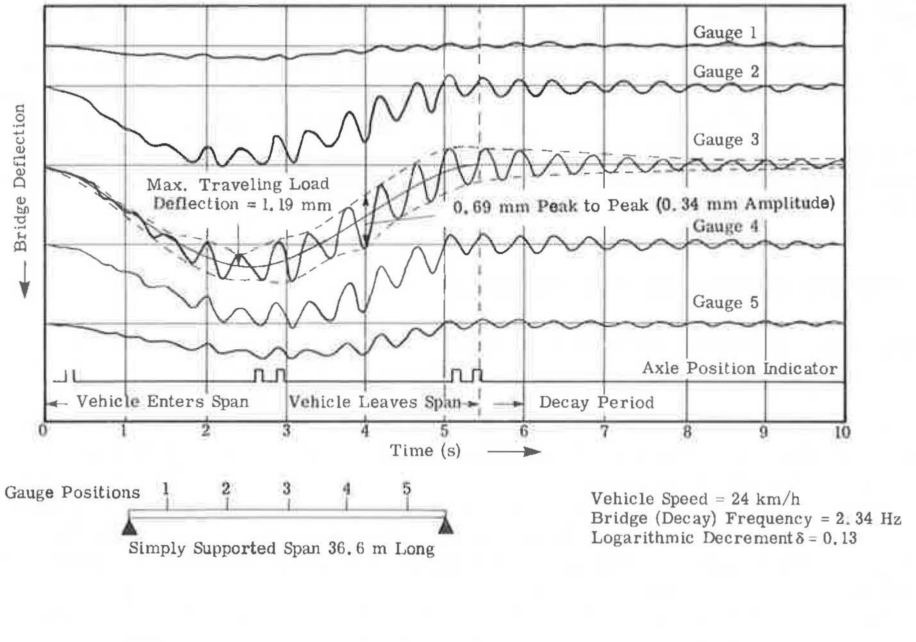


Figure 3. Bridge deflections.



A complete treatment of the theory of the complicated viscoelastic properties and layering that correspond to a roadbed has not yet been achieved. It is likely that treatment of the properties of the roadbed as a pseudohomogeneous medium that is part of the source will constitute the most effective approach. This treatment is certainly feasible when the coefficients for propagation and attenuation are obtained from experimental data. The roadbed can be rather simply included in the source by using composite attenuation coefficients like those that exist for earth materials. Given such an overall factor, multiplying the source does not represent a significant deviation from a derivation using first principles because it would be possible to incorporate an overall attenuation factor in the forcing function to account for the absorption and cushioning effect of the tire and suspension of the vehicle. Thus, one possible characterization of the source would include three critical parameters: the distribution of the flow of vehicles, the spectrum of irregularities in the highway, and the attenuation factor for the roadbed.

Types of Waves

There are four types of waves relevant to the vibrations experienced by structures near highways:

1. Longitudinal or compressional body, p-waves;
2. Shear or transverse body, s-waves;
3. Surface or Rayleigh, r-waves; and
4. Boundary or interface, b-waves.

The p-waves and s-waves are collectively known as body waves, which radiate into the entire half space of the soil, but r-waves, such as water ripples, are confined near the surfaces. The b-waves (e.g., refraction arrivals and Love and Stoneley waves), which are similar to r-waves, occur only if layered media are present and only if the shear moduli of the underlying layer are greater than those of the overlying layer.

The geometric attenuation, or spreading, of body waves is 6 dB per doubling of distance (dd) for a point source and 3 dB/dd for a line source. For r-waves, it is 3 dB/dd for a point source and vanishes for a line source. The reduced geometric attenuation of r-waves and the fact that for surface excitations the partition of energy into p-waves, s-waves, and r-waves is approximately 1:5:14 indicate that r-waves are of primary importance to the ground vibration problem. Figure 4 shows the behavior of r-waves for different values of Poisson's ratio ν, which is the ratio of the s-wave and p-wave speeds.

