Speed Actuated Rollover Advisory Signs for Trucks on Highway Exit Ramps

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ABSTRACT

Special truck rollover-warning signs were examined for effectiveness in slowing tractor-trailer trucks to a speed below that associated with rollover on highway exit ramps. Advisory speeds were verified for trucks at three highway exit ramps with high truck rollover crash frequencies; rollover-warning signs specific to trucks were posted to supplement the standard speed advisory signs already in place. The supplemental rollover-warning sign was equipped with a yellow light that was triggered to flash for every second tractor-trailer truck traveling above a predetermined ramp approach speed. Mean speeds at midramp associated with the flashing sign were lower than for the nonflashing sign. Although the flashing signs did not significantly increase the number of trucks in strict compliance with maximum safe speeds, they did significantly reduce the number of trucks that were traveling more than 5 mph and 10 mph faster than the calculated maximum safe speed. These findings suggest that speed-actuated rollover advisory signs specific to trucks may reduce truck rollover crashes at highway ramps.

INTRODUCTION

Disproportionate numbers of tractor-trailer crashes (9 percent) and tractor-trailer rollover crashes (17 percent) occur on freeway ramps compared with other segments of freeways (FHWA, 1986). A recent study of large truck (gross vehicle weight > 10,000 lb) crashes on highway ramps in Virginia concluded that crash risk increases with increasing ramp curvature and with the magnitude of the difference between truck speed on the highway approaching the ramp and the ramp's posted speed limit (Garber, Chowdhury, and Kalaputapu, 1992). On some ramps, posted advisory speeds, which are generally calculated to prevent cars and trucks from skidding on wet roadways, may not be low enough to prevent rollovers by tractor-trailers. Crash data have shown that risk of rollover increases as axle load and center of gravity rise and width decreases; fully loaded trucks are 5 to 10 times more likely to roll over on ramps than lightly loaded trucks (Ervin, 1983).

The Federal Highway Administration FHWA (1986) supported a simulation study of freeway interchange ramps that had been identified as overinvolved in tractor-trailer rollover and jackknife crashes. This analysis of the influence of design features on crash experience indicated that the American Association of State Highway and Transportation Officials' policy on geometric design results in a very slim margin of error for large trucks on freeway ramps. Problematic features included side friction factors, superelevation transitions, compound curves, ramp downgrades, curbs on curved ramps, and wet surface friction on high-speed ramps. The report noted that "the practical focus of the countermeasure evaluation program will likely be on signage" (FHWA, 1986, p. 121).

Signs designed to warn drivers of hazardous curves on roads and ramps are specified by the U.S. Department of Transportation (FHWA, 1983, 1988). These black and yellow warning signs address speed (advisory exit and ramp speed signs and supplemental advisory speed panel) and curvature (curve warning signs for turns and curves, large arrow signs, and chevron alignment signs). None of these is specifically intended to warn heavy truck drivers of an increased risk of rollover at individual locations. Some states use a special speed warning sign that depicts a tipping truck on ramps where rollovers have occurred.

Signage may not be enough, however. Even when advisory speeds are set low enough to accommodate tractor-trailers, they may be ignored, especially if the need for the low speed is not apparent. For example, an exit ramp that begins with a gradual curve leading to a sharp curve may

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have an appropriate advisory speed posted for the sharp curve, but this will not be evident to drivers entering the ramp. Special advisory speed signs directed specifically to drivers of large trucks may be more useful than standard signage in slowing such vehicles to a speed below that associated with rollover on hazardous ramps. The FHWA (1986) has explicitly recommended examining the effectiveness of both standard and special signage.

In the present study, three freeway ramps with high frequencies of truck rollovers were studied in detail. After determining that the currently posted ramp advisory speeds were appropriate but ignored by a substantial portion of tractor-trailer drivers, a new truck rollover-warning sign that included a speed advisory panel and a yellow flashing light that could be actuated for individual trucks was installed at each ramp. The study was intended to evaluate the incremental effects of, first, adding a truck rollover-warning sign to the standard speed advisories and, second, actuating the flashing light for trucks traveling at high speeds as they approached the ramps. However, because of difficulties and delays in the installation of the signs, only the incremental effect of the speed actuated flashing light was assessed in this report.

METHOD

The highway ramps used for this study were identified from Michigan Department of Transportation computerized crash records as among those in Michigan with higher than average frequencies of truck rollover crashes over three years (1985 through 1987). The characteristics of these three ramps are summarized in Table 1. Data on the number of tractor-trailers using the ramps were not available, and the high frequencies could in part be a function of traffic volume.

Exit ramp approaches on the Michigan highways used in this study were marked by black and yellow warning signs, with the word "ramp," an advisory speed limit, and an arrow indicating the direction of the curve. The exit speed signs specified by the FHWA do not require the directional arrow (FHWA, 1988). Speeds posted on these signs, which remained in place during the study, were 35 mph for sites 1 and 2, and 20 mph for site 3, which had very restricted geometry.

Verifying Posted Ramp Advisory Speed

To compare the posted advisory speed with the advisory speed for trucks based on rollover threshold, it was necessary to first calculate the maximum acceptable lateral acceleration for tractor-trailers and then to determine the maximum safe speed. For each truck and loading condition there is a lateral acceleration above which the truck will roll over; this is called the rollover threshold.

