

Stopping Sight Distance Design for Large Trucks

DOUGLAS W. HARWOOD, WILLIAM D. GLAUZ, AND JOHN M. MASON, JR.

Stopping distance requirements for large trucks are compared with current AASHTO stopping sight distance criteria. Key elements affecting stopping sight distance for trucks include perception-reaction time, truck braking distance, and truck driver eye height. The paper stresses the variability of truck driver braking performance and the safety benefits associated with antilock brake systems for trucks. Findings indicate that trucks with conventional brake systems may require stopping sight distances greater than those recommended by current AASHTO policy. The increased values potentially affect all related stopping sight distance design considerations (horizontal and vertical curvature, intersection sight distance, and highway-railroad grade crossings). The magnitude of increase, however, is highly dependent on individual driver brake performance capabilities. For drivers whose emergency braking performance is equivalent to the worst performance observed in braking tests for conventional brake systems, substantially greater stopping sight distance and longer vertical curves would be needed than are used under current AASHTO criteria. Drivers with braking performance equivalent to the best performance observed in braking tests for conventional brake systems require only slightly longer stopping sight distance than current AASHTO criteria and require vertical curve lengths that are shorter than current AASHTO criteria. If antilock brake systems are eventually mandated for trucks, current AASHTO stopping sight distance policy would adequately accommodate the needs of large trucks.

Sight distance is the length of roadway ahead that is visible to the driver. The minimum sight distance available on the roadway should be sufficiently long to enable a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path. This minimum sight distance, known as stopping sight distance, is the basis for design criteria for crest vertical curve length and minimum offsets to horizontal sight obstructions. Not only is the provision of stopping sight distance critical at every point on the roadway, but stopping sight distance also forms the basis for a number of additional highway design and operational criteria, including intersection sight distance, railroad-highway grade crossing sight distance, and warning sign placement.

This paper examines the suitability of current stopping sight distance design criteria for large trucks in light of available data concerning truck characteristics, including braking distance and driver eye height. The paper uses the current AASHTO Green Book (1) stopping sight distance model as

the basis for determining truck requirements. Nevertheless, the authors recognize that this model is itself in need of a thorough review to determine whether it meets the sight distance needs of drivers.

CURRENT DESIGN CRITERIA

This section summarizes the current AASHTO design criteria for stopping sight distance.

Stopping Sight Distance Criteria

Stopping sight distance is determined in the AASHTO Green Book (1) as the sum of two terms: brake reaction distance and braking distance. The brake reaction distance is the distance traveled by the vehicle from the driver's first sighting of an object necessitating a stop to the instant the brakes are applied. The braking distance is the distance required to bring the vehicle to a stop once the brakes are applied.

The numerical values for the stopping sight distance criteria in the AASHTO Green Book are based on the following equation:

$$S = 1.47 t_{pr} V + \frac{V^2}{30f} \quad (1)$$

where

- S = stopping sight distance (ft),
- t_{pr} = perception-reaction time (sec),
- V = initial vehicle speed (mph), and
- f = coefficient of tire-pavement friction.

The first portion of Equation 1 represents the brake reaction distance, and the second term represents the braking distance. The factors that influence braking distances are discussed later in this paper. The coefficient of sliding friction is used by AASHTO in Equation 1 to determine the braking distance for a locked-wheel stop by a passenger car.

Table 1 presents the AASHTO Green Book criteria for stopping sight distance. These criteria are based on an assumed perception-reaction time (t_{pr}) of 2.5 sec and the assumed values of speed and coefficient of friction shown in the table. The two values shown for the assumed speed, brake reaction distance, braking distance on level, and stopping sight distance represent minimum and desirable designs, respectively. The subsequent analyses in this report are based on the desirable sight distances, which are applicable to stopping by a vehicle traveling at the design speed of the highway.

D. W. Harwood and W. D. Glauz, Midwest Research Institute, 425 Volker Blvd., Kansas City, Mo. 64110. J. M. Mason, The Pennsylvania State University, University Park, Pa. 16820.

TABLE 1 AASHTO CRITERIA FOR STOPPING SIGHT DISTANCE (1)

Design Speed (mph)	Assumed Speed for Condition (mph)	Brake Reaction		Coefficient of Friction <i>f</i>	Braking Distance on Level (ft)	Stopping Sight Distance	
		Time (sec)	Distance (ft)			Computed (ft)	Rounded for Design (ft)
20	20-20	2.5	73.3- 73.3	0.40	33.3- 33.3	106.7-106.7	125-125
25	24-25	2.5	88.0- 91.7	0.38	50.5- 54.8	138.5-146.5	150-150
30	28-30	2.5	102.7-110.0	0.35	74.7- 85.7	177.3-195.7	200-200
35	32-35	2.5	117.3-128.3	0.34	100.4-120.1	217.7-248.4	225-250
40	36-40	2.5	132.0-146.7	0.32	135.0-166.7	267.0-313.3	275-325
45	40-45	2.5	146.7-165.0	0.31	172.0-217.7	318.7-382.7	325-400
50	44-50	2.5	161.3-183.3	0.30	215.1-277.8	376.4-461.1	400-475
55	48-55	2.5	176.0-201.7	0.30	256.0-336.1	432.0-537.8	450-550
60	52-60	2.5	190.7-220.0	0.29	310.8-413.8	501.5-633.8	525-650
65	55-65	2.5	201.7-238.3	0.29	347.7-485.6	549.4-724.0	550-725
70	58-70	2.5	212.7-256.7	0.28	400.5-583.3	613.1-840.0	625-850