The r-wave is a nondispersive wave polarized in the vertical plane parallel to the direction of propagation. Its propagation velocity is approximately 95 percent of the s-wave velocity, which, in turn, is approximately 50 percent of the p-wave velocity (e.g., 1 km/s in clay). r-wave particle motion within a depth of one-fifth wavelength of the surface is a retrograde ellipse whose vertical axis is about twice as long as one horizontal axis. Below this depth, the particle orbit changes from retrograde to direct, and the orbit size decays exponentially below a depth of one-half wavelength at an attenuation rate (which depends on Poisson's ratio and the dissipation rate) of greater than 16 dB/wavelength.

The p-waves have an amplitude only in the direction of propagation; the s-waves have an amplitude transverse to the direction of propagation, i.e., verticle or horizontal. The r-waves have amplitudes in both the vertical direction and the direction of propagation. The important case of b-waves results when there is hard rock beneath the surface soil layer and where wave propagation is along the boundary. There is usually less attenuation than for s-waves, p-waves, and r-waves propagating through the soil. Sometimes there can be peculiar magnification effects at distances where the b-wave propagates down to the hard rock, moves across at a faster speed, goes back up to the surface, and arrives at the same time as either the s-waves, p-waves, and r-waves. The presence of boundaries causes reflected waves of mixed polarization. For example,

Figure 4. Dimensionless velocity versus depth ratios for Rayleigh wave.

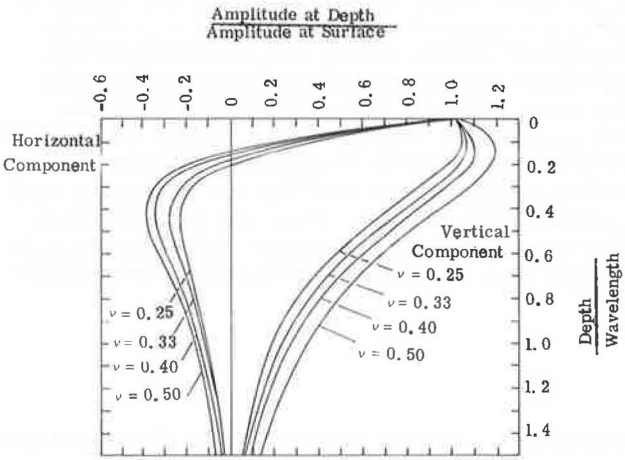
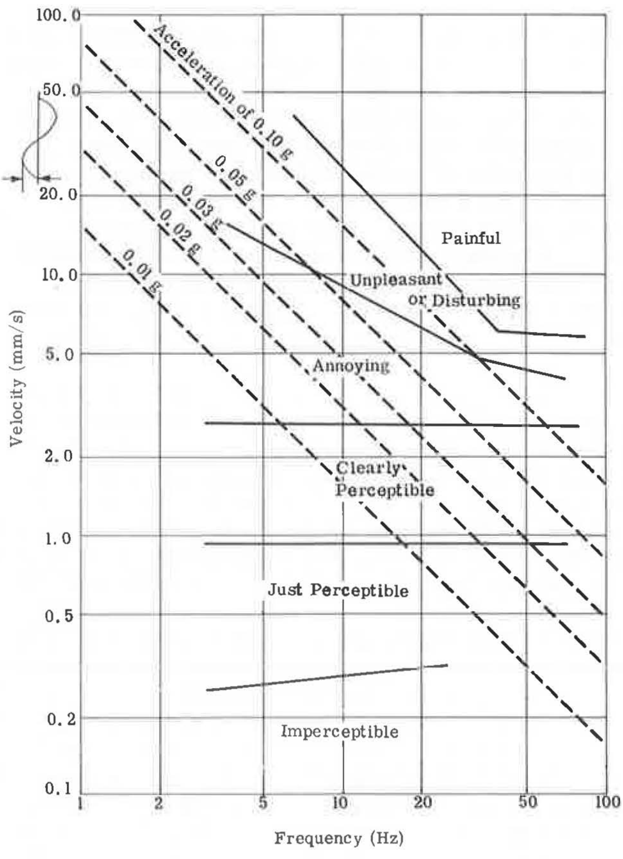


Figure 5. Human sensitivity to vertical vibrations.



pure p-waves or vertically polarized s-waves, which reflect from a horizontal boundary, cause a reflected wave with both polarizations.

The dissipation rate in earth materials is empirically determined to be proportional to frequency throughout the 1- to 20-Hz frequency range of interest (simple models of viscoelastic materials, however, yield an attenuation parameter proportional to the square of the frequency). Measurements of dissipation rates for typical materials are on the order of 3 dB to 30 dB per 100 ft (30 m) depending on frequency.

Thus, a vibration impulse will usually be detected at a distance as a slight compressional wave followed by two successively stronger waves that are separated by a relatively short interval. In addition, waves reflected from interfaces and air-coupled waves can be superimposed on this motion. The quantitative calculation of wave propagation has received considerable attention: Lamb's classic analysis of elastic waves in a homogeneous halfspace (7) and the treatment of inhomogeneities, anelasticity, and arbitrary interfaces by finite difference or finite element methods developed for the study of nuclear weapons effects. Analytical calculations, even for relatively simple models, rapidly become mathematically complex so that computer approximations must be used if precise results are desired. Such precision is generally not required for environmental problems, however, because other variables affect vibration.

STRUCTURAL RESPONSE

Any structure resting on soil possesses a fundamental oscillatory resonance, typically from 10 to 20 Hz, as well as higher bending or shear flexural resonances of structural components from 50 Hz on up into the audible range. These resonances are determined by the structure's construction, size, geometry, and, especially, the manner in which it is coupled to (i.e., in contact with) the ground. Much knowledge can be acquired from the analyses of structural response to earthquakes and blasting operations. Although the performance of detailed analyses of frequency response for most structures is a complicated problem, numerical methods using high-speed computers are now able to determine the structural vibration of buildings rather accurately, provided the nature of the excitations can be prescribed.

The effects of vibration on structures can be classified according to structural or primary damage, in which the integrity or safety of the building is in jeopardy, and architectural or secondary damage (such as plaster cracking), in which nonessential elements of a building are damaged. Accelerations above 0.1 g (or 0.98 m/s^2) at frequencies above 3 Hz and velocities above 50,800 μm/s (or 2.0 in./sec) at frequencies below 3 Hz are currently considered to be unsafe for buildings by the U.S. Bureau of Mines. The vibrations related to normal highway operations are usually unable to cause structural damage. When combined with other natural stresses such as the variation in temperature and humidity and the differential settling of the foundation, highway-induced vibrations may well be able to initiate or aggravate architectural damage.

HUMAN RESPONSE

Vibration produces human response through three methods: mechanical motion, vestibular response, and psychological factors. Mechanical motion includes the movement of the various portions of the body in relation to a stationary external location and adjacent portions of the body. The motions are produced in response to vibrational excitement of any part of the body. However, for the situations important to the traffic-induced vibration problem, the excitation should be considered as being applied to either the feet or the back side of the body. That is, emphasis should be placed on vibration situations experienced by the typical person when standing, sitting, or lying down at home or work.

Psychological responses to vibration are displayed in people's attitudes, feelings, and work performance. Depending on their background, they may like, dislike, or be indifferent to a given vibration. These effects may be direct responses to the vibration

or may involve emotional experiences and associations. The subjective response produced can be difficult to measure quantitatively, but the personal reactions that are produced may be sufficiently extreme to require that they be considered in any analysis. At present, few data are available on the psychological response to long-term exposure to vibration. Qualitatively, however, there appears to be a great effect present in the area of fatigue. Goldman and von Gierke (8) state that continuous exposure to vibrations only slightly above the level of human perception leads to irritation and fatigue.

Human tolerance is most widely used when vibration levels are interpreted. Tolerances curves such as shown in Figure 5 as a function of velocity and frequency are often used to determine the relative levels of vibration that are sustained and accepted as part of the environment. For traffic-generated vibration these curves are not necessarily sufficient, and a measurement of the intrusiveness of the vibration must be considered. The intrusiveness of traffic is the greatest in the home, where it is felt that traffic noises are out of place and more annoying.

The effect of vibrations on humans is a multifaceted problem involving both physiological and psychological responses (the pathological response involving illness is not experienced with environmental vibrations). It has been determined, mostly from aerospace research, that certain frequencies excite resonances in specific organs or organ groups in the human body. These resonant frequencies are, depending on the position and muscle tension of the body, 3 to 5 Hz for the thorax-abdomen system, 2 to 3 Hz for the shoulder and head, 20 to 30 Hz for the head alone, and 2 to 12 Hz for the whole body. All are well within the frequency range of highway-generated vibrations.

Furthermore, the cutaneous (vibrotactile) receptors and mechanoreceptors (somatic detectors) are able to perceive accelerations of 0.01 *g* at frequencies between 1 and 35 Hz, which is below the levels causing structural damage. This low threshold (or high sensitivity) to vibration and the instinctive fear of ground motion in all animals, including man, frequently lead to subjective or psychological responses to vibration as unacceptable at levels at which structural damage is not possible. Annoying effects that are frequently visually or audibly perceived, such as the motion of hanging fixtures or the rattling of dishes or windows, can result from secondary resonances even though the structural vibration levels are not directly perceivable. There is a great deal of literature about the subjective responses to vibration and subjective rating criteria. However, no universal criterion or metric value for subjective ratings of vibration has been established because of the large number of experimental parameters, nonuniform experimental methodology, and lack of understanding of intermodal factors (e.g., traffic noise), which may either mask or combine synergistically with vibration. (Vibration criteria based on the best available data, however, have been proposed by the International Organization for Standards).

CONTROL AND ABATEMENT MEASURES

Whiffin and Leonard (2) and Bata (5) point out that maintenance of a smooth highway with the minimal number of irregularities due to potholes, slab misalignments, and undulations is one of the most effective controls for vibration. At sites that are particularly sensitive to vibration, speed limits may have to be reduced, large vehicles excluded, or perhaps, in extreme cases, all traffic excluded. Near the highway, trenches or steel sheet piling may be introduced to lessen vibration impacts. Such techniques do not, however, hold much promise because of the nature of long wavelengths of traffic-induced vibrations. Probably most promising is isolation of the roadbed or nearby buildings with an insulating shell of sand or some other material. Full-scale experiments must be conducted to quantify the effectiveness of any proposed control or abatement technique.

SUMMARY

Traffic-induced vibration appears, at least under certain circumstances, to be a significant pollution problem. Further research is required to characterize the propagation

and attenuation characteristics within the complex geological and structural surroundings in which complaints are likely to occur. A better understanding of the propagation and attenuation mechanisms of traffic-induced vibration, achieved through both full-scale experiment and theory, will allow the design and implementation of effective control and abatement strategies. Research must also be conducted to formulate vibration criteria to quantify impacts and to determine when corrective measures need to be instituted.

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EFFECT OF CERTAIN ROADWAY CHARACTERISTICS ON ACCIDENT RATES FOR TWO-LANE, TWO-WAY ROADS IN CONNECTICUT

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ABRIDGMENT

This study identified and defined which roadway elements are statistically correlated with accident occurrence and evaluated the relative merit of each element as an index of accident prediction. Of the three principal factors associated with accidents, the vehicle, the driver, and the roadway, this paper considers contribution of the roadway. Four selected geometric elements, roadway width, horizontal curvature, vertical clearance, and restricted sight distance were rated for adequacy, and these ratings were then correlated with accident rates. Multiple linear regression analyses were performed to examine these relationships. The resulting correlation coefficients were quite small. Of the four geometric characteristics considered, restricted sight distance and horizontal curvature appear to have some effect on accident rates and vertical clearance appears to have no effect.

•MOTOR vehicle accidents have increased as automobile registration and population have increased. There were 3,100 fatalities on roads in 1912 and 55,800 in 1973. Though the total number of fatalities has increased from 1925 to 1973 (1), the fatality rate has decreased from 17.9 to 4.3 per 100 million vehicle miles (160 million vehicle km). Of the total 1,060 accident deaths in Connecticut in 1973, about 50 percent or 516 were fatalities resulting from motor vehicles (1). In 1973, the annual economic waste attributable to highway accidents totaled $13.9 billion for the nation. These figures indicate the enormous magnitude of the highway safety problem.

Our national goal in highway safety is to provide for a substantial reduction in the number of lives lost, in the number of crippling injuries, and in the staggering cost of property damage. The nation must take an aggressive step in support of the technological innovations and actions required to reduce this drain on the country's resources. Because of this problem, much effort has been expended in increasing overall knowledge of the factors affecting highway safety to provide information for making sound decisions about programs designed to improve safety performance.

The principal elements related to accident causation are the driver, the vehicle, and the environment, including roadway. Of these factors, roadway geometric characteristics are among the most important determinants. Roadway characteristics, therefore, may provide an effective means for predicting accident experience on a given section of roadway.

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STUDY OBJECTIVE

This research identified and defined roadway elements that are statistically correlated with accident occurrence and evaluated the relative merit of each element as an index of accident prediction. Mathematical models were developed to depict the effect of four geometric characteristics: roadway width, horizontal curvature, vertical clearance, and restricted sight distance on accident rates. Such information is useful both in the design of safe, new facilities and in improvement of existing high-accident locations for safer operation.

DATA ACQUISITION AND REDUCTION

Accident data for the 5-year period from July 1964 to June 1969 on two-lane, two-way rural state highways were obtained from the Accident Analysis Unit of the Connecticut Department of Transportation. In this study 31,211 motor vehicle accidents on Connecticut rural roads were considered. The available accident data were not stratified into fatal, injury, or property damage because of sample size requirements. For the analysis, 1,548 sections of roadway varying in length from 0.30 to 8.87 miles (0.48 to 14.20 km) were used. Each roadway section had uniform characteristics with regard to the variables considered. Highway geometric characteristics considered in the analysis were

1. Pavement width,
2. Shoulder width,
3. Horizontal curvature,
4. Vertical clearance, and
5. Sight distance restrictions.

Pavement and shoulder width were combined and rated as roadway width. Adequacy ratings for these four variables were obtained from the Connecticut Department of Transportation (2). For the calculation of ratings, actual dimension of the worst feature (i.e., least width, worst curvature) in a section was compared with the desirable geometric standard. Each individual element was evaluated empirically with a rectilinear scale of 0 to 100 points on which 50 is the threshold of adequacy. Threshold of adequacy is based on the tolerable design standards for various geometric design elements. A condition equal to standard or better was rated 100. All highway sections were rated for lowest overhead obstruction, whether or not such obstructions existed. Thus, for the sections without restrictions, the vertical clearance rating was considered to be 100 points. Restricted sight distance is defined as the shortest distance of roadway surface that can be seen by an operator of an automobile from a given point on the roadway when the view is limited by a fixed obstruction. This design characteristic was evaluated by measuring the reduction of the maximum safe speed below an assumed criterion at the location of the most restricted sight distance within a highway section under study.

These elemental ratings were then adjusted in accordance with the amount of traffic use. Adjustments for volume involved the use of a base volume (average daily traffic = 5,000) above which the ratings were reduced and below which the ratings were increased. These adjusted elemental ratings were combined into a geometric characteristic index (GCI) on a 100-point log scale. A GCI of 77 points, based on the department's previous work, was considered to be the threshold of adequacy in relation to the combined effect of all four elements rated.

For each section considered, the total number of all accidents that occurred during the 5-year period was tabulated, and total accident rate per 100 million vehicle miles (160 million vehicle km) was computed. Accident rate was used as a dependent variable. A multiple linear regression program for use on the IBM 360-65 was used with minor modifications. The computer program provided correlations between accident rates and the individual variables considered and gave regression coefficients for the model.

The computer analysis resulted in the development of four regression models given below. For equations 1 through 4, the variable definitions are

Y = accident rate,
X_1 = adequacy rating for roadway width,
X_2 = adequacy rating for horizontal curvature,
X_3 = adequacy rating for vertical clearance,
X_4 = adequacy rating for restricted sight distance,
X_5 = GCI, and
X_6 = section length in miles.

$$Y = 141.023 + 0.775X_1 - 0.527X_2 + 1.074X_3 - 0.518X_4 \quad (1)$$

where $R^2 = 0.051$. Equation 1 relates accident rate to the four geometric variables.

$$Y = 181.345 - 0.304X_5 \quad (2)$$

where $R^2 = 0.003$. Equation 2 relates accident rate to GCI.

$$Y = 180.160 + 0.794X_1 - 0.586X_2 + 0.88X_3 - 0.631X_4 \quad (3)$$

where $R^2 = 0.073$. Equation 3 relates accident rate to roadway sections with GCI = 77.

$$Y = 261.620 - 21.254X_6 \quad (4)$$

where $R^2 = 0.017$. Equation 4 relates accident rate to section length.

In addition to the above analyses, the data were classified into five ADT groups (0 to 1,400; 1,500 to 3,900; 4,000 to 6,900; 7,000 to 9,900; and 10,000 to 24,900), and a multiple linear regression model was developed for each ADT group.

DISCUSSION OF RESULTS

In this study, ratings were used, instead of actual values for various geometric variables, to indicate a comparison with the desirable standards for each geometric element. Thus, a roadway section that has adequate geometric standards can be checked for safety by this analysis.

Of the four independent variables considered in this research, accident rate was better correlated with the restricted sight distance rating than the others. As restricted sight distance rating increases, accident rate decreases. That is, accident rate is higher on roadway sections that are inadequate from the standpoint of sight distance requirements. If safety is to be built into highways, the design must provide sight distances of sufficient length to give drivers enough time and distance to make the speed and distance judgments required for vehicle control.

The next best correlation with accident rate was obtained for the horizontal curvature rating. The lower the degree of curvature of a curve was, the higher the rating was, and hence, the lower the accident rate was. This conclusion agrees with the results of studies by Raff (3), who concluded that accident rates vary with the degree of curvature and that sharp curves have higher accident rates than flat curves. Kihlberg and Tharp (4) found that 19 percent more multivehicle accidents occurred on curved

segments than on straight segments (curvature and gradient under 4 degrees and 4 percent respectively).

Of the four geometric variables studied, the vertical clearance rating had no correlation with the accident rate. Most of the sections considered have unlimited vertical clearance. Low correlation was also found between roadway width rating and the accident rate. This finding agrees with that of Sparks (5) who found no significant relation between accident rate and surface width. Our study, however, indicated that, as the roadway width rating increased, accident rate also increased.

The R^2 value in equation 1 of 0.051 indicates that only 5.1 percent of the variation in the accident rate is accounted for. Similarly, equation 3 explains only 7.3 percent of the variation. R^2 for equation 2 is quite low (0.003) and indicates no relation between accident rate and GCI. This is contrary to the expected results. The correlation of accident rate with section length is also quite low ($R^2 = 0.017$). Regression equations relating accident rate to GCI, for all five ADT groups, had low R^2 values. The models are therefore not useful in making accurate or meaningful prediction of accident rates.

It was expected in the beginning of the study that the selected variables would be able to explain a larger portion of the variation in accident rate; however, results did not support this. Following are some of the possible reasons for the low correlations obtained.

1. The accident rates include intersection accidents that cluster in a short length of the section and distort the accident rate for the study section. Elimination of intersection accidents from the data may improve the results.
2. Although most of the study sections had adequacy ratings based on geometric features existing at the time of accident occurrence, the geometric features on some study sections were changed between the time of accident occurrence and rating determination.
3. Part of the reason for lack of correlation between accident rate and GCI seems to be related to the method of calculation of GCI. GCI apparently should not be a simple summation of element ratings for the variables considered, as used in this analysis; it should probably be an empirically computed value from the ratings.
4. Vehicle and driver, the other two components of the system, were not considered in this study.
5. Other geometric variables, such as grade surface type, surface texture, and control of access, were not included in this study.
6. Influence of environment and weather, such as high winds and atmospheric electricity, on accidents was also excluded.
7. Further stratification of accident data into fatal, injury, and property damage accidents and into single- and multiple-vehicle accidents may improve the correlation between the variables to a great extent.

CONCLUSIONS

Based on the analysis of available data for two-lane, two-way rural highways in Connecticut, the following conclusions seem valid.

1. No significant effect of the geometric variables on total accident rate could be found.
2. Of the four geometric variables investigated, vertical clearance had no significant effect on the accident rate.
3. Statistically, the regression equations obtained are not significant. Only 5 percent of the variation in accident rate is explained by the geometric characteristics included in this study. However, the sections with 0 to 1,400 ADT accounted for 9.75 percent of the variation in accident rate. In sections below the threshold of adequacy (GCI < 77), the variation explained is 7.3 percent. This indicates that the remaining variation may be caused by other geometric features not considered in this study and by other environmental variables and variables associated with the driver and the

vehicle. Therefore, sections with poor sight distance and sharp horizontal curvature should be given top priority in highway safety improvement programs.

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