

## **ROLE OF TRAFFIC CONTROL DEVICES AND TRAFFIC REGULATIONS IN SAFELY ACCOMMODATING HEAVY VEHICLES ON THE HIGHWAY**

This chapter discusses the role of traffic control devices and traffic regulations in safely accommodating heavy vehicles on the highway. The applications of traffic control devices and traffic regulations addressed in this chapter include:

- differential speed limits for passenger cars and heavy vehicles
- lane use restrictions for heavy vehicles
- heavy vehicle prohibitions on particular roads
- exclusive lanes or exclusive roadways for heavy vehicles
- signing and marking of interchange ramps
- restriction of sign visibility by heavy vehicles
- signal timing to accommodate heavy vehicles

### **DIFFERENTIAL SPEED LIMITS FOR PASSENGER CARS AND HEAVY VEHICLES**

Differential speed limits are speed limits that restrict all heavy vehicles, or at least heavy vehicles of a specific size, weight, or axle configuration, to traveling at lower speeds than the rest of the traffic stream. Proponents of differential speed limits argue that heavy vehicles have limited maneuvering and braking capabilities and should be required to travel at lower speeds in mixed traffic to help accommodate their differences from passenger cars. It has also been maintained that lower speeds for heavy vehicles should reduce their accident risk. Proponents of uniform speed limits (i.e., the same speed limit for passenger cars and heavy vehicles) argue that differential limits may increase speed variance, resulting in more traffic conflicts and, thus, more accidents between trucks and other types of vehicles. Increased speed variance has been

shown to be related to increased accident frequency (31, 32). It has also been maintained that the higher driver position in a heavy vehicle provides greater sight distance than for passenger car drivers, giving truck drivers more time to stop.

The highway agency survey in Appendix B found that 31 percent of state highway agencies have implemented differential speed limits for passenger cars and trucks and 9 percent of state highway agencies are considering differential speed limits. Table B-3 in Appendix B shows the specific combinations of passenger car and truck speed limits that have been used. In all cases, the differences in speed limits for passenger cars and trucks is either 8 or 16 km/h (5 or 10 mi/h).

In a recent study, Garber et al. (33) compared the safety effects of uniform speed limits for all vehicles with differential speed limits for passenger cars and trucks. Accident, speed, and volume data were obtained from ten states for rural highways for the period 1991 to 2000. These states were divided into four policy groups based on the type of speed limit employed during the period: maintenance of a uniform speed limit only, maintenance of a differential speed limit only, a change from a uniform to a differential speed limit, and a change from a differential to a uniform speed limit. Table 10 presents an overview of data availability from the various states included in the study.

Statistical analyses were used to evaluate speed and accident rate changes over time within the four policy groups. A before-after analysis was conducted for those states that had changed from a uniform to a differential speed limit (or vice versa) during the study period. For the states that maintained the same speed limit over the entire

**Table 10. Overview of data availability on speed limits from various states (33)**

Rural interstate speed limits (1991-2000)		Accident data	Speed data
Policy Group 1:	Maintained a uniform speed limit		
Arizona	121 km/h (75 mi/h)	Y	N
Iowa	105 km/h (65 mi/h)	N	Y
Missouri	89 km/h (55 mi/h) before 1996 113 km/h (70 mi/h) after 1996	Y	N
North Carolina	105 km/h (65 mi/h) before 1996 113 km/h (70 mi/h) after 1996	Y	N
Policy Group 2:	Maintained a differential speed limit (passenger cars/trucks)		
Illinois	113/105 km/h (70/65 mi/h)	N	Y
Indiana	105/97 km/h (65/60 mi/h)	N	Y
Washington	No speed limits	N	N
Policy Group 3:	Changed from uniform to differential speed limit (passenger cars/trucks)		
Arkansas	From: 105 km/h (65 mi/h) To: 113/105 km/h (70/65 mi/h) 1996	Y	N
Idaho	From: 105 km/h (65 mi/h) To: 121 km/h (75 mi/h) 1996 To: 121/105 km/h (75/65 mi/h), 1998	Y	Y
Policy Group 4:	Changed from differential to uniform speed limit (passenger cars/trucks)		
Virginia	From: 105/89 km/h (65/55 mi/h) To: 105 km/h (65 mi/h), 1994	Y	Y

10-year period, the data were categorized into two subperiods, 1990 to 1995 and 1996 to 2000, in order to determine whether significant changes occurred over time even without a change in speed limit. Table 11 presents the results of the before-after accident analysis.

The Garber et al. study found no consistent safety benefits with differential speed limits. The mean speed, 85th percentile speed, median speed, and accident rate generally increased over the 10-year period, regardless of whether a differential or uniform speed limit was in place.

After the enactment of the Surface Transportation and Uniform Relocation Assistance Act in 1987, several states changed the speed limit on rural Interstate highways from 89 to 105 km/h (55 to 65 mi/h). Because of concern about the impact of the increased speed limit on accidents involving trucks, some of these states imposed a differential speed limit, restricting the maximum speed limit for trucks to 89 km/h (55 mi/h). To determine the safety effect of this strategy, Garber and Gadiraju (34) conducted a study of sites in California, Michigan, Maryland, Virginia, and West Virginia. At some of the study sites, a uniform speed limit of either 89 or 105 km/h (55 or 65 mi/h)

was maintained. At other study sites, a differential speed limit of 105 km/h (65 mi/h) for passenger cars and 89 km/h (55 mi/h) for trucks was implemented.

Speed and accident data were used to evaluate the effects of differential speed limits on vehicle speeds and accident characteristics. Accident data were collected at each site for three years prior to and at least one year after the effective date of the change in speed limit. Results of the before-after analysis indicated the following:

- Compared with the uniform speed limit of 105 km/h (65 mi/h), the differential speed limit has no significant effect in reducing: (a) nontruck/truck accident rates or (b) two-vehicle accident rates.
- The differential speed limit increases the interaction among vehicles in a traffic stream as a result of the increase in speed variance.
- The imposition of the differential speed limit on Interstate highways with AADT less than 50,000 vehicles per day may result in higher accident rates for certain accident types, such as rear-end and side-

**Table 11. Results of before-after accident analysis (33)**

Policy group	State	Type of accident rate	Before-after analysis result			
			All sites		ADT filtered sites	
			Difference	Significant	Difference	Significant
Group 1: maintained a uniform limit	Arizona	Total	+	N	+	Y
		Fatal	+	N	+	N
		Rear end	+	N	+	Y
		Total truck involved	+	N	+	Y
		Truck-involved fatal	+	N	+	Y
		Truck-involved rear end	+	N	+	N
	Missouri	Total	+	N		
		Fatal	-	N		
		Rear end	+	N		
		Total truck involved	+	Y		
		Truck-involved fatal				
		Truck-involved rear end				
	North Carolina	Total	+	Y	+	Y
		Fatal	+	N	-	N
		Rear end	+	Y	+	Y
		Total truck involved	+	N	+	N
		Truck-involved fatal	-	N	-	N
		Truck-involved rear end	+	N	+	N
Group 3: Charged from uniform to differential limit	Arkansas	Total	-	N	+	N
		Fatal	+	N	+	N
		Rear end	+	N	+	N
		Total truck involved	+	N	+	Y
		Truck-involved fatal				
		Truck-involved rear end				
Group 4: Changed from differential to uniform limit	Idaho	Total	-, +	N, N	-, +	N, N
		Fatal	-, +	N, N	-, +	N, N
		Rear end	-, +	N, N	-, +	N, N
		Total truck involved	-, +	N, N	-, +	N, N
		Truck-involved fatal	-, 0	N, N	-, 0	N, N
		Truck-involved rear end	-, +	N, N	-, +	N, N
Group 4: Changed from differential to uniform limit	Virginia	Total	+	N	+	N
		Fatal	-	N	-	N
		Rear end	+	N	+	Y
		Total truck involved	+	Y	+	Y
		Truck-involved fatal	+	N	+	N
		Truck-involved rear end				

swipe accidents, although the results were not statistically significant.

The National Highway Traffic Safety Administration (NHTSA) also conducted a study (35) following the passage of the 1987 Federal legislation. Accident data were analyzed from four states that raised the speed limit following the legislation. Two of the states (Georgia and Florida) had uniform 105 km/h (65 mi/h) speed limits while the other two (Ohio and Virginia) had differential speed limits of 105 km/h (65 mi/h) for passenger cars and 89 km/h (55 mi/h) for trucks.

In the states with differential speed limits, the study showed a higher percentage of accidents involving trucks that were exceeding the speed limit. This result may be expected since trucks in Ohio and Virginia were more likely to exceed the truck speed limit of 89 km/h (55 mi/h) than trucks in Georgia and Florida with a uniform speed limit of 105 km/h (65 mi/h) for both passenger cars and trucks. However, there appeared to be very little difference in the percentages of trucks involved in “high-speed” accidents [exceeding 105 km/h (65 mi/h)] between the two types of speed limits.

Just as the 1987 Federal legislation provided an opportunity to evaluate the safety effects of differential speed limits, Zaremba and Ginsburg (36) conducted a before-after study following the enactment of the mandatory 89 km/h (55 mi/h) speed limit in 1974. They investigated the safety effects of rear-end accidents involving passenger cars and trucks in four states. Three of the four states had differential speed limits before the law was enacted. The results suggested that with the change from a differential to a uniform speed limit, the overall reduction in rear-end accident rates was approximately 15 percent on high-speed roadways. In this analysis, rear-end accidents were then separated into two categories: car-struck-in-rear-by-truck (CSRT) and truck-struck-in-rear-by-car (TSRC) accidents. Accident rate reductions of 5 and 34 percent, respectively, were observed for these two categories. The TSRC accident rate, in particular, had a substantial reduction due to the uniform and lower speed limit.

A 1974 study by Hall and Dickinson (37) evaluated speed and accident data from 84 study sites located on Interstate, U.S., and state routes in Maryland. Multiple regression analysis was used to determine whether a significant relationship could be found among speed parameters, accidents, and accident rates. Figure 11 illustrates the distribution of accidents by type of vehicles involved. Trucks were involved in 15.5 percent of all accidents on roadway sections with a differential speed limit and 19.5 percent of all accidents on roadway sections without a differential speed limit. However, the accident analysis found no relationship between posted differential speed limit and truck accidents, although truck compliance with the differential limit was comparatively low.

Harkey and Mera (38) conducted a study to determine whether differential or uniform speed limits were more beneficial to safety and traffic operations on Interstate highways. Speed and accident data were collected from 12 states employing both types of limits. Sites included rural and urban Interstate locations and represented the following speed limits for cars/trucks: 89/89 km/h (55/55 mi/h), 105/89 km/h (65/55 mi/h), 105/97 km/h (65/60 mi/h), and 105/105 km/h (65/65 mi/h). Accident type, accident severity, and vehicle type involvement (e.g., car-into-truck vs. truck-into-car) were examined. The results of the accident analysis indicated the following:

- The states with differential speed limits experienced higher proportions of car-into-truck accidents for rear-end collisions; however, this difference was not statistically significant.
- The states with uniform speed limits experienced higher proportions of truck-into-car accidents for all collision types, including rear-end and sideswipe accidents.
- There were no differences in fatal accident proportions between the differential and uniform speed limit states, but the states with uniform speed limits did experience a higher proportion of injury accidents.

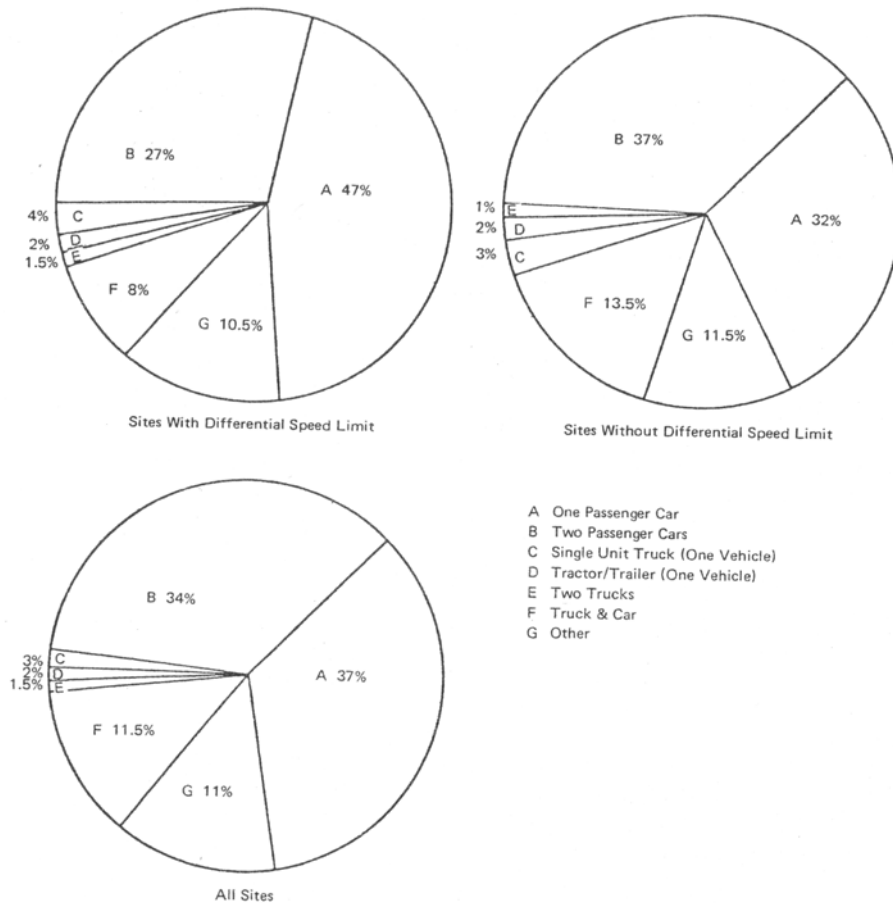


Figure 11. Distribution of accidents by type of vehicle involved (37).

Overall, the accident analysis showed very little difference in overall accidents or accident severity between the states with respect to the type of speed limit. However, the findings do suggest that the types of collisions and the roles of the vehicles involved may be impacted by the type of speed limit. In the states with differential speed limits, the car-truck rear-end collisions were more likely to involve cars striking trucks. In the states with uniform speed limits, the car-truck accidents were more likely to involve trucks striking cars. Following the passage of the 1987 Federal legislation, Baum et al. (39) conducted a study that compared vehicle speeds on rural Interstates in California and Illinois, which have a differential speed limit, with those in Arizona and Iowa, which have a uniform speed limit. The results of the study were as follows:

- A posted differential speed limit on rural Interstates was found to reduce high truck speeds on the faster roads.
- Trucks represent a smaller percentage of the high-speed traffic in states with differential speed limits than in states with uniform speed limits when average car speeds exceed 102.0 km/h (63.4 mi/h). Specifically, for each 1.6-km/h (1-mi/h) increase in mean car speed over 102.0 km/h (63.4 mi/h) on rural Interstates, the odds relative to cars of a truck traveling about 113 km/h (70 mi/h) decreases by 20 percent in the states with differential speed limits compared with states having uniform speed limits.
- Trucks travel 2.3 km/h (1.4 mi/h) slower in states with differential speed limits than in those without. This difference increases to

4.8 km/h (3.0 mi/h) for the fastest 5 percent of trucks.

In summary, differential speed limits have been shown to reduce the speeds of trucks relative to passenger cars, but no accident reduction effect of differential speed limits has been demonstrated. Indeed, there is concern that by increasing speed variance, differential speed limits may increase overall accident rates. The Appendix C survey showed concerns on the part of the trucking industry that differential speed limits may be adverse to safety.

### LANE USE RESTRICTIONS FOR HEAVY VEHICLES

Lane restrictions are restrictions whereby all trucks, or at least trucks of a specific size, weight, or axle configuration, are restricted from traveling in specified lanes on a roadway. There are several variations in truck lane restriction strategies. One type of lane restriction restricts trucks from using the left lane(s) of a highway, typically a freeway

with three or more lanes in each direction of travel; another type restricts trucks to using only the right lane of a highway. Figure 12 illustrates a truck lane restriction in the left lane.

Lane restrictions can be implemented on a mandatory or a voluntary basis; however, in many states, no attempts are made to enforce the restrictions. Lane restrictions may be implemented on either a site-specific or statewide basis, depending on the motivation behind the restriction and justification of its use. Most site-specific restrictions exist in areas with grades, where trucks have difficulty maintaining speed, or where there are unusual safety concerns. Most lane restrictions operate 24 hours a day to ease enforcement efforts and motorist confusion.

Truck lane restrictions are usually implemented for one of the following purposes:

- to improve traffic operation and efficiency
- to improve safety
- to extend pavement life

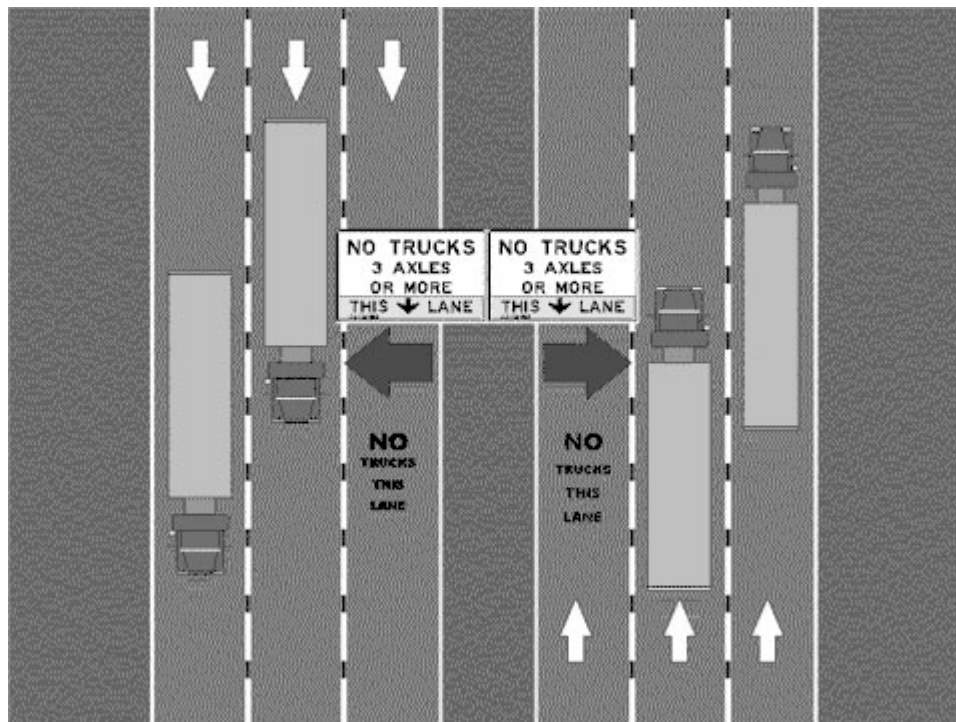


Figure 12. Truck lane restriction in left lane (40).

From a traffic operational standpoint, the presence of large trucks in the traffic stream is perceived to restrict the free flow of traffic, resulting in low speeds, large headways, and ultimately, an underutilization of the facility. To improve traffic operation and efficiency, trucks are most often restricted from traveling in the extreme left lanes, thus reserving these faster lanes for passenger cars. From a safety standpoint, large trucks are thought to present a safety hazard because of their decreased stopping capabilities, lack of maneuverability, and large size, which occupies more lane space and blocks motorists' visibility.

The survey results reported in Appendix B indicate that 37 percent of highway agencies have used and 9 percent are considering restrictions on truck and bus use of the left lane. Six percent of highway agencies have used and 11 percent are considering restricting all trucks and buses to the right lane. The majority of respondents to the trucking industry survey consider such restrictions undesirable or unnecessary; approximately 36 of the industry survey respondents indicated that such restrictions of trucks from the left lane were highly desirable or desirable at some locations.

Garber and Gadiraju (41) conducted a study to determine the effect of truck lane restrictions and differential speed limits on traffic flow, speeds, headways, and accident patterns. Nine test sites, with relatively high truck percentages, were selected from sections of Interstate and arterial highways in Virginia. Speed, traffic volume, and accident data were obtained in order to determine the speed-flow relationships for different traffic lanes at different locations and the relationship between congestion and accident rates on multilane highways. Traffic flow models and models relating accident rates to congestion were developed. Simulation was then used to study the effects of truck lane restrictions and differential speed limits on traffic volumes, speeds, headways, and accident rates. Using the model relating congestion and accident rates, and the hourly counts and truck volumes from the simulation results, the expected changes in accident rates were determined.

The results did not indicate any safety benefits from the implementation of lane restrictions and

differential speed limits, but suggested a potential for an increase in accident rates if the strategies were imposed on highways with high volumes and a high percentage of trucks. A slight increase in truck-related and all-vehicle accidents were observed in the right lane, although these increases were not statistically significant.

To improve safety on the Capital Beltway, the Virginia Department of Highways and Transportation implemented a lane restriction that banned trucks and tractor-trailers from the farthest left (median) lane (42). For analysis purposes, vehicles were classified as either tractor-trailers (any combination, with a three-axle minimum), single-unit trucks larger than a panel truck, and other vehicles. An evaluation of the lane restriction indicated the following:

- A slight reduction in the total number of accidents for both trucks and passenger cars was observed.
- The number of injury accidents decreased by approximately 20 percent.
- Tractor-trailer trucks experienced the highest accident rate of all vehicle types.
- The number of tractor-trailer accidents occurring in the median lane was less than the number of accidents occurring outside the median lane after the tractor trailer had, just prior to the accident, been traveling in the median lane. In other words, the weaving action of trucks moving out of the median lane because of the restriction appeared to have resulted in an increase in tractor-trailer accidents.

Secondary results of this study were as follows:

- Truck and truck/trailer volumes were lowest in the median lane and highest in the far right lanes, prior to the implementation of the lane restriction.
- No changes in speed were detected for any vehicle type.
- Motorists supported the program because they felt less intimidated by the trucks.

The Nevada Department of Transportation (DOT) conducted a study (43) to determine the impact on

pavement deterioration of a voluntary truck lane restriction. On an Interstate test site in Nevada, trucks were requested to travel in the left-hand lane to ease the pavement deterioration rate in the well-traveled right lane. While the focus of this study was pavement deterioration, the researchers noted that the redistribution of trucks had no significant impact on traffic accidents.

In 1988, Florida conducted a six-month study (44, 45) to determine the effect of prohibiting large trucks from using the left lane on I-95 between the hours of 7:00 a.m. and 7:00 p.m. With signs posted about every mile—and with good media coverage and strict police enforcement—98 percent compliance was achieved. The accident rate for all vehicles decreased 2.5 percent for a 24-hour period but increased 6.3 percent during the hours of restriction. The proportion of accidents involving trucks with three or more axles decreased 3.3 percent during the hours of the restriction.

To reduce the number of crashes involving combination trucks on Houston freeways, officials from the City of Houston and the Houston District of the Texas Department of Transportation (TxDOT) decided to conduct a 36-week lane restriction demonstration project (46) on a freeway in Houston. During the demonstration period, trucks were prohibited from using the left lane of the freeway. It was decided that a 13-km (8-mi) section of the I-10 East Freeway was most appropriate for the demonstration project. Traffic volume data were reviewed to determine compliance with the truck lane restriction by measuring the percentage of trucks in the left lane compared to other lanes. Accident data were compiled during the demonstration project and compared to data taken on the same stretch of road prior to the restriction. The study results indicated a 68 percent reduction in accidents. Average compliance rates were generally in the 70 to 80 percent range. Furthermore, passenger car drivers overwhelmingly supported the project. The success of the demonstration project has resulted in TxDOT considering implementation of the restriction on additional freeways in Houston.

The evidence on the safety effectiveness of truck lane restrictions is mixed. Prior to the Houston study discussed above, no previous study had shown an overall decrease in accident experience. The

Houston study showed a positive result in one freeway corridor over an eight-month period. This result is promising but further data are needed before a safety benefit from lane restrictions could be considered documented.

## HEAVY VEHICLE PROHIBITIONS

In a review of countermeasures for truck accidents on urban freeways, Fitzpatrick et al. (44) identified several locations where trucks are prohibited from using certain facilities. In each case, the prohibition had been made for reasons other than safety (e.g., reduce congestion, reduce pavement wear, etc.). Thus, no safety evaluations were conducted. Obviously, if trucks are prohibited from using a facility, the facility will no longer experience truck-related accidents. However, the safety effect of diverting trucks to other facilities is not known. A summary of the truck restriction locations is presented below:

- In an effort to reduce congestion, San Diego has restricted trucks from Route 163 through scenic Balboa Park. The merging of traffic from five to two lanes, a 6 percent grade, and a lack of acceleration and deceleration lanes for interchanges all contribute to heavy congestion on the freeway. Public opinion prohibits construction of additional lanes because of the extensive landscaping and scenic location of the freeway.
- A truck ban currently exists on the Pasadena Freeway in Los Angeles (now restored to its original name, Arroyo Seco Parkway) primarily because the pavement of the facility, which opened in 1940, is too weak to support trucks. The California Department of Transportation (Caltrans) reports that with no trucks, this 178-mm (7-inch) pavement is still in good condition. The only large vehicles allowed on the freeway are transit buses and trucks making local pickups and deliveries.
- There is also a truck avoidance policy currently in effect for the Harbor Freeway (I-710) in Los Angeles during major reconstruction. It is only a voluntary ban,



and Caltrans reports that the reduction in truck volume is negligible.

- Beginning in December 1978, a new truck restriction required that trucks traveling through Atlanta use the I-285 bypass instead of freeways that run through the center of the city. In evaluating compliance with this ban, a survey conducted by the Georgia Department of Transportation showed a violation rate of 5.4 percent.

### **EXCLUSIVE LANES OR ROADWAYS FOR HEAVY VEHICLES**

As a result of the increasing volumes of heavy vehicles on major highways, highway agencies are becoming interested in the provision of exclusive lanes or exclusive roadways for heavy vehicles. The survey reported in Appendix B found that exclusive lanes for trucks and buses only have been used or considered by 17 percent of highway agencies, exclusive lanes for buses only by 20 percent of highway agencies, and exclusive roadways for heavy vehicles only by 3 percent of highway agencies.

In a review of countermeasures for truck accidents on urban freeways, Fitzpatrick et al. (44) identified several locations where separate truck facilities were either in use or were being considered. No evaluations of the effect of this countermeasure on truck accidents were available. Obviously, if trucks are removed from a facility, the facility will no longer experience truck-related accidents. However, the safety of the separate truck facility is not known. A summary of the locations is presented below:

- A 53-km (33-mi) segment of the New Jersey Turnpike consists of interior lanes for passenger cars only and exterior lanes for trucks, buses, and passenger cars. Located within the same right-of-way, the interior and exterior roadways each have three lanes in each direction, with the exception of a 16-km (10-mi) section that has only two lanes in each direction on the exterior roadway. Each roadway has 3.6-m (12-ft) lanes and 3.6-m (12-ft) shoulders. Opposing directions of travel are separated by a concrete median barrier, and the passenger-

car-only lanes are separated from the truck/bus/car lanes by a metal beam guardrail.

- In California, the reconstruction of a section of I-5 north of Los Angeles resulted in two parallel roadways. After completion of the new interstate roadway, the old roadway was maintained to carry truck traffic.
- Truck facilities have been considered for the corridor connecting the San Pedro ports and downtown Los Angeles. Proposals include using the paved Los Angeles River channel as an exclusive truck facility, and using the Alameda Street corridor to carry trucks and trains within a right-of-way also shared by passenger cars.
- Truck facilities have also been considered for the I-10 Houston-Beaumont (Texas) corridor and the Houston North Freeway (I-45). Studies of these potential sites concluded that construction of an exclusive truck facility was not warranted because of limited truck volumes along certain sections of the corridor and the estimated cost of the facilities.

An earlier study in Texas examined various approaches to handling increases in truck volumes. One approach included a study (47) to investigate the feasibility of an exclusive truck roadway in the median of the I-35 corridor between Dallas-Ft. Worth and San Antonio. The objectives of this study included:

- establish critical geometric design elements for exclusive truck facilities
- identify typical cross sections to accommodate truck lanes within an existing median area
- prepare alternative access control configurations to serve exclusive truck facilities
- develop a moving-analysis computer program to evaluate geometric constraints and operational performance along a specific corridor

The researchers determined that modifications to highway design policy should be considered in the

following areas in development of criteria for the design of exclusive truck facilities:

- Vehicle characteristics
- Sight distance
- Horizontal alignment
- Vertical alignment
- Cross-section elements

Several of the design recommendations made in this study have since been incorporated in the AASHTO *Green Book (1)*.

A key issue in designing exclusive truck facilities is to decide how trucks enter and leave the facility. Several alternatives for allowing access to and from an exclusive truck facility were considered including:

- *Existing Ramps*—Trucks enter the freeway on ramps designated for both cars and trucks and then move to the appropriate lanes designated for trucks only. Adequate advance signing and decision sight distance are necessary for successful operation.
- *Frontage Roads*—Trucks still interact with other traffic on the cross-street intersections near the trunk ramp terminals. A disadvantage to this alternative is the potential for adverse effects on intersection capacity.
- *Exclusive Truck Routes*—Large vehicles must enter or exist at an interchange or intersection specifically designed for trucks or other large vehicles. This is advantageous in providing direct access to specific truck traffic generators, such as large industrial complexes, and in avoiding congested areas.

No estimates of the safety performance of such facilities have been developed.

#### **SIGNING AND MARKING OF INTERCHANGE RAMPS**

Sharp horizontal curves, particularly on interchange ramps, have been found by a number of highway agencies to require warning signs to advise heavy vehicles of safe operating speeds. Typically, such installations have used a warning sign showing a

truck tipping over with an advisory speed (see example in Figure 13). The highway agency survey reported in Appendix B found that 31 percent of highway agencies had used advisory speed limits for all trucks on specific ramps and 60 percent had used advisory speed limits for all vehicles on specific ramps. Regulatory speed limits on ramps were used much less often (by 6 percent of highway agencies or less). Special warning signs for trucks (e.g., the truck rollover sign) were used by 57 percent of highway agencies. Twenty-six percent of highway agencies have used special warning signs for trucks accompanied by a permanent flasher. Thirty-seven percent of highway agencies had found a need to reconstruct particular ramp curves to change their radius or superelevation.



Figure 13. Truck rollover warning sign typically used at curves on interchange ramps.

Research by Knoblauch and Nitzburg (48) addressed ramp signing for trucks and methods for treating interchange ramps that are prone to cause high center of gravity vehicles to lose control and overturn. The research involved several studies including:

- A state-of-the-practice review was conducted in 12 states to determine the nature and extent of the truck rollover accident problem, determine procedures for identifying problem ramps, and identify active and passive treatments currently being used at problem ramps.
- A “design-a-sign” study using 61 professional truck drivers was conducted to

attempt to identify critical ramp characteristics and to develop innovative procedures for effectively communicating this information to approaching drivers.

- A series of laboratory studies were conducted to identify specific sign elements and formats that most effectively warn truck drivers about potentially dangerous ramps.
- Field tests were conducted at interchange ramps in Virginia and Maryland that had experienced problems with truck rollover accidents. A truck tipping sign with activated flashing beacons was installed at the ramp and an advance warning sign was installed prior to the ramp.

The results of the research are summarized below:

- The sign formats that were best understood by truck drivers consisted of the rear silhouette of a tipping truck, a diagrammatic arrow, and an advisory speed indication.
- Truck drivers prefer the use of advance warning signs located well in advance of a ramp and the use of flashing lights or beacons to identify particularly hazardous locations.
- Truck drivers understood from the sign that they had to be more careful when they were hauling a top-heavy load than when they were hauling a regular load.
- In the first field test, the sign with the tipping truck produced a slight short-term reduction in truck ramp speeds at one of the two experimental sites. However, the effect dissipated within 3 months of the sign installation.
- In the second field study, the sign with the tipping truck and the flashing beacons (that were activated when the truck approached the ramp) combined with an advance warning sign approximately 457 m (1,500 ft) upstream from the ramp produced no statistically significant change in truck speeds. There was, however, a 6.4-km/h (4-mi/h) reduction in the 90th and 95th percentile speeds of top-heavy trucks, suggesting that the truck tipping sign with

flashers may have an effect on the most targeted group-high-speed, top-heavy trucks.

- In the third field test, the addition of flashing beacons to an existing tipping truck sign and an advance warning sign had no effect on the approach or ramp speeds of trucks.

Maryland and Virginia (44) reevaluated ramp speeds on the Capital Beltway to determine whether the posted speeds were appropriate for trucks. Virginia reduced speeds on 44 ramps and Maryland also reduced speeds on several ramps. California is evaluating turning roadways to determine the adequacy of speed signing for trucks.

An ITS application for improving safety on ramp curves is presented in Chapter Five. Retting et al. (49) evaluated the effect on traffic speeds of experimental pavement markings on freeway exit ramps. A special pavement marking pattern was employed that narrowed the lane width of both the ramp curve and a portion of the tangent section leading into the curve by use of a gradual inward taper of existing edgeline or exit gore pavement markings or both. Traffic speeds were analyzed before and after installation of the pavement markings at four experimental ramps in New York and Virginia. Results indicated that the markings were generally effective in reducing speeds of passenger vehicles and large trucks. The markings were associated with significant reductions in the percentages of passenger vehicles and large trucks exceeding posted exit-ramp advisory speeds.

The literature shows that truck rollover signs and other similar measures are potentially effective in reducing truck speeds, particularly those considered most likely to roll over. However, the safety effectiveness of such signing has not been demonstrated.

#### **RESTRICTION OF SIGN VISIBILITY BY HEAVY VEHICLES**

Heavy vehicles are generally large in size and may block the ability of other drivers to see highway signs. In the survey reported in Appendix B,

20 percent of highway agencies indicated that they had encountered safety problems related to the obstruction of sign visibility by trucks and buses.

A paper by Schorr (50) examined both the blockage of roadside signs when a passenger car is passing a truck and the blockage of overhead signs when a passenger car is following a truck. When a passenger car is passing a truck on the left, the passenger car driver's view of signs on the right side of the roadway is blocked for some distance. The most critical position for the passenger car driver is when the front of his car is even with the rear of the truck. In this position, the passenger car driver's view of roadside signs is blocked for 46 m (150 ft). Since roadside signs may be legible for more than 46 m (150 ft) and since the passing driver may have had an opportunity to see the same sign while following the truck before he began the passing maneuver, this situation is not critical (50).

Sign blockage for passenger car drivers does become critical, however, when two or more trucks are traveling together in the right lane. For example, if a second truck is traveling within 19 m (63 ft) in front of the first truck, the passing driver's view is blocked for 139 m (455 ft) from the rear of the first truck. If three trucks are traveling together in the right lane, roadside signs may be blocked for as much as 320 m (1,050 ft) (50).

The potential for obstruction of the view of passing drivers to roadside signs cannot be remedied through changes in the criteria for horizontal and vertical placement of signs, but may require that critical signs be supplemented with overhead signs or with signs placed on the left side of the roadway.

The passenger car driver's view of overhead signs may also be blocked when closely following a truck. When following a truck by five car lengths [29 m (95 ft)], a passenger car driver does not have a full view of an overhead sign mounted with 4.9 m (16 ft) of vertical clearance until the car is within 43 m (140 ft) of the sign. At a speed of 80 km/h (50 mi/h), an overhead sign would be visible to the passenger car driver for only 1.9 s. This situation can be remedied by mounting overhead signs higher or by providing supplementary roadside signs (50).

The Appendix B survey indicated that highway agencies had taken the following actions to improve sign visibility:

- Placing regulatory signs on both sides of the roadway on freeways
- Using double stop signs or placing stop signs on both sides of the road
- Using overhead signs
- Placing an additional traffic signal head over the opposing through lane
- Additional use of advance warning signs

Ullman and Dudek (51) recently developed mathematical models to evaluate the effect of roadway geometrics and large trucks on variable message sign readability.

Al-Kaisy and Bhatt (52) developed a simulation approach to study the occlusion of ground-mounted traffic signs by heavy vehicles on multilane highways. This study is part of a more extensive research effort to examine the different factors that determine the effect of heavy vehicles on the visibility of traffic signs. The model simulates roadway geometry and traffic signs as well as the movement and location of passenger cars and trucks on the facility upstream of the subject traffic sign. The model also accounts for other traffic conditions such as traffic volumes, percentage of trucks, lane utilization, and average speeds of passenger cars and trucks. The occlusion of ground-mounted traffic signs by heavy vehicles was estimated by two measures:

- the probability of a traffic sign being occluded by heavy vehicles under certain traffic and geometric conditions
- the likelihood of a passenger car driver missing the sign based on the minimum time required for the driver to detect, recognize, and read the message.

There are no available studies that quantify the extent to which sign blockage by heavy vehicles creates safety problems for other vehicles.

## **SIGNAL TIMING TO ACCOMMODATE HEAVY VEHICLES**

The *Manual on Uniform Traffic Control Devices* (MUTCD) (22) specifies an interval 3 to 6 s for the yellow vehicle change interval at traffic signals. The yellow signal display may be followed with an all-red clearance interval and such clearance intervals are frequently used at intersections with substantial truck volumes.

Since implementation of the North American Free Trade Agreement (NAFTA), some highways in the border areas of Texas have experienced an increase in truck traffic. The higher truck volumes have resulted in increased pavement damage and traffic delay at rural, high-speed signalized intersections. A decrease in safety has also been observed at these intersections due to truck braking limitations. Research by Sunkari et al. (53) developed a system to reduce the number of stops made by trucks at high-speed signalized intersections. The system incorporated truck priority logic and used loop detectors and a classifier to identify trucks approaching the intersection. The system was implemented at an intersection in Sullivan City, Texas, and was effective in reducing the number of stopping maneuvers made by trucks at the intersection. However, no evaluation was conducted to determine the effect of this system on safety.

## **SAFETY IMPROVEMENTS FOR NIGHT DRIVING**

Two respondents to the trucking industry survey reported in Appendix C noted the need to provide lane lines that are more visible at night and in adverse weather. FHWA is currently considering guidelines for increasing the retroreflectivity of lane lines and other pavement markings. Other respondents to the industry survey noted the need for more rest areas and pulloffs, the need to improve lighting and enforcement at rest areas, and the need for more enforcement of failure to dim headlight beams at night.

The highway agency survey reported in Appendix B noted only one potential safety issue related to truck and bus travel at night. This issue is the need to improve low visibility of border stations at night; only a limited number of states operate agricultural inspection stations of this type on high-speed highways near state borders.

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## ITS INITIATIVES FOR IMPROVING SAFETY IN HIGHWAY/HEAVY VEHICLE INTERACTIONS

This chapter addresses ITS programs intended to improve the safety of heavy trucks and buses. The largest ITS program directly related to commercial trucks is the Commercial Vehicle Operations (CVO) program. However, because this program is intended primarily to improve the operational efficiency of commercial vehicle operators and agencies, only a brief overview of the program is presented first. The types of ITS programs that are discussed in greatest detail in this chapter concern speed management technologies. Several ITS systems have been deployed at locations of steep downgrades and/or sharp horizontal curves to reduce the speeds of trucks. Other types of programs that are addressed include advanced technologies to improve the traffic flow along the mainline facility near inspection (weigh) stations and collision avoidance systems designed to improve bus safety.

### ITS COMMERCIAL VEHICLE OPERATIONS (CVO) PROGRAM

The purpose of the ITS/CVO program is to define, pilot test, and deploy technologies, information systems, and networks to enhance roadway safety, credentialing, and operations (54). ITS/CVO applications fall into four areas:

**Safety Information Exchange:** Improve targeting of high-risk operators by providing inspectors better access to current safety information; automate safety inspection activities; and support deployment of in-vehicle technologies designed to improve safety.

**Electronic Credentialing:** Automate administration functions and enhance data communications capabilities of state and administrative agencies to enable paperless transactions between motor carriers and regulatory agencies.

**Electronic Screening:** Screen commercial vehicles at fixed weigh stations, ports of entry, and mobile inspection sites for safety, size/weight, and credential compliance at mainline speeds.

**Motor Carrier Operations:** Improve motor carrier safety and efficiency by providing timely, accurate information to fleet managers and accelerate development and deployment of emerging technologies.

The ITS/CVO services focus on enabling seamless information exchange between motor carriers, regulators, and safety enforcement agencies. Thus, the ITS/CVO program allows enforcement agencies to focus their resources on unsafe motor carriers and provides motor carriers access to current information that can be used to improve fleet operations and safety.

In 1998, the FMCSA conducted research to examine information and technology use by motor carriers and help guide the development of effective ITS/CVO services. The study found:

- 53 percent of surveyed carriers used computer-aided routing and dispatching systems (CAD)
- 41 percent of surveyed carriers used electronic data interchange (EDI) technology
- 72 percent of surveyed carriers used mobile communication technologies
- 10 percent of surveyed carriers used on-board computers (OBC)

In addition, the study concluded that the characteristics of individual motor carriers (size of fleet, type of haul, routing variability, etc.) and their primary operational objectives (on-time performance, safety assurance, cost avoidance, etc.) directly impact a carrier's choice of

technologies and perceived value of ITS/CVO services.

### **WARNING SYSTEMS FOR LONG DOWNGRADES**

The primary objective of warning systems for long downgrades is to warn specific truck drivers that their speed is above a recommended safe descent speed for the geometric conditions and that they should reduce their speed in order to lower their potential for losing control of the vehicle on the downgrade. For many years, highway agencies have used fixed signing to advise truckers on the appropriate speed or gear for descending particular grades. The highway agency survey reported in Appendix B found that 74 percent of highway agencies have used downgrade signing to promote proper speed and gear selection. Several ITS systems have now been installed across the country to provide real-time information to heavy vehicle drivers about to descend a grade. Over 78 percent of respondents to the industry survey reported in Appendix C indicated that such systems are desirable or highly desirable.

#### **Colorado**

In 1997, the Colorado DOT installed a Downhill Truck Speed Warning System (DTSWS) inside the Eisenhower Tunnel in the westbound lanes of I-70 to reduce the number of truck-related crashes that occur on the long downgrade that follows this tunnel (55). The downgrade is about 16 km (10 mi) in length with grades between 5 and 7 percent. This stretch of highway carries a significant volume of truck traffic. In 1998 and 1999, average monthly counts of heavy trucks were approximately 30,000, or 1,000 trucks per day. From 1990 to 1996, 106 truck-related crashes occurred along this 16-km (10-mi) downgrade. Two runaway truck ramps are located on the downgrade within 3.2 km (2 mi) of the tunnel, and over a 5-year period from 1995 to 1999 the truck escape ramps were used 106 times, approximately twice per month.

The DTSWS consists of loop detectors, weigh-in-motion (WIM) devices, and a variable message

sign (VMS). The DTSWS calculates a safe descent speed, based upon the truck's axle configuration and gross vehicle weight and the grade profile of the highway, and displays the advisory speed for each passing truck of greater than 18,200 kg (40,000 lb). The VMS that displays the advised descent speed is located approximately 76 m (250 ft) beyond the loop detectors and WIM strips. The system is located inside the Eisenhower tunnel so that drivers receive the message before reaching the downgrade.

In 1999 an evaluation of the DTSWS was conducted to determine the effectiveness of the system. Because the DTSWS had not been operating for a long enough time to assess whether it had significantly reduced truck-related crashes, the primary objective of the evaluation was to compare speeds of trucks descending the grade after exiting the tunnel with the DTSWS either on or off. Data for the evaluation were collected over a 4-day period, 2 days with the DTSWS display on and 2 days with the DTSWS display off. Data were collected for 2 hours on each day so a total of 8 hours of data were collected. In addition, a survey was distributed to truck drivers at a weigh station located near the downgrade to assess their awareness of the speed warning system and rate its potential effectiveness.

Overall, the DTSWS appeared to significantly reduce truck descent speeds for most weight ranges above 18,200 kg (40,000 lb). A recommendation was made to revise the advised speeds and their corresponding weight ranges, indicating that the advised speeds should be within ranges that many drivers are willing to accept as good advice. Thus, reducing the risk of providing advisor speeds that are too low and which many drivers will simply ignore as being unrealistic. The truck drivers surveyed also responded positively to the DTSWS and its potential to improve safety along the downgrade.

#### **Oregon**

Due to a high number of truck-related crashes on Interstate 84 at Emigrant Pass, the Oregon DOT installed a Downhill Speed Information System



(DSIS) warning system at the location as part of its ITS/CVO “Green Light” Project (56). Emigrant Pass has a 6 percent downgrade for 10 km (6.2 mi) with sharp curves. Between 1993 and 1996, a total of 40 truck-related crashes occurred Emigrant Hill, resulting in 3 fatalities and 28 injuries. The DSIS hardware and software was installed in 2000, but the system did not become operational until 2002. Prior to considering installation of the DSIS, Oregon DOT implemented runaway truck ramps and static truck advisory signs at the pass location.

The DSIS consists of high-speed, WIM scales in the roadway and automatic vehicle identification (AVI) devices that recognize in-truck “Green Light” transponder signals. The “Green Light” project is primarily a truck weigh station “preclearance” system. In less than 1 second, a computer measures the weight of a truck, reads the “Green Light” transponder signal (if the truck is equipped), and sends a customized message to a roadside VMS advising the driver of a safe range of speed for that truck to descend the hill. Properly weighed, transponder-equipped trucks receive a personalized advisory message on the VMS addressed to the driver by name (e.g., “Tate” in the following example) such as:

TRUCK ADVISORY  
TATE  
18 MPH DOWNHILL

Improperly weighed, transponder-equipped trucks receive a general message, such as:

TRUCK ADVISORY  
TATE  
STEEP DOWNGRADE

Trucks that are not equipped with a “Green Light” transponder do not receive a message. Figure 14 shows the roadside VMS at Emigrant Pass displaying an advisory message.

Oregon DOT is planning to conduct an evaluation of the system, including an analysis of crash data, escape ramp incidents, and speed data.

#### West Virginia

In 1998 West Virginia Division of Highways installed a downhill truck warning system at the top of a long, steep downgrade on Interstate 64 at Sandstone Mountain (56). Prior to the installation of the system, a large number of runaway truck incidents occurred on the downgrade, resulting in



Figure 14. Oregon’s downhill speed information system (57).

incidents occurred on the downgrade, resulting in runaway ramp uses or serious crashes. Incidents were occurring several times a month.

The system, deployed at the top of the mountain, consists of two VMSs, driven by a computer that obtains weight and classification data from loops and piezo sensors in each lane. Every vehicle is weighed and classified. The system utilizes a table, based upon the Grade Severity Rating System, to determine a recommended speed choice, and the advisory speed message is displayed on the VMS. The message is updated for every vehicle passage.

### DYNAMIC CURVE WARNING SYSTEMS

Truck rollover crashes occur frequently along the U.S. highway system and often result in serious injuries. In 1998, 207 trucks were involved in fatal rollover crashes, and approximately 10,580 commercial trucks were involved in nonfatal rollover crashes (58). Truck rollover crashes typically occur at freeway exit ramps with tight curves that require a reduced speed compared to the normal travel speed on the freeway and on sharp curves following steep downgrades.

To help mitigate the occurrence of rollover crashes, intelligent rollover warning systems have been installed at several problem locations. The effectiveness (48) and feasibility of deploying such systems was examined by FHWA in the early 1990s (59). Intelligent rollover warning systems are designed to calculate the rollover potential of vehicles and direct warning messages to specific drivers if necessary. Directed messages are conveyed to drivers via VMSs or flashing lights only when potential rollovers are detected. In this manner, dynamic curve warning systems alert only those drivers with a high probability of entering into a rollover situation. The most basic systems typically incorporate one vehicle parameter such as speed or vehicle height, while the more sophisticated systems can incorporate several vehicle parameters such as speed, weight, live load, nonlive load, vehicle height, and vehicle configuration for calculating the rollover potential of a vehicle.

### California

The California DOT (Caltrans) installed five speed-based curve warning systems along I-5 near the Sacramento River Canyon in Shasta County (60). The five sites include:

1. Sidehill Viaduct—Postmile 30.00 (SB)
2. O'Brien—Postmile 32.30 (SB)
3. Salt Creek—Postmile 37.53 (SB)
4. La Moine—Postmile 49.23 (SB)
5. Sims Road—Postmile 57.90 (NB)

The components of the systems at each site include: a VMS, a radar speed-measuring device, and control/communication equipment. Specific messages and graphics can be displayed on each VMS every 3 to 4 seconds. Some of the standard messages displayed on the VMSs are shown in Figure 15.

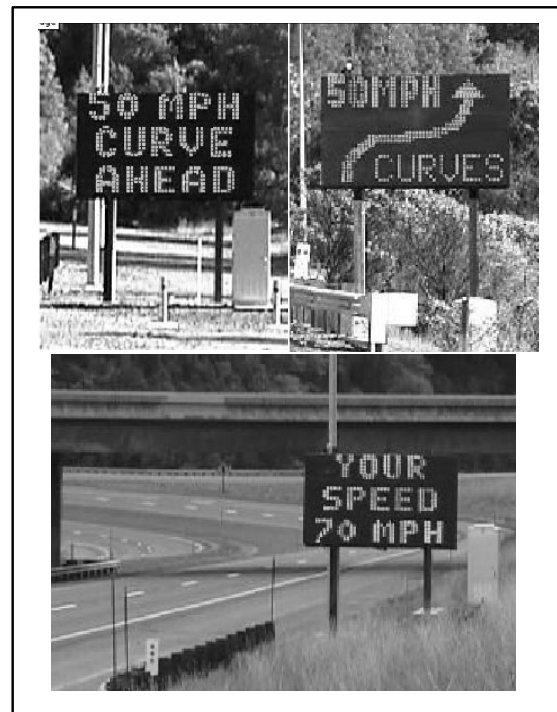


Figure 15. Several standard messages for dynamic curve warning systems in California (60).

An evaluation of the effectiveness of this speed-based curve warning system was conducted. The evaluation consisted primarily of a comparison of speed data gathered before and after installation of the warning system. Speed data were collected 9

months prior to the system's installation and again 2 months, 5 months, and 10 months after operation began. Crash data were also gathered, and surveys were distributed to truck drivers and passenger car drivers approximately 2 months and 10 months after installation.

Preliminary results indicate reductions in both operating speeds and crashes. At three of the five installation sites, reductions in truck operating speeds were observed during at least one of the three data collection periods after the warning system began operation. At two sites, each with downgrades greater than 5 percent, significant reductions in truck speeds were observed during all three periods after installation. It was also noted that speed reductions were smaller for the later time periods, possibly indicating that drivers were becoming less sensitive to the system. Due to a lack of crash data, a meaningful before-after crash analysis was not performed, but preliminary analysis showed a reduction in truck-related crashes. Survey results indicated approximately 72 percent of truck drivers thought the system was useful, and approximately 81 percent of passenger car drivers thought the system was useful.

Prior to installing and evaluating the curve warning system in the Sacramento River Valley, Caltrans installed a speed-based warning system on a freeway-to-freeway connector ramp located at postmile 14.74 (SB) on I-5 in San Joaquin County (61). The ramp is on a downgrade leading to a short radius curve. The components of the system included:

- Inductive loop, piezoelectric sensor, and inductive loop combination (detector system)
- Control/communication equipment
- Static warning sign with two flashing yellow beacons

A before and after crash analysis revealed that in the 6.3 years prior to installation of the system, six truck rollover crashes occurred on the ramp. During the first 2 years after installation of the system, zero truck rollover crashes occurred. Installation of the system did produce a reduction in truck rollover

crashes, but the number of crashes was too few for the difference to be statistically significant. Since no truck rollover crashes occurred in the after period, it was concluded that some of the safety improvement at the site could be attributed to the curve warning system.

## Texas

The Texas DOT evaluated the effectiveness of a speed-based truck warning system installed on a freeway-to-freeway loop ramp located in Houston, Texas (62). The system used three infrared light-beam sensors with a special microcontroller-based signal processor to determine a vehicle's speed, height, and length. When a vehicle exceeded its maximum safe speed, a static warning sign with flashing yellow beacons was activated.

A before and after speed-change study was conducted to measure the effectiveness of the system in effecting a speed reduction of trucks thought to be potential danger on the loop ramp. The study revealed that violating trucks in the higher initial speed range, 100 to 113 km/h (62 to 70 mi/h), reduced speed more than those in the lower speed range, 90 to 100 km/h (56 to 62 mi/h), under both the "before" and "after" operating conditions. In addition, the additional average speed reduction for all violating trucks attributed to the effect of the flashers being activated was 3 km/h (2 mi/h).

## Missouri

The Missouri DOT installed a curve warning system at a location with a sharp curve after a history of rollover accidents at the site (56). Traffic studies indicated that the problem was due to excessive speeds of trucks, which caused loads to shift. Static signs in the area were not effective in solving the problem.

Components of the system include: two signs, two flashers, and one narrow band microwave height detector. The system activates wigwag flashers mounted above truck rollover warning signs only when tall vehicles encroach the microwave

beam from a single direction. The system has performed satisfactorily, but no formal evaluation on its effectiveness has been conducted. A photograph of the system is shown in Figure 16.

### Virginia and Maryland

A curve warning system, which incorporates multiple vehicle parameters to assess the potential for vehicle rollover, was designed and installed at three ramps on the Capital Beltway (I-495) in Virginia and Maryland (63). The installations are located at:

1. I-495W/I-95S in Springfield, Virginia
2. I-495W/Route 123N in McLean, Virginia
3. I-495E/I-95N in Beltsville, Maryland

This system calculates a vehicle rollover threshold speed based upon a truck's weight, rollover threshold factor, and the geometrics of the ramp (radius and superelevation of curve). The components of the system include:

- Weigh-in-motion (WIM) detectors

- Loop magnetic detectors (speed detectors)
- Radar sensing height detectors
- Warning signs
- Controller/communication equipment

Figure 17 shows the typical placement of the components for both one-lane and two-lane ramps.

An evaluation of the system was performed looking at both speed and crash data. In analyzing the speed data, the average speed at WIM Station 2 was compared to the average speed reduction from WIM Station 2 to WIM Station 3. This analysis revealed all three installations caused truck drivers to reduce their speeds exceeding the maximum safe speed for the ramp. On average there was a 25 percent speed reduction from WIM Station 2 to WIM Station 3 when the VMS was activated at all three sites. The before and after crash evaluation showed 10 reported truck rollover-type crashes in the before period across all sites and 0 truck rollover-type crashes in the 3-year after period.



Figure 16. Missouri curve warning system (56).

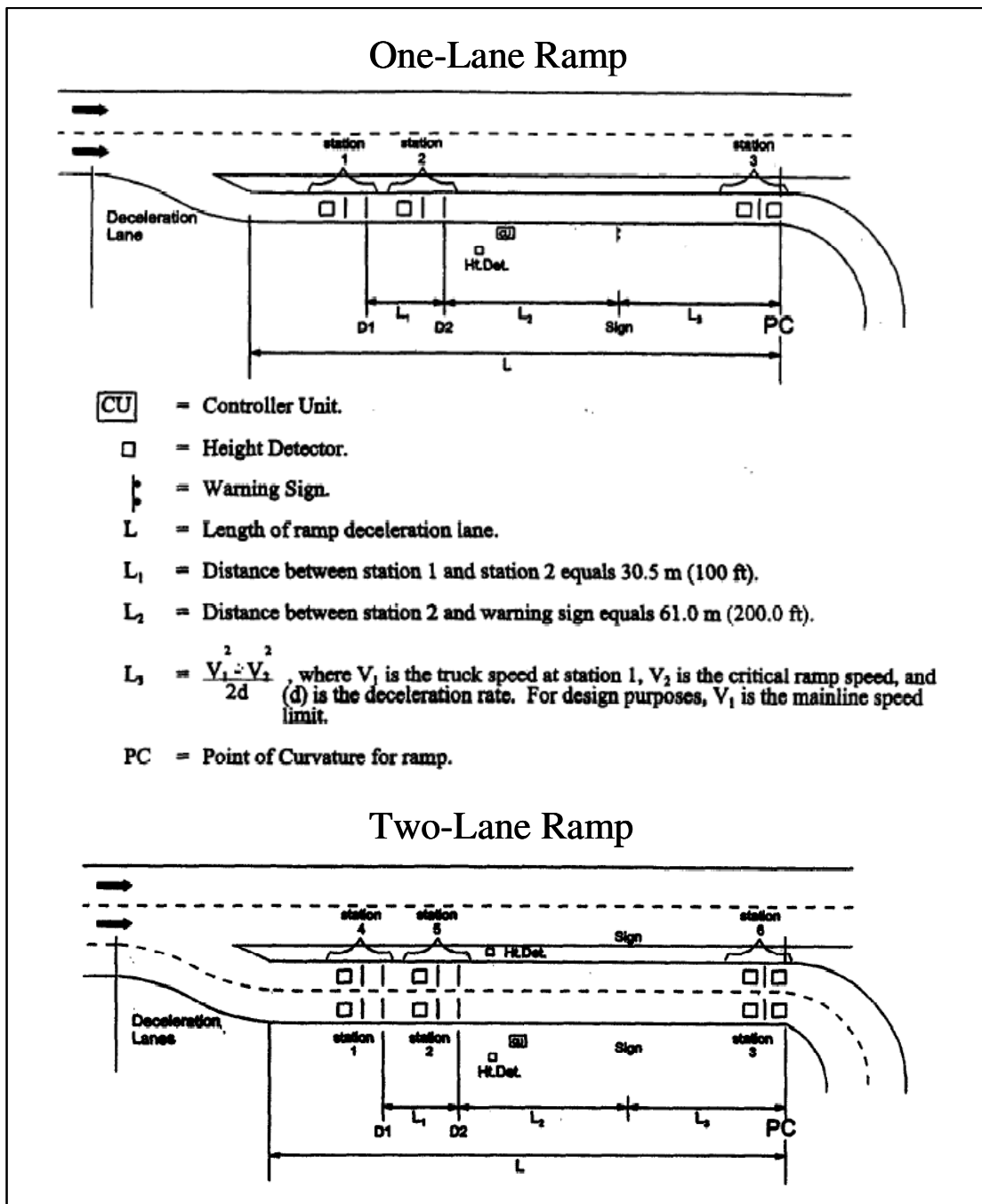


Figure 17. Typical placement of system components (63).

#### Pennsylvania

The Pennsylvania DOT has installed a system similar to that on the Capital Beltway at two ramp locations and has observed positive short-term results (58).

#### Comparison of Systems

Baker et al. (58) investigated the different types of dynamic curve warning systems that have been deployed by highway agencies across the U.S. In particular, Baker et al. compared the number of

false messages generated by speed-based curve warning systems to the number of false readings generated by speed/weight-based warning systems. The rationale for comparing false readings was to maximize the effectiveness of curve warning systems, the warning must be targeted to specific drivers. If the system is activated repeatedly when there is no actual danger, this type of system might become increasingly ignored by drivers over the long term. This could pose a problem for vehicles that are truly at risk and need to be warned of their situation.

Figure 18 conceptually compares the rollover warning thresholds obtained from both speed-based and speed/weight-based rollover warning systems. Case studies revealed that there is an added advantage of incorporating weight in addition to speed and classification when warning trucks of potential rollover. It was that speed-based rollover warning systems generated

approximately 44 to 49 percent more false warnings compared to systems that incorporate vehicle weight into the rollover decision criteria. In the long run, accurate system performance will ensure truck drivers will continually respond to the messages displayed by dynamic curve warning systems.

### WEIGH STATIONS

Inspections of commercial vehicles at weigh stations are conducted to verify motor carrier compliance with safety, size and weight, and credential regulations. These regulations are in place to protect public investment in roadway infrastructure and to improve traffic safety (64). However, the diverging and merging of trucks as they enter and exit weigh stations can interrupt the flow of traffic on mainline facilities, particularly when weigh stations become congested and queues

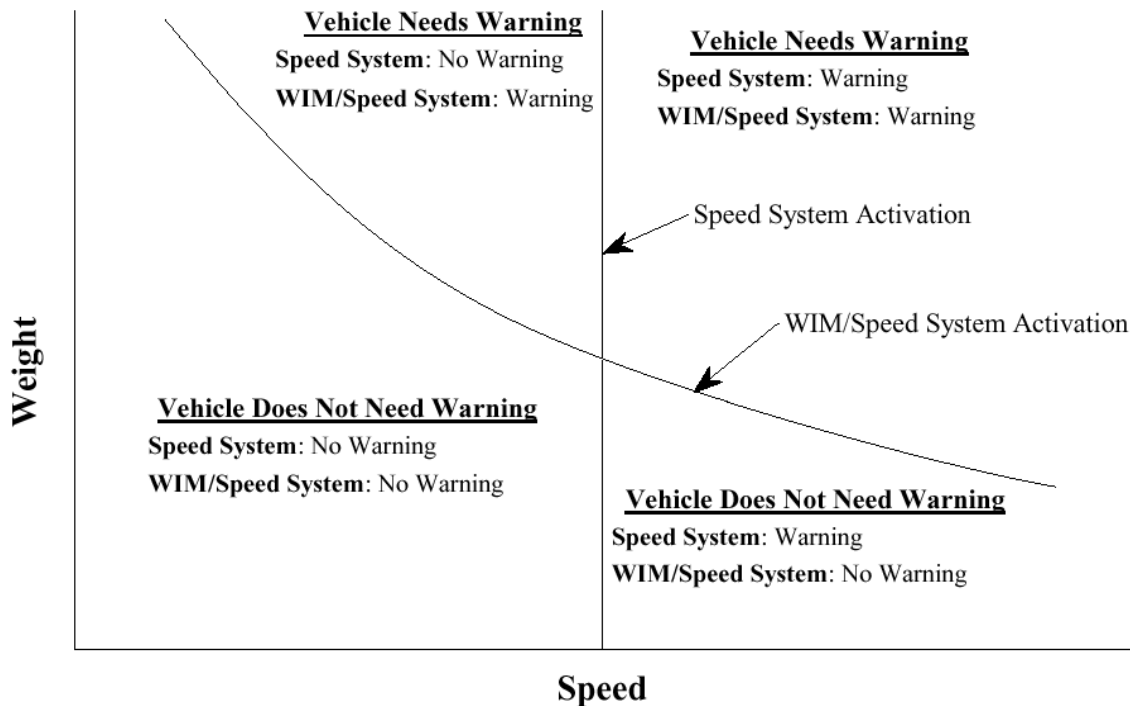


Figure 18. Comparison between speed-based and speed/weight-based rollover systems (58).

of trucks overflow from the inspection facilities onto the freeways. Electronic screening of vehicles approaching a weigh station is increasingly being used to focus inspection activities on those vehicles most likely to be in violation of applicable regulations.

One of the potential benefits of electronic screening of commercial vehicles is improved traffic flow near weigh stations. Two studies have been conducted to evaluate the impact that electronic screening technologies have on safety near weigh stations. Utilizing microscopic simulation, Saka and Glassco (65) modeled various traffic patterns for baseline (pre-electronic screening) and post-ITS situations (with electronic screening technology). Saka and Glassco analyzed the safety effectiveness of electronic screening technology based upon percent reductions in sudden deceleration of vehicles from shockwave phenomena and percent reduction in duration of truck-queue overflow resulting from a high traffic intensity. Simulation results supported the hypothesis that the use of electronic screening technologies at weigh station facilities significantly reduces the frequency of high-risk traffic phenomena (e.g., hard braking and truck-queue overflow), translating into a reduction in the likelihood of incidents in the vicinity of weigh station facilities. The stochastic nature of crashes made it difficult to quantify the percent reduction in the expected crash frequency from the use of electronic screening technologies.

Benekohal et al. (64) evaluated the effectiveness of electronic screening for interstate application by collecting speed, volume, and conflict data at several sites at a weigh station in Illinois. Benekohal et al. developed the following model to predict the number of merging conflicts near a weigh station:

$$\text{No. of Merge Conflicts} = 0.001776 \times [T_{en} \times (C_r + C_c) + 0.00000169 \times T_{en} \times C_r \times C_c] \quad (9)$$

where:  $T_{en}$  = truck volume on the entrance ramp  
 $C_r$  = car volume on the outside (right) lane  
 $C_c$  = car volume on the center lane.

The model shows that a significant number of conflicts will occur during low volume conditions, but it also shows that electronic screening, by reducing the truck volume on the entrance ramp, will reduce traffic conflicts and improve safety near weigh stations.

### COLLISION AVOIDANCE WARNING SYSTEMS

The Port Authority of Allegheny County is conducting a major field test of collision avoidance warning systems in Pittsburgh, Pennsylvania (66). The testing involves a side collision avoidance system that has been installed on 100 buses. Each bus is fitted with a dozen sensors that are spaced about 1.8 m (6 ft) apart and mounted between 0.8 and 1.3 m (2.5 and 4.2 ft) above the road surface. The sensors emit sonar signals that reflect off objects near the bus. An on-board computer measures the time it takes an emitted sound wave to return after bouncing off a hard object. The system can detect stationary roadside objects at least 0.3 m (1 ft) in diameter when the bus is moving and can detect a passenger car while both the bus and car are in motion. The system alerts the operator through visual indicators when an object is detected.

In a similar project, the San Mateo County Transit District in San Carlos, California is testing a frontal collision warning system (FCWS). Two buses were equipped with FCWS sensors that included radar systems, ultrasonic sensors, and laser range finders. These systems are designed to enhance transit operations through accident reductions.

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