Table 1
Summary of Freeway Ramp Sites

	Site 1 I-96 East	Site 2 I-96 West	Site 3 I-94 West
Exit Type	Left-lane exit	Left-lane exit	Right-lane exit
Roadways	Freeway to freeway	Freeway to freeway	Urban arterial to freeway
Speed Limit	Cars-65 mph Trucks-55 mph	Cars-65 mph Trucks-55mph	45 mph
Posted Ramp Speed	35 mph	35 mph	20 mph

Rollover thresholds of heavy trucks can be measured directly using a tilt table (Winkler, 1987). However, Ervin (1983) established analytical methods based on measurable details of a truck's suspension, width, and loading to calculate its rollover threshold. Rollover threshold drops as a truck's suspension stiffness and cargo weight increase, its track width decreases relative to its wheelbase, and its center of gravity rises.

Using Equation 1, the maximum acceptable lateral acceleration was calculated by subtracting a factor representing a "margin of safety" from the generalized fleet rollover threshold and dividing the difference by a factor that accounts for truck steering difficulties at lateral accelerations above 0.14g (FHWA, 1986). (1)

$$a_{ymax} = \frac{R - M}{S}$$

where a_{ymax} = maximum acceptable lateral acceleration,
R = rollover threshold,
M = factor representing a margin of safety, and
S = steering factor.

Here, 0.27g was chosen as the generalized fleet rollover threshold, 0.11g was chosen as the factor representing a margin of safety, and 1.15 was chosen as the value of the steering factor (FHWA, 1986). The maximum acceptable lateral acceleration for all ramps studied was 0.14g.

To calculate a truck advisory speed, the relationship between lateral acceleration and speed was determined for each ramp. Such a relationship is normally used to determine curve advisory

speeds for passenger cars based on curve radius, superelevation, and the lowest expected value of side friction (AASHTO, 1984).

(2)

$$f = \frac{V^2}{Rg - e}$$

where f = side friction factor (dimensionless),
V = velocity (ft/sec).
R = curve radius (ft),
g = gravitational acceleration constant (32.2 ft/sec^2), and
e = superelevation (dimensionless).

By substituting lateral acceleration (expressed as a multiple of g) for f, the same expression relates the maximum acceptable lateral acceleration to velocity, for cases where the curve's radius and superelevation are known.

(3)

$$a_{ymax} = \frac{V^2}{Rg - e}$$

Because reliable field measures of radius and superlevation were not available, lateral acceleration on each ramp was measured by an accelerometer mounted to a light boat trailer that was towed by a car along the ramps at several constant speeds. Recorded accelerations were plotted for each speed and a curve of the form of Equation 4 was fitted to each plot using a least squares procedure (Appendix Figures A-1, A-2, and A-3).

(4)

$$a_y = AV^2 - B$$

where a_y = lateral acceleration (multiples of g),

A = estimated coefficient that is equivalent to the inverse of the product of the radius of curvature of the ramp and g (acceleration due to gravity),

V = velocity (mph), and

B = estimated coefficient that is equivalent to superelevation of the ramp at the point requiring the maximum side friction.

Next, using the maximum desirable lateral acceleration (0.14g, from Equation 1) at midramp, the region of sharpest curvature for all three ramps, the corresponding maximum safe midramp speed for each ramp was read from its speed/lateral acceleration curve. The maximum safe midramp speed was 41.5 mph for site 1, 38.0 mph for site 2, and 22.0 mph for site 3. These calculations yielded ramp advisory speeds consistent with those posted by Michigan except at site 1, where the posted advisory speed of 35 mph was lower. To avoid inconsistent signage, the advisory speeds posted on the new rollover-warning signs were the same as on the existing ramp warning signs.

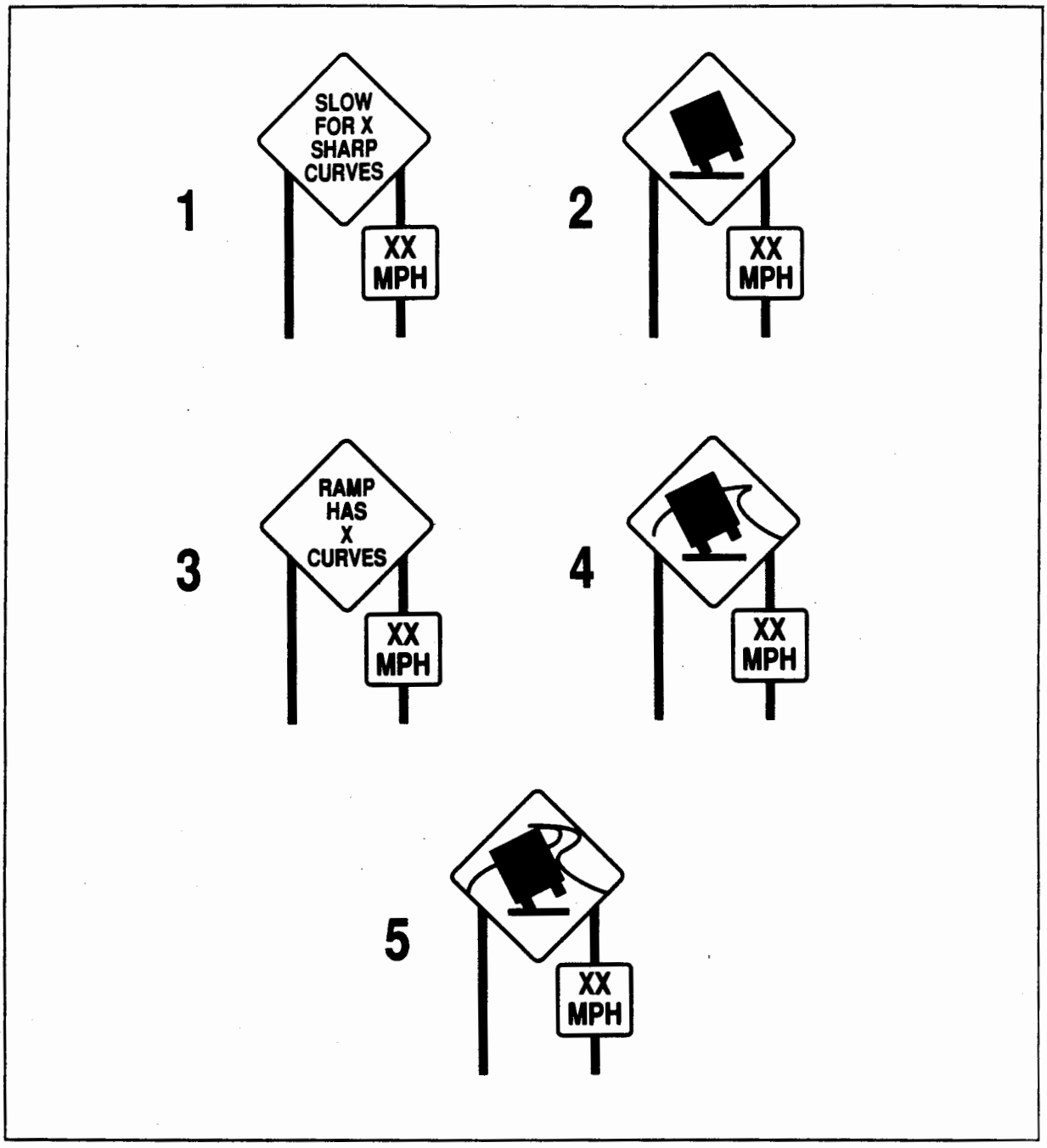
Sign Development

The truck rollover-warning sign design was based on survey responses of 38 experienced truck drivers, who were shown several signs designed to give warning of a truck rollover hazard (Figure 1). A simple black on yellow silhouette of a truck tipped to one side, which was most frequently rated best by surveyed drivers, was selected (Figure 2). The advisory speed was posted on a separate black on yellow panel (MUTCD W13-1) (FHWA, 1988) mounted on the sign post; the yellow light was located to the right of the silhouette panel.

Data Collection

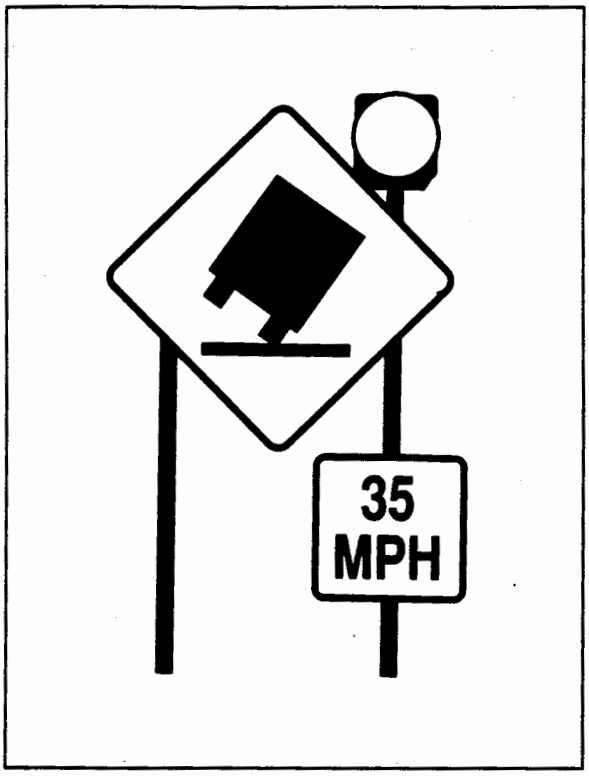
To ensure that measured speeds were not influenced by other vehicles, only the speeds of relatively isolated tractor-trailer combination trucks were recorded; to reduce effects of novelty, data were not compiled for use in the analyses until the sign had been in place for at least 30 days. All

Figure 1
Sign Versions Used in Trucker Sign Preference Survey



data were collected in daylight and in dry weather. Data collection was completed for site 1 in June 1990, site 2 in November 1990, and site 3 in July 1991.

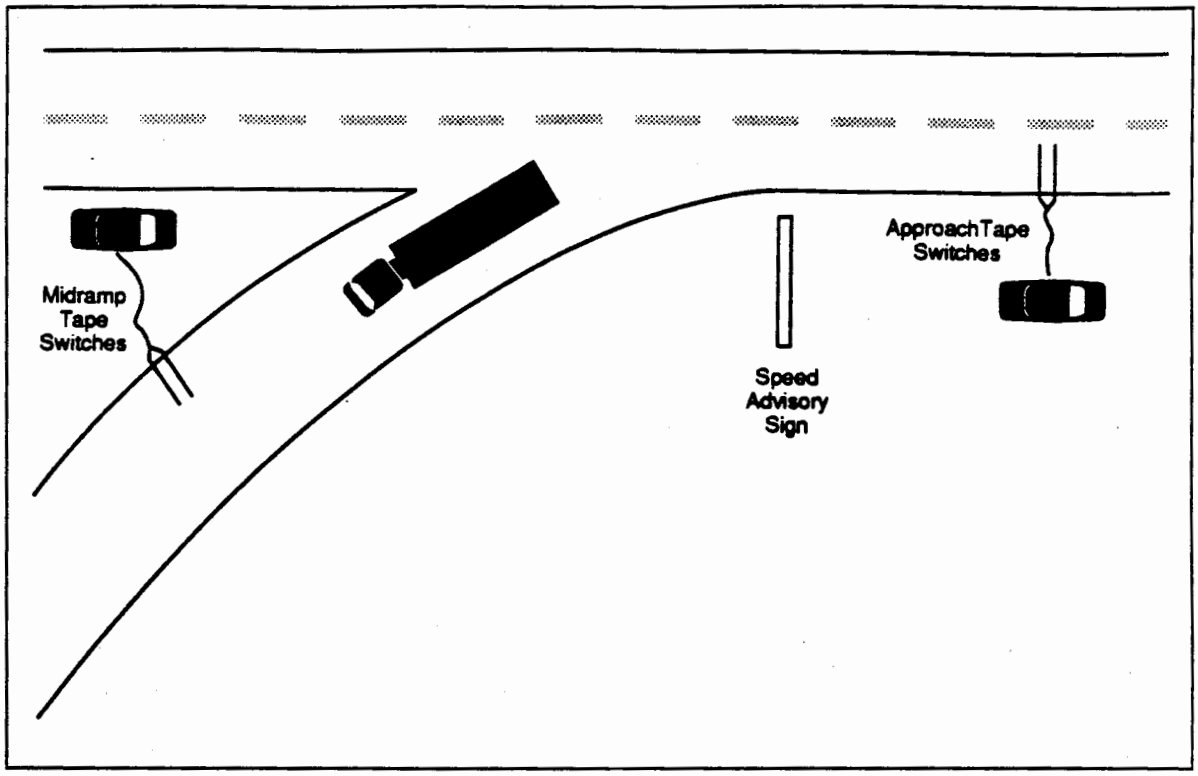
Figure 2
Rollover-Warning Sign with Flashing Light



Two speed measurements for each tractor-trailer truck were collected at each ramp -- one on the approach and one near the ramp's minimum radius of curvature (midramp). Pairs of Tapeswitches™ with a separation of 10 feet were installed on the approach and at midramp and connected to an electronic time recorder (Figure 3). Experimenters located in nearby parked vehicles recorded how long it took for each truck chosen to cross each pair of switches and calculated its speed at each pair.

For each ramp, a minimum approach speed was determined so that only those trucks whose speed was high enough to present a reasonable likelihood of rollover would be included in the study. The minimum approach speed for each ramp was based on preliminary truck speed data that had been collected at each ramp prior to installing the truck rollover-warning sign. Observed midramp speeds were examined to identify associated approach speeds. The approach speed that corresponded most nearly with the analytically determined maximum safe midramp speed was used as a criterion of inclusion; trucks that approached at lower speeds were excluded from the study because their midramp

Figure 3
Typical Ramp Speed Data Collection Set Up



speeds were typically below the maximum safe speed. Minimum approach speeds were 52 mph for site 1, 40 mph for site 2, and 20 mph for site 3.

Twenty-five to 30 percent of all the tractor-trailer trucks on these ramps were excluded because they did not meet the minimum approach speed. Another 15-20 percent were eliminated because they had empty flatbed trailers (which have a relatively high rollover threshold) or were not sufficiently isolated from other traffic. For the remaining tractor-trailers, experimenters manually triggered the flashing light for every second truck; for the alternate trucks, the light was not triggered. This study design permitted the evaluation of the speed actuation effect while controlling for other sources of variation in truck speeds, such as time of day, day of week, weather, and so on.

At site 1, speed data were collected for 1,000 trucks (500 without flasher, 500 with); at site 2, data were collected for 992 trucks (494 without flasher, 498 with); at site 3, speed data were collected for 964 trucks (479 without flasher, 485 with).

Analyses

The speeds of trucks using the ramps when the yellow light was flashing on the rollover-warning sign were compared with those of trucks traveling the same ramps with the rollover-warning sign without the flashing light. An analysis of variance (ANOVA) was performed to assess the main effects and interaction effects of approach speed, site, and sign type (flashing or nonflashing) on mean midramp speeds. For this analysis, truck approach speeds for each site were dummy coded as a categorical variable having a value from 1 to 4 representing its speed quartile.

An odds ratio analysis was also performed to assess the effect of sign type on the odds of exceeding the maximum safe speed by any amount, by more than 5 mph, and by more than 10 mph at each site. The odds ratio compares the odds for excessive speed when the sign was flashing with the odds for excessive speed when the sign was not flashing. The odds for excessive speed for a given site and sign type was defined as the number of trucks exceeding a specified midramp speed threshold divided by the number of trucks traveling below the maximum safe speed.

For example, when the sign was not flashing at site 1, there were 148 trucks exceeding the maximum safe midramp speed by more than 5 mph, and 171 trucks not exceeding the maximum safe midramp speed at all. In other words, in this case there were 87 trucks traveling by more than 5 mph over the maximum safe speed for each 100 trucks traveling at safe speeds, corresponding to "unsafe" speed odds of 0.87 (=148/171). When the sign was flashing, there were 107 trucks exceeding the maximum safe speed and 173 not exceeding it, corresponding to unsafe speed odds of 0.62 (= 107/173). The odds ratio for unsafe speeds (i.e., the ratio of unsafe speed odds with flashing and nonflashing signs) was therefore 0.71 = 0.62/0.87. The odds ratio can be used to compare the numbers of trucks with flashing and with nonflashing signs that would be expected to exceed the maximum safe midramp speed by at least 5 mph for every 100 trucks not exceeding it under the same sign condition. Generally, an unsafe speed odds ratio of less than one indicated that the flashing sign was associated with lower odds for excessive speeds than the nonflashing sign. In the example, the value of this odds ratio corresponds to an approximately 29 (= 100 x (1 - 0.71)) percent reduction.

Separate odds ratios were computed using various speed thresholds for sites 1, 2, and 3. For each speed threshold, the odds ratios for sites 1-3 were tested for homogeneity (similarity) using the Breslow-Day test. When the Breslow-Day test does not reject the hypothesis of homogeneity, as was the case here, it is legitimate to obtain a single odds ratio estimate for more than one data set (Breslow and Day, 1980). A single, overall odds ratio estimate for the three ramps was computed by the Mantel-Haenszel method (Breslow and Day, 1980).

RESULTS

Mean midramp speeds for the flashing and nonflashing signs, grouped into octiles by approach speed, are plotted for each site in Figures 4, 5, and 6. The ANOVA indicated highly significant main effects for sign type, speed quartile, and site (Table 2). Although the sign-type-by-site interaction was nearly significant, mean midramp speeds associated with the flashing sign were lower than for the nonflashing sign at all three sites (Table 3). The greatest effect of sign type was found at site 2 (I-96 West), where the mean midramp speed associated with the flashing sign was 1 mph lower than for the nonflashing sign. The speeds at sites 1 and 3 in particular suggested that the effect of the flashing sign was greater for trucks approaching at higher speeds, and the interaction effect of approach speed and sign type was nearly statistically significant.

Figure 4
Approach and Midramp Speeds on I-96 East for Nonflashing and Flashing Signs - Site 1

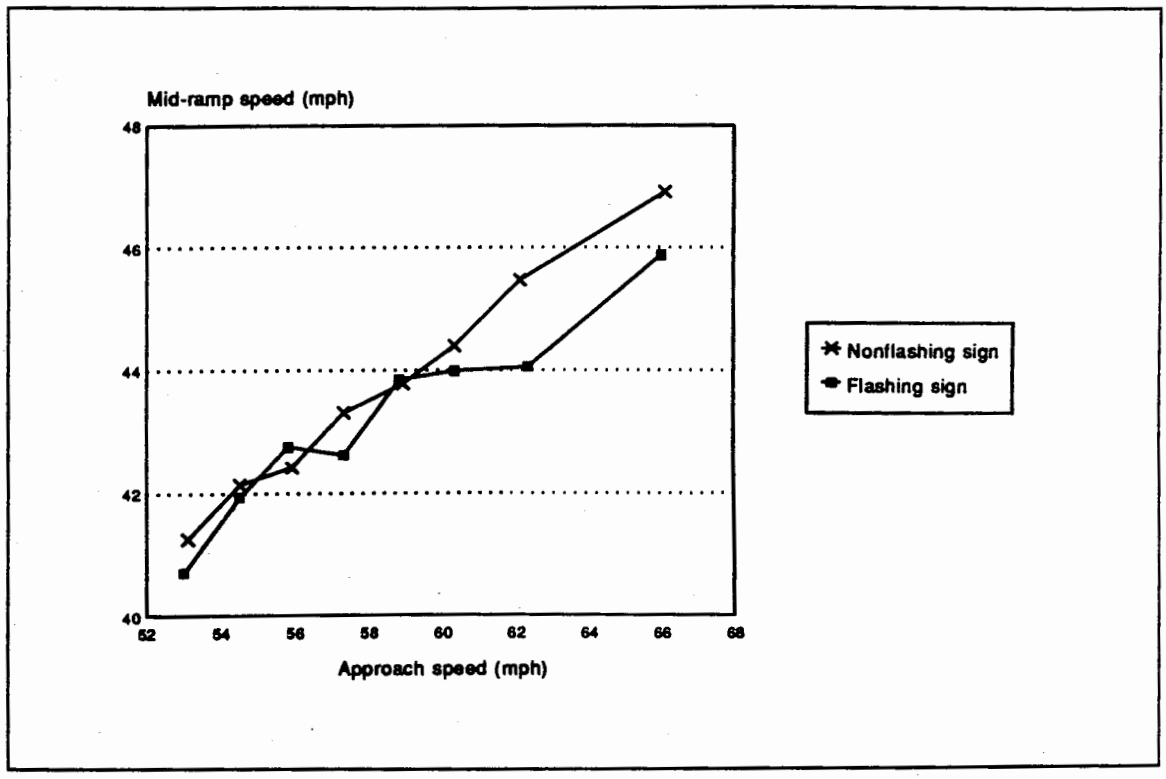


Figure 5
Approach and Midramp Speeds on I-96 West for Nonflashing and Flashing Signs - Site 2

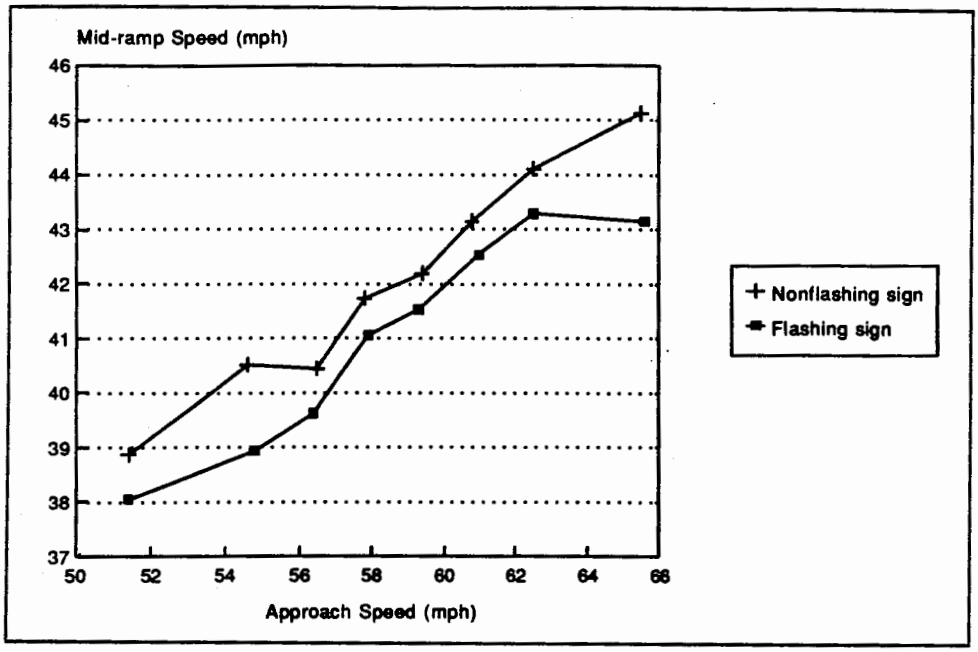


Figure 6
Approach and Midramp Speeds on I-94 West for Nonflashing and Flashing Signs - Site 3

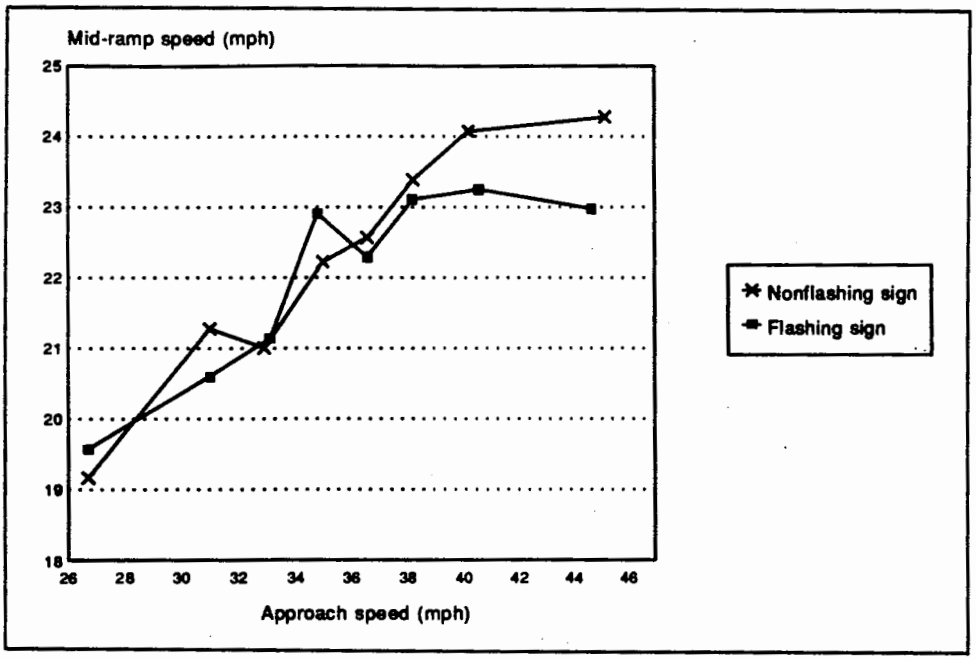


Table 2
Analysis of Midramp Speed Variation in Terms of Main Effects and Interactions for Sign Type (Flashing vs. Nonflashing), Approach Speed Quartile, and Site

Source of Variation	Degrees of Freedom	Type III* Sum of Squares	Mean Square	F Value	Significance of F
Main Effects					
Sign Type	1	204	204	13.7	0.00
Approach Speed Quartile	3	7,068	2,356	158.4	0.00
Site	2	276,551	138,275	9,296.3	0.00
Two-way Interactions					
Sign Type x Approach Speed Quartile	3	110	37	2.5	0.06
Sign Type x Site	2	83	42	2.8	0.06
Approach Speed Quartile x Site	6	151	25	1.7	0.12
Three-way Interactions					
Sign Type x Approach Speed Quartile x Site	6	30	5	0.3	0.91
Model	23	287,174	12,486	839.4	0.00
Error	2,932	43,611	15		
Corrected Total	2,955	330,785	112		

$R^2 = 0.87$

* Type I and Type III sums of squares were nearly identical; Type III was chosen because of slight variation in cell counts.

Table 4 presents truck counts for four midramp speed ranges (e.g., not exceeding maximum safe speed, exceeding maximum safe speed by any amount, by at least 5 mph, and by at least 10 mph), and the odds comparing truck counts exceeding the maximum safe midramp speed by various amounts to truck counts not exceeding the maximum safe midramp speed by site and sign condition (flashing and nonflashing). The ratio of the odds for exceeding the maximum safe midramp speed by some amount, with and without flashing signs, and the percentage difference between the proportion of vehicles exceeding maximum safe midramp speed, with and without flashing signs, are also given in

Table 3
Mean Midramp Truck Speeds by Speed Quartile, Sign Type, and Site

	Speed Quartile				
	1	2	3	4	All
Site 1					
Nonflashing Sign	41.6	43.0	44.0	46.3	43.8
Flashing Sign	41.7	42.6	43.9	44.9	43.2
Site 2					
Nonflashing Sign	39.5	41.0	42.5	44.6	42.0
Flashing Sign	38.5	40.3	41.8	43.2	41.0
Site 3					
Nonflashing Sign	20.0	21.1	22.7	23.9	22.0
Flashing Sign	19.8	21.4	22.8	23.1	21.7

Table 4. The last row of Table 4 presents the overall odds ratios comparing the odds that a truck exceeded the maximum safe midramp speed when the sign was flashing to similar odds when it was not flashing.

The flashing signs significantly reduced the number of trucks in some excess speed ranges for both site 1 (I-96 East) and site 2 (I-96 West). The odds ratio was not statistically significantly different from 1.00 in any excess speed range for site 3 (I-94 West). Overall, flashing signs were associated with a 13 (100 x(1 - 0.87)) percent reduction in the odds that a truck would exceed the maximum safe midramp speed by any amount, but this reduction was not statistically significant at the five percent level. The comparable reduction in the odds for a truck exceeding the maximum safe midramp speed by at least 5 mph was 32 percent, and this reduction was statistically significant at the five percent level. The reduction in the odds for a truck exceeding the maximum safe midramp speed by a least 10 mph was 46 percent; this reduction was also statistically significant.

In a similar vein as shown in Table 4, the reduction (expressed as the percentage change) in the percentage of trucks exceeding the maximum safe speed was progressively greater with increasingly larger excess speed amounts. There was only a 1 to 7 percent reduction in the percentage of trucks exceeding the safe speed by any amount; a 14 to 28 percent reduction was found for trucks exceeding the safe speed by more than 5 mph; and a 33 to 43 percent reduction occurred for an excess speed of more than 10 mph. There were too few trucks exceeding the maximum safe speed by more than 15 mph to support an odds ratio analysis.

Table 4
Frequency and Odds[1] of Trucks Exceeding Maximum Safe Ramp Speed by Selected Amounts with Nonflashing and Flashing Signs

Sign Type	No. of Observations	Trucks Within Safe Speed		Trucks Exceeding Safe Speed[2] By More Than											
				Any Amount				5 mph				10 mph			
		No.	(%)	No.	Odds	Odds Ratio	Percent Change[3]	No.	Odds	Odds Ratio	Percent Change[3]	No.	Odds	Odds Ratio	Percent Change[3]
Site 1															
Nonflashing	500	171	(34)	329	1.92	1.00		148	0.87	1.00		23	0.13	1.00	
Flashing	500	173	(35)	327	1.89	0.98		107	0.62	0.71*		13	0.08	0.56	
							(-1)				(-28)				(-43)
Site 2															
Nonflashing	493	94	(19)	399	4.24	1.00		198	2.11	1.00		46	0.49	1.00	
Flashing	498	125	(25)	373	2.98	0.70*		172	1.38	0.65*		31	0.25	0.51*	
							(-7)				(-14)				(-33)
Site 3															
Nonflashing	479	215	(45)	264	1.23	1.00		31	0.14	1.00		0	—	—	
Flashing	485	229	(47)	256	1.12	0.91		22	0.10	0.67		1	—	—	
							(-4)				(-30)				—
Overall Odds Ratio[4]						**0.87**				**0.68***				**0.54***	

* Odds ratio is statistically significantly different from 1.00 based on 95 percent confidence interval.

[1] Odds are defined as number of trucks exceeding speed threshold divided by number of trucks within safe speed.

[2] Safe ramp speeds were: (site 1) 41.2 mph; (site 2) 38 mph; (site 3) 21.8 mph.

[3] Change is defined as the percent difference between proportions of vehicles exceeding maximum safe ramp speed by selected amount with flashing sign and nonflashing sign, divided by proportion of vehicles exceeding maximum safe ramp speed by the same amount with nonflashing sign.

[4] Odds ratios were homogenious across three sites in all cases indicating that pooling odds ratios over all sites is appropriate. Odds ratios were pooled using Mantel-Haenszel method.

—Insufficient data

DISCUSSION

This study of three Michigan freeway ramps with high rollover frequencies revealed that, although warning signs posted appropriate advisory speeds, many tractor-trailers exceeded those speeds by at least 5 mph and 10 mph. Although no rollovers occurred during the study period, such speeds are well above the maximum safe speeds for tractor-trailers calculated in this study. Results from this study suggest that a flashing truck speed advisory warning sign activated for tractor-trailers that are likely to exceed the maximum safe speed is more effective than a similar but nonflashing warning sign in reducing speeds of the fastest tractor-trailer trucks at the critical curve sections of freeway ramps. The results also suggest that the flashing sign is especially effective in reducing the speed of the most egregiously speeding trucks on freeway ramps.

In addition to the special truck rollover-warning sign installed for this study, the approaches to the ramps studied here had already been equipped with speed advisory signs that were more descriptive than those specified by the FHWA; thus these results may understate the effectiveness of the special sign. These results suggest that a conspicuous rollover-warning sign that is clearly directed toward individual truck drivers would be more effective in reducing truck speeds than current advisory speed signs. Unfortunately, the study was not able to determine whether the addition of a truck-specific nonactuated rollover-warning sign by itself has any effect on truck speeds.

Previous research has shown that rollover threshold is related to speed, axle loads, center of gravity height, and width. In this study, the flashing warning sign was manually triggered on the basis of approach speed alone. Future improved automated techniques may be able to trigger warning signs using additional factors to identify each vehicle's rollover threshold. Until that is possible, triggering warning signs based on truck speed alone is still likely to reduce rollovers.

The results of this study appear to offer a promising treatment for highway ramps that have a history of tractor-trailer rollover crashes that are related to excess speed. Future research may be able to evaluate the effectiveness of flashing speed advisory signs at sites offering a broader range of geometric and truck speed characteristics.

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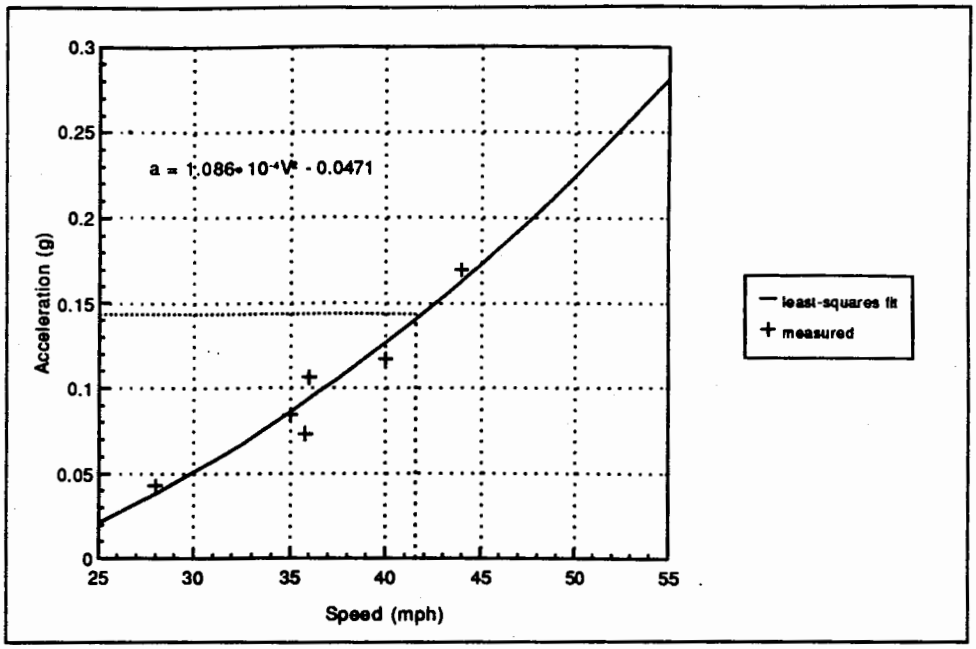
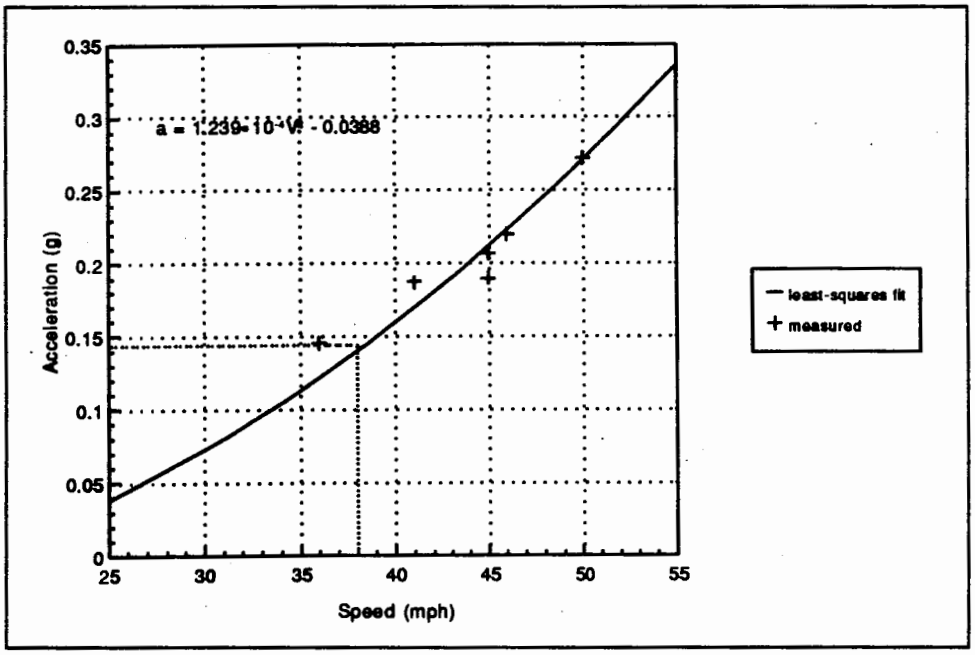
Appendix Figure A-1
Midramp Speed and Lateral Acceleration - Site 1



Appendix Figure A-2
Midramp Speed and Lateral Acceleration - Site 2



Appendix Figure A-3
Midramp Speed and Lateral Acceleration - Site 3