TABLE 2 CORRECTION TO AASHTO STOPPING SIGHT DISTANCE FOR GRADES (1)

Increase for Downgrades				Decrease for Upgrades			
Design Speed (mph)	Correction in Stopping Distance (ft)			Assumed Speed for Condition (mph)	Correction in Stopping Distance (ft)		
	3%	6%	9%		3%	6%	9%
30	10	20	30	28	—	10	20
40	20	40	70	36	10	20	30
50	30	70	—	44	20	30	—
60	50	110	—	52	30	50	—
65	60	130	—	55	30	60	—
70	70	160	—	58	40	70	—

Correction of Stopping Sight Distance Criteria for Grades

Stopping sight distance is also affected by roadway grade because longer braking distance is required on a downgrade and a shorter braking distance is required on an upgrade. The AASHTO Green Book accounts for grade effects on stopping sight distance with the following equation:

$$S = 1.47 t_{pr} V + \frac{V^2}{30(f + G)} \quad (2)$$

where *G* equals percent grade/100 (+ for upgrade, - for downgrade). Table 2 presents the corrections to the stopping sight distance criteria for upgrades and downgrades recommended in the AASHTO Green Book.

Application of Stopping Sight Distance Criteria to Crest Vertical Curves

Vertical crests limit the sight distance of the driver. Crest vertical curves designed in accordance with the AASHTO

criteria should provide stopping sight distance at least equal to the requirements of Table 1 at all points along the curve. The minimum length of a crest vertical curve, as a function of stopping sight distance (*S*), is calculated by AASHTO as follows:

For *S* less than L_{min} ,

$$L_{min} = \frac{AS^2}{100(\sqrt{2H_e} + \sqrt{2H_o})^2} \quad (3)$$

For *S* greater than L_{min} ,

$$L_{min} + 2S - \frac{200(\sqrt{H_e} + \sqrt{H_o})^2}{A} \quad (4)$$

where

L_{min} = minimum length of vertical curve (ft),

S = stopping sight distance (ft),

A = algebraic difference in percent grade,

H_e = height of driver's eye above roadway surface (ft), and

H_o = height of object above roadway surface (ft).

TABLE 3 MINIMUM VERTICAL CURVE LENGTHS (IN FEET) NEEDED TO PROVIDE AASHTO STOPPING SIGHT DISTANCE

Algebraic Difference in Percent Grade	Design Speed (mph)					
	20	30	40	50	60	70
2	60	90	150	260	610	1,070
4	60	120	300	650	1,220	2,130
6	60	170	450	970	1,820	3,190
8	70	240	600	1,280	2,420	4,260
10	90	290	740	1,610	3,030	5,320

Note: Based on AASHTO driver eye height of 42 in for a passenger car.

Equations 3 and 4 are based on the geometric properties of a parabolic curve. The AASHTO Green Book also suggests that it is typical practice to use a minimum vertical curve length that is at least three times the value of the design speed (expressed in mph). For stopping sight distance, the driver eye height (H_e) used by AASHTO is 3.5 ft, and the object height (H_o) used is 6 in. Table 3 presents the minimum vertical curve lengths required to attain the desirable stopping sight distance criteria in Table 1 as a function of design speed.

Application of Stopping Sight Distance Criteria to Horizontal Curves

Sight distance can also be limited by obstructions on the inside of horizontal curves, such as trees, buildings, retaining walls, and embankments. Horizontal curves designed in accordance with the AASHTO Green Book would provide sight distance at least equal to the requirements of Table 1 along the entire length of the curve. For a circular horizontal curve, the line of sight is a chord of that curve, and the sight distance is measured along the centerline of the inside lane. The minimum offset to a horizontal sight obstruction at the center of the curve (known as the middle ordinate of the curve) is computed in accordance with the following equation:

$$M = R \left(1 - \cos \frac{28.65 S}{R} \right) \quad (5)$$

where

M = middle ordinate of curve (ft),
 R = radius of curve (ft), and
 S = stopping sight distance (ft).

CRITIQUE OF CURRENT DESIGN CRITERIA

This section reviews the recent literature relevant to stopping sight distance criteria and its application to crest vertical curves and horizontal curves. These criteria are based on consideration of a passenger car as the design vehicle. The critique calls attention to differences between passenger cars and trucks that are relevant to stopping sight distance design.

Table 4, prepared by Glennon (2), summarizes the historical evolution of the AASHTO stopping sight distance criteria. The Glennon summary addresses the following aspects of stopping sight distance criteria:

- Assumed speed for design,
- Brake reaction time,
- Coefficient of tire-pavement friction,
- Eye height, and
- Object height.

Each of these factors is discussed below.

Assumed Speed for Design

The assumed speed for stopping sight distance design has historically been less than the design speed of the highway, because it was assumed that drivers travel more slowly on wet pavements than on dry pavements. This assumption was used to derive the lower value of stopping sight distance in Table 1. AASHTO notes that recent data have shown that drivers travel about as fast on wet pavements as they do on dry pavements. Therefore, the higher values of stopping sight distance in Table 1 are based on braking by a vehicle traveling at the design speed of the highway. All analyses of stopping sight distance in this paper have been conducted with the assumption that the braking vehicle—passenger car or truck—is initially traveling at the design speed of the highway.

Brake Reaction Time

The AASHTO criteria for stopping sight distance are based on a brake reaction time of 2.5 sec. This choice for brake reaction time has been confirmed as appropriate for most drivers by a number of studies, including, most recently, Johansson and Rumar (7) and Olson et al. (8).

The brake reaction time is a driver characteristic and is assumed to be applicable to truck drivers as well as passenger car drivers, although experienced professional truck drivers could reasonably be expected to have shorter brake reaction times than the driver population as a whole. Nevertheless, the air brake systems commonly used in tractor-trailer combination trucks have an inherent delay of approximately 0.5 sec in brake application (9). For purposes of this analysis, it is assumed that these factors offset one another and that the 2.5-sec brake reaction time is appropriate for trucks.

Coefficient of Tire-Pavement Friction

The coefficients of friction shown in Table 1 were chosen from the results of several studies cited in Figure III-1 of the AASHTO Green Book, and they are intended to represent the deceleration rates used by a passenger car in locked-wheel braking on a poor, wet pavement. The results cited by AASHTO that most closely match the criteria in Table 1 are from a 1951 study by Moyer and Shupe (10) and are based on locked-wheel skid test results obtained for new passenger car tires.

An exceedingly important feature of truck stopping distance is that trucks cannot safely make a locked-wheel stop without the risk of losing control of the vehicle. The discussion of braking distances later in this paper shows that the deceleration rates used by trucks in making controlled stops are

TABLE 4 EVOLUTION OF AASHTO STOPPING SIGHT DISTANCE POLICY (2)

YEAR	DESIGN PARAMETERS			ASSUMED TIRE/PAVEMENT COEFFICIENT OF FRICTION	ASSUMED SPEED FOR DESIGN	EFFECTIVE CHANGE FROM PREVIOUS POLICY
	Eye Height (feet)	Object Height (Inches)	Perception/ Reaction Time (Seconds)			
1940 (3)	4.5	4	Variable-- 3.0 Sec. @ 30 mph to 2.0 Sec. @ 70 mph	DRY-- f Ranges from 0.50 @ 30 mph to 0.40 @ 70 mph	DESIGN SPEED	---
1954 (4)	4.5	4	2.5	WET-- f Ranges from 0.36 @ 30 mph to 0.29 @ 70 mph	Lower Than Design Speed (28 mph @ 30 mph Design Speed; 59 mph @ 70 mph Design Speed)	No Net Change in Design Distances
1965 (5)	3.75	6	2.5	WET-- f Ranges from 0.36 @ 30 mph to 0.27 @ 80 mph	Lower Than Design Speed (28 mph @ 30 mph Design Speed; 64 mph @ 80 mph Design Speed)	No Net Change in Design Distances
1971 (6)	3.75	6	2.5	WET-- f Ranges from 0.35 @ 30 mph to 0.27 @ 80 mph	Minimum Values-- Same as 1965; Desirable Values-- DESIGN SPEED	Desirable Values are up to 250 feet greater than minimum values
1984 (1)	3.50	6	2.5	WET-- f slightly lower than 1970 values for higher speeds	Minimum Values-- Same as 1965; Desirable Values-- DESIGN SPEED	Computed values always rounded up giving slightly higher values than 1970

generally lower than the deceleration rates used by passenger cars making locked-wheel stops.

Driver Eye Height

The minimum crest vertical curve criteria for stopping sight distance in Table 3 are based on a driver eye height for passenger cars of 3.5 ft (42 in). The driver eye heights for trucks are much greater than for passenger cars, which may partially or completely offset their longer braking distances on crest vertical curves. Nevertheless, the greater eye heights of truck drivers provide no comparable advantage for sight obstructions on horizontal curves unless the truck driver is able to see over the obstruction.

A review of recent evaluations of truck driver eye height, including studies by Middleton et al. (11), Burger and Mulholland (12), and Urban Behavioral Research Associates, Inc. (13), found that truck driver eye heights can range from 71.5 to 112.5 in. Middleton et al. estimated the average driver eye height for a conventional tractor to be 93 in. This value was also used by Olson et al. (8) in their recent studies of stopping sight distance. Nevertheless, it is important to remember that 93 in represents an average truck driver eye height and that below average eye heights should also be considered. This paper includes sensitivity analyses for truck driver eye heights of 75 and 93 in.

Object Height

The object height used in determining the crest vertical curve lengths in Table 3 is 6 in. As shown in Table 4, a 4-in object

height was used prior to 1965. The AASHTO Green Book presents the object height as an arbitrary rationalization of possible hazardous objects that could be found in the roadway. Others maintain that object height has historically represented a subjective tradeoff of the cost of providing sight distance to the pavement and did not represent any particular hazard (2). The recent analysis of this issue by Olson et al. (8) assumed that the object height was meant to represent a specific possible hazard, but questioned the use of a 6-in object based on a study by Woods (14), which found that about 30 percent of compact and subcompact passenger cars could not clear an object of that height. Whatever interpretation of object height is chosen, the crest vertical lengths for trucks should not be affected because trucks typically have underclearances substantially greater than 6 in.

Horizontal Sight Obstructions

Increased eye height provides truck drivers no advantage over passenger car drivers at a horizontal sight obstruction, unless the truck driver is able to see over the obstruction. Nevertheless, Olson et al. (8) indicate that the minimum offset to a horizontal sight obstruction (represented by the middle ordinate of the curve computed with Equation 5) is normally required only near the center of a horizontal curve. Figure 1 illustrates a sight distance envelope—or “clear sight zone”—where horizontal sight obstructions should not be present. The figure illustrates that less than the maximum offset to horizontal sight obstructions is needed within a distance to either end of the curve equal to half of the stopping sight distance.

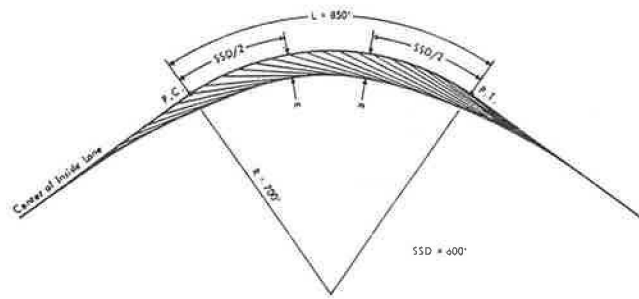


FIGURE 1 Example sight obstruction envelope on horizontal curves for condition where the stopping sight distance is less than the length of the curve.

Another problem associated with stopping sight distance on horizontal curves cited by Olson et al. (8) and Neuman et al. (15) is that the tire-pavement friction available for braking is reduced by the portion of the available tire-pavement friction that is required for cornering. Olson et al. express the available friction for braking on a horizontal curve as

$$f^2 = f_t^2 - \left(\frac{V^2}{15R} - e \right)^2 \quad (6)$$

where

- f = coefficient of friction available for braking,
- f_t = total available coefficient of friction,
- V = vehicle speed (mph),
- R = radius of curvature (ft), and
- e = superelevation rate (ft/ft).

Equation 6 implies that the required stopping sight distances on horizontal curves should be longer than on tangents.

TRUCK BRAKING DISTANCE

Braking distance is defined in the AASHTO Green Book as "the distance required to stop the vehicle from the instant brake application begins." Braking distance is used in the determination of many highway design and operational criteria, including stopping sight distance, intersection sight distance, vehicle change intervals for traffic signals, and advance warning sign placement distances. Currently all of these design and operational criteria are based on passenger car braking distances and do not consider the longer braking distances required for trucks. The process of bringing a truck to a stop involves a complex interaction among the driver, the brake system, the truck tires, the dimensions and loading characteristics of the truck, and the pavement surface characteristics. Because truck braking is much more complex than passenger car braking, it is necessary to discuss the role of each of these characteristics in determining truck braking distances.

Tire-Pavement Friction in Braking Maneuvers

Vehicles are brought to a stop by brakes that retard the rotation of the wheels and allow tire-pavement friction forces to decelerate the vehicle. An understanding of the forces involved in tire-pavement friction is, therefore, critical to the understanding of braking distances.

The coefficient of braking friction (f_y) is defined as the ratio of the braking force (F_y) generated at the tire-pavement interface to the vertical load (F_z) carried by the tire. This can be expressed as

$$f_y = \frac{F_y}{F_z} \quad (7)$$

On a horizontal curve, tire-pavement friction also supplies a cornering force to keep the vehicle from skidding sideways. The coefficient of cornering friction (f_x) is the ratio of the cornering force (F_x) generated at the tire-pavement interface to the vertical load (F_z) carried by the tire. In other words,

$$f_x = \frac{F_x}{F_z} \quad (8)$$

Figure 2 illustrates that both braking and cornering friction vary as a function of percent slip, which is the percent decrease in the angular velocity of a wheel relative to the pavement surface as a vehicle brakes. A freely rolling wheel is operating at 0 percent slip. A locked wheel is operating at 100 percent slip, with the tire sliding across the pavement. Figure 2 shows that the coefficient of braking friction increases rapidly with percent slip to a peak value that typically occurs between 10 and 15 percent slip. The coefficient of braking friction then

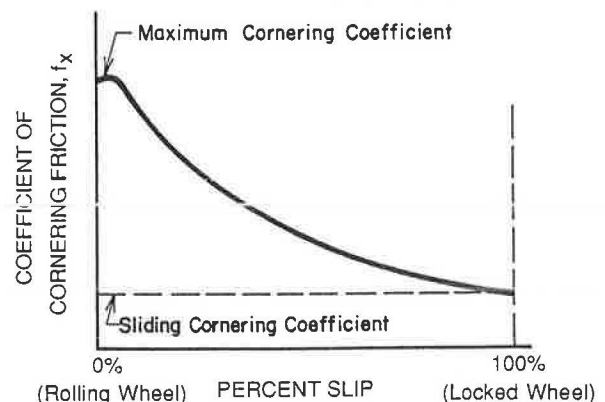
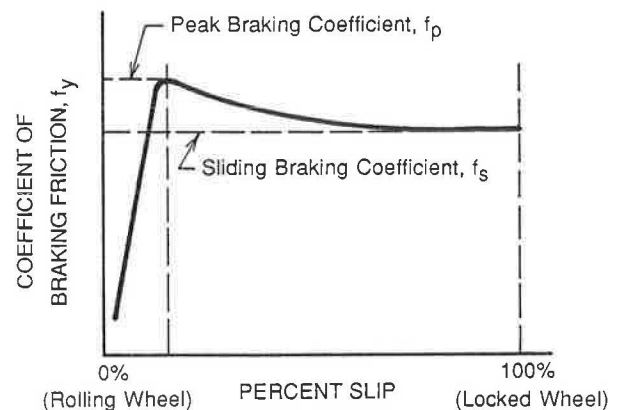


FIGURE 2 Variation of braking and cornering friction coefficients with percent slip.

decreases as percent slip increases, reaching a level known as the coefficient of sliding friction at 100 percent slip.

The coefficient of cornering friction has a maximum value at 0 percent slip and decreases to a minimum at 100 percent slip. Thus, when a braking vehicle locks its wheels, it will lose its steering capability because of a lack of cornering friction.

Locked-Wheel Braking versus Controlled Braking

The discussion of Figure 2 implies that braking maneuvers can be performed in two ways: locked-wheel braking and controlled braking. Locked-wheel braking occurs when the brakes grip the wheels tightly enough to cause them to stop rotating, or "lock," before the vehicle has come to a stop. Braking in this mode causes the vehicle to slide over the pavement surface on its tires. Locked-wheel braking uses sliding friction (100 percent slip), represented by the right end of the graph in Figure 2, rather than rolling or peak friction. The sliding coefficient of friction takes advantage of most of the friction available from the pavement surface, but it is generally less than the peak available friction. On dry pavements, the peak coefficient of friction is relatively high, with very little decrease in friction at 100 percent slip. On wet pavements, the peak friction is lower, and the decrease in friction at 100 percent slip is generally larger.

The braking distance required for a vehicle to make a locked-wheel stop can be determined from the following relationship:

$$BD = \frac{V^2}{30f_s} \quad (9)$$

where

BD = braking distance (ft),
 V = initial speed (mph), and
 f_s = coefficient of sliding friction.

The coefficient of sliding friction in Equation 9 is mathematically equivalent to the deceleration rate used by the vehicle expressed as a fraction of the acceleration of gravity (g or 32.2 ft/sec²). The coefficient of friction, and thus the deceleration rate, may vary as a function of speed during the stop, so f_s in Equation 9 should be understood as the average coefficient of friction or average deceleration rate during the stop.

Controlled braking is the application of the brakes in such a way that the wheels continue to roll without locking while the vehicle is decelerating. Drivers generally achieve controlled braking by "modulating" the brake pedal to vary the braking force and to avoid locking the wheels. Controlled braking distances are governed by the rolling coefficient of friction, which occurs at a value of percent slip to the left of the peak available friction shown in Figure 2. Because of the steep slope of the braking friction curve to the left of the peak and the braking techniques used by drivers to avoid wheel lockup, the average rolling friction attained is generally less than the sliding friction coefficient. Therefore, controlled braking distances are usually longer than locked-wheel braking distances.

Locked-wheel braking is commonly used by passenger car drivers during emergency situations. Passenger cars can often stop in a stable manner, even with the front wheels locked. In this situation, although the driver loses steering control, the vehicle generally slides straight ahead. On a tangent sec-

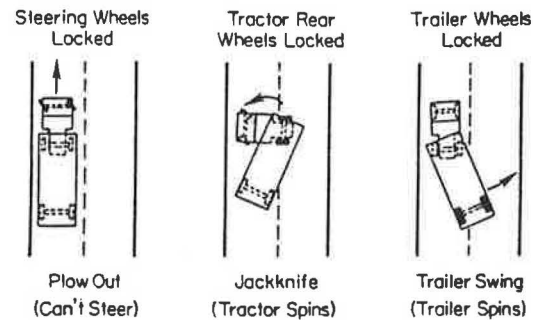


FIGURE 3 Tractor-trailer dynamics with locked wheels (16).

tion of road, this is perhaps acceptable behavior; on a horizontal curve, the vehicle may leave its lane, and possibly the roadway.

Trucks, in contrast, have much more difficulty stopping in the locked-wheel mode. Figure 3 illustrates the different dynamic responses of a tractor-trailer truck if its wheels are locked during emergency braking (16). The response depends on which axle is the first to lock—they usually do not all lock together. When the steering wheels (front axle) are locked, steering control is eliminated, but the truck maintains rotational stability. If the rear wheels of the tractor are locked, the axle(s) slides and the tractor rotates or spins, resulting in a "jackknife" loss of control. If the trailer wheels are locked, those axles will slide and the trailer will rotate out from behind the tractor, which also leads to loss of control. Although a skilled driver can recover from the trailer swing through quick reaction, the jackknife situation is generally not correctable. None of these locked-wheel stopping scenarios for trucks is considered safe. Therefore, it is essential that trucks stop in a controlled braking mode and that highway design and operational criteria recognize the longer distances required for trucks to make a controlled stop.

The braking distance for a vehicle to make a controlled stop can be determined from the following relationship:

$$BD = \frac{V^2}{30f_r} \quad (10)$$

where f_r equals the coefficient of rolling friction. As in the case of sliding friction, the coefficient of rolling friction (f_r) in Equation 10 represents the average coefficient of friction or average deceleration rate during the entire controlled stop.

Recent Research on Truck Braking Distance

In research at the University of Michigan Transportation Research Institute (UMTRI), Olson et al. (8) suggested a model to predict braking distance as a function of pavement surface characteristics, tire characteristics, vehicle braking performance, and driver control efficiency. Parametrically, the model expresses the coefficient of rolling friction, f_r , as

$$f_r = f_p \times TF \times BE \times CE \quad (11)$$

where

f_p = peak braking friction coefficient available given the pavement surface characteristics,

- TF = adjustment factor for tire tread depth (8),
 BE = adjustment factor for braking efficiency (the efficiency of the braking system in using the available friction, typically 0.55 to 0.59 for conventional braking systems), and
 CE = adjustment factor for driver control efficiency (the efficiency of the driver in modulating the brakes to obtain optimum braking performance, typically 0.62 to 1.00 for conventional braking systems).

A paper by Fancher (17), derived from the study by Olson et al. (8), used the model in Equation 11 to predict truck braking distances. Figure 4 shows the braking distances for trucks under controlled and locked-wheel stops with new and worn ($2/32$ -in tread depth) tires in comparison with the braking distances assumed in the AASHTO Green Book. The braking distances predicted by Fancher are substantially longer than the distances for locked-wheel braking by a passenger car assumed by AASHTO. Figure 4 is based on a pavement with a skid number of 28 at 40 mph (SN_{40}) and a driver who uses 100 percent of the vehicle braking capability. Most truck drivers would require even longer stopping distances.

The data show that the braking performance of truck drivers under emergency conditions may vary widely. Most truck drivers have little or no practice in emergency braking situations. This lack of expertise in modulating of the brakes in emergency situations results in braking distances that are longer than the vehicle capability. Olson et al. (8) studied the effect of driver efficiency on braking distance using both experienced test drivers and professional truck drivers without test track experience. The study found that the driver control efficiencies ranged from 62 to 100 percent of the vehicle capability. The braking performance of the drivers tended to improve during the testing period as the drivers gained experience in modulating the brakes. Because so many drivers on the road lack experience in emergency braking, the Olson study recommended the use of a driver efficiency of 62 percent in stopping sight distance design criteria. It should be recognized

that this is a very conservative choice. Experienced drivers can operate at efficiencies approaching 100 percent. Furthermore, in the future, antilock brake systems could eliminate the concern over driver efficiency by providing computer-controlled modulation of the brakes to achieve minimum braking distance.

Because truck drivers exhibit such a range of emergency braking performance, a sensitivity analysis of stopping sight distance requirements to truck driver braking performance is presented in this paper. The driver with the worst performance in this sensitivity analysis is assumed to utilize 62 percent of the vehicle braking capability (that is, $CE = 0.62$ in Equation 11). The driver with the best performance is assumed to utilize 100 percent of the vehicle braking capability (that is, $CE = 1.0$).

Figure 5 illustrates the deceleration rates (values of f_r) used to develop Figure 4. Figure 6 shows that the deceleration rates for controlled stops on a wet pavement by the best-performing driver ($CE = 1.0$) are generally between 0.20 and 0.25 g, and that they are relatively insensitive to vehicle speed. In contrast, Appendix B of the report by Olson et al. shows deceleration rates as high as 0.5 g in controlled stops on a wet pavement by experienced drivers. These tests were performed at the Chrysler Proving Ground on a pavement that apparently has a very high peak friction coefficient even when wet. The data in Figures 4 and 5 were derived theoretically from the model given in Equation 11.

Antilock Brake Systems

During the mid-1970s, regulations for truck braking distances were adopted, which resulted in the introduction of antilock brake systems on trucks. Shortly afterwards the restrictions were removed by court order, and because of a lack of consumer interest, trucks equipped with antilock brakes were no longer commercially available from domestic truck manufacturers. Since that time, with technological advancements and

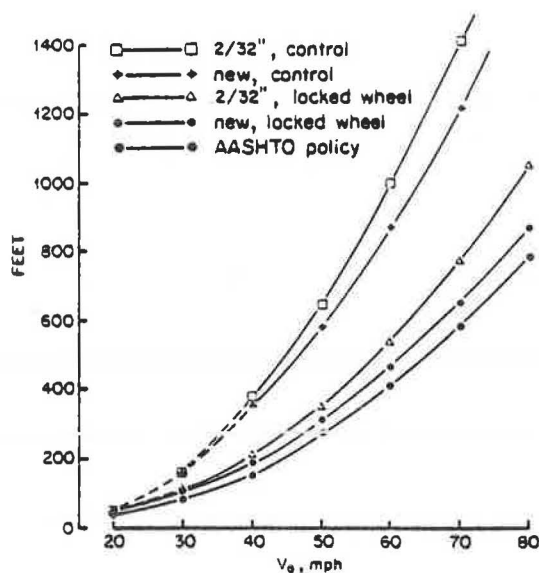


FIGURE 4 Truck braking distances on a poor, wet road (17).

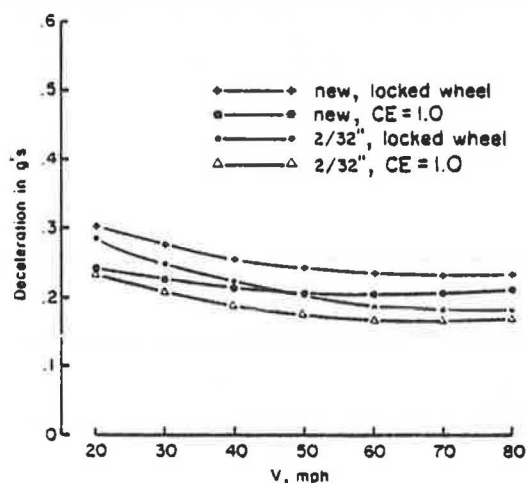


FIGURE 5 Truck deceleration rates on a poor, wet road (17).

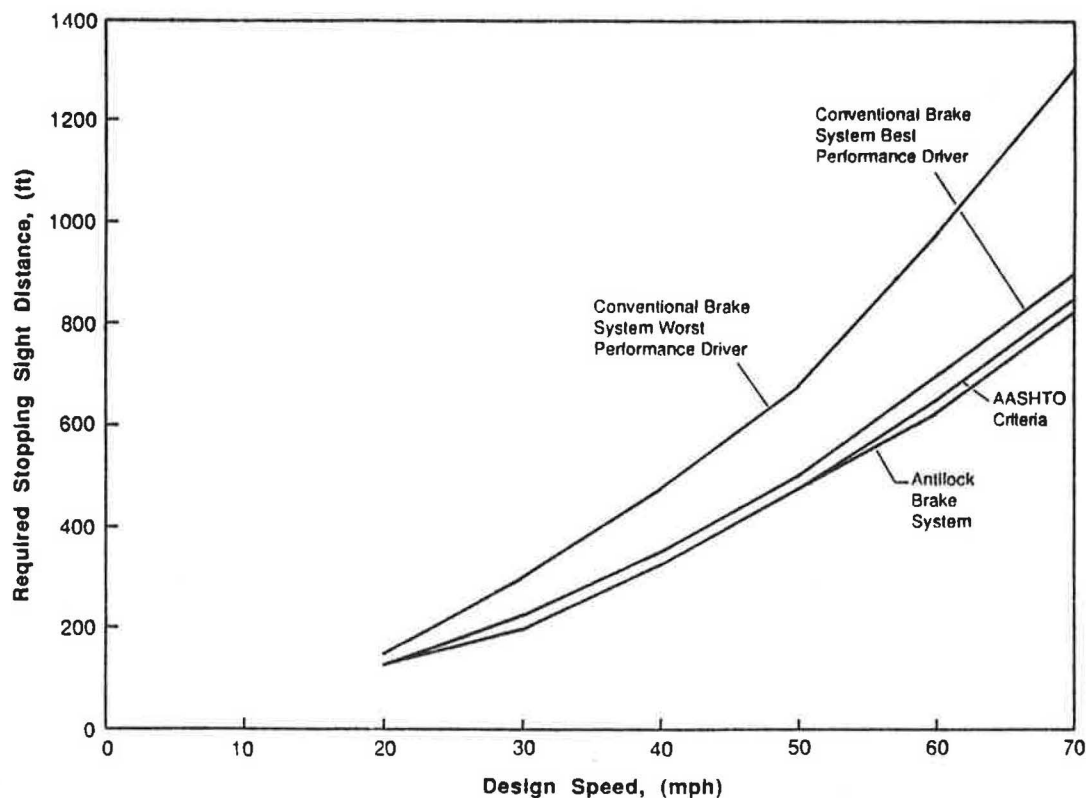


FIGURE 6 Comparison of stopping sight distance requirements for trucks with current AASHTO criteria.

improved design, antilock braking systems have gained acceptance in Europe and are slowly being reintroduced into the United States, primarily through imported passenger cars. It is possible that antilock brake systems for trucks will become common in the United States (or may be required by regulation) within 5 to 10 years. Thus, the improvements in truck braking distances that might result from antilock brake systems need to be considered in the development of future highway design criteria.

The purpose of antilock brakes is to take the fullest advantage of available tire-pavement friction capabilities without locking the wheels and losing vehicle control. Antilock brake systems are designed to achieve and maintain the peak coefficient of tire-pavement friction shown in Figure 2, maximizing the braking effect.

Antilock brake systems operate by monitoring each wheel for impending lockup. When wheel lockup occurs or is anticipated, the system releases brake pressure on the wheel. When the wheel begins to roll freely again, the system reapplies braking pressure. The system constantly monitors each wheel and readjusts the brake pressure until the wheel torque is no longer sufficient to lock the wheel. Present antilock brake systems are controlled by onboard microprocessors.

A recent NHTSA study (18) of the performance of a commercially available antilock brake system on a two-axle, single-unit truck found a 15 percent reduction in braking distance for a straight line stop from 60 mph on a wet, polished concrete pavement surface with an SN_{40} of approximately 30 (similar to the surface used by the AASHTO Green Book in the specification of stopping sight distance standards). Tests on

other pavement surfaces and in other types of maneuvers found decreases in braking distance up to 42 percent with the antilock brake system. Furthermore, in addition to improving the braking efficiency by operating closer to the peak braking friction coefficient, antilock brake systems should also minimize the increase in braking distance caused by driver inexperience.

Design Values for Truck Braking Distance

The literature does not provide a clear indication of which braking distances should be used in highway design criteria. Many of the factors that influence braking distances, such as pavement characteristics and driver efficiencies, vary widely. For purposes of the evaluation of current highway design and operational criteria in this paper, three braking scenarios have been presented for consideration in the development of design criteria for trucks. These three scenarios are tractor-trailer truck with a conventional brake system and the worst-performing driver; tractor-trailer truck with a conventional brake system and the best-performing driver; and a tractor-trailer truck with an antilock brake system. Deceleration rates and braking distances for these three scenarios are shown in Table 5. These data are based on the results obtained by Fancher (17) and shown in Figures 4 and 5, with a minor change in the assumption concerning pavement surface properties (from SN_{40} of 28 assumed by Fancher to SN_{40} of 32 assumed by the AASHTO Green Book). All of the braking distances in Table 5 are appropriate for an empty truck with relatively good

TABLE 5 TRUCK DECELERATION RATES AND BRAKING DISTANCES FOR USE IN HIGHWAY DESIGN^a

Vehicle Speed (mph)	Deceleration Rate (g)				Braking Distance (ft)			
	AASHTO Policy	Worst Performance Driver ^b	Best Performance Driver ^c	Antilock Brake System	AASHTO Policy	Worst Performance Driver ^b	Best Performance Driver ^c	Antilock Brake System
20	0.40	0.17	0.28	0.36	33	77	48	37
30	0.35	0.16	0.26	0.34	86	186	115	88
40	0.32	0.16	0.25	0.31	167	344	213	172
50	0.30	0.16	0.25	0.31	278	538	333	269
60	0.29	0.16	0.26	0.32	414	744	462	375
70	0.28	0.16	0.26	0.32	583	1,013	628	510

^a Based on an empty tractor-trailer truck on a wet pavement with $SN_{40} = 32$.

^b Based on driver control efficiency of 0.62.

^c Based on driver control efficiency of 1.00.

radial tires (at least $1\frac{1}{32}$ in of tread depth). The braking distances for empty trucks are generally longer than braking distances for loaded trucks because truck brake systems are adjusted to be most effective when the truck is loaded. The braking distances in Table 5 are based on the assumption that the front-axle brakes of the truck are operational and have no automatic limiting valve.

The data for the worst-performing driver in Table 5 are based on an assumed 62 percent driver control efficiency (*CE* in Equation 11), which represents a very conservative, worst-case condition. The data for an experienced driver are based on a driver control efficiency of 100 percent and thus represent the full capability of conventional brake systems. Most truck drivers on the road today have control efficiencies that fall between these two extremes. The data for an antilock brake system represent deceleration rates between 0.31 and 0.36 g, which are consistent with the results of recent NHTSA tests. These estimates for antilock brake systems represent an improvement of 20 to 30 percent over the best-performing driver with a conventional brake system. The available NHTSA data (18) show this to be a conservative estimate of the improvement that could be obtained from future antilock brake systems.

It is important to note that the estimates of deceleration rate and braking distances in Table 5 for trucks equipped with antilock brake systems are very similar to the AASHTO criteria for passenger cars, which are also shown in the table.

SENSITIVITY ANALYSES

Sensitivity analyses were performed to investigate the differences in stopping sight distance requirements for trucks and passenger cars. The stopping sight distance criteria for passenger cars were represented by the AASHTO criteria. The sensitivity analyses also examined the implications of the stopping sight distance analysis results for crest vertical curves and for horizontal sight obstructions.

Stopping Sight Distance

Stopping sight distance criteria for trucks were derived using the AASHTO stopping sight distance relationship given in

Equation 1. The stopping sight distance criteria for trucks were based on the same brake reaction time (t_{pr}) as the AASHTO criteria. The design speed of the highway is used as the initial vehicle speed in the braking maneuver. Three cases are considered for the coefficients of friction or deceleration rates used by truck drivers for controlled stops: a truck with a conventional braking system and the worst-performing driver, a truck with a conventional braking system and the best-performing driver, and a truck with an antilock brake system. The estimated deceleration rates for these three cases, shown in Table 5, are based on braking on a poor, wet road by an empty tractor-trailer truck with good tires.

Table 6 presents the stopping sight distance requirements for trucks derived from the data discussed above in comparison with the current AASHTO criteria. This comparison is also illustrated in Figure 6. Table 6 and Figure 6 show that the worst-performing driver with a conventional braking system requires substantially more stopping sight distance than the AASHTO criteria, up to 425 ft more sight distance for a 70-mph design speed. The stopping sight distance requirements for the best-performing driver with a conventional braking system are only slightly higher than the current AASHTO criteria. Thus, the assumption made about the braking performance capability, or braking control efficiency, of the driver is critical to stopping sight distance. There are essentially no data available to indicate the actual distribution of braking control efficiencies for working truck drivers.

Table 6 also shows that the sight distance requirements for

TABLE 6 STOPPING SIGHT DISTANCE REQUIREMENTS FOR TRUCKS IN COMPARISON WITH CURRENT AASHTO CRITERIA

Design Speed (mph)	Required Stopping Sight Distance (ft)			
	AASHTO Criteria	Controlled Braking ^a		Antilock Brake System
		Worst Performance Driver	Best Performance Driver	
20	125	150	125	125
30	200	300	250	200
40	325	500	375	325
50	475	725	525	475
60	650	975	700	600
70	850	1,275	900	775

^a Based on deceleration rates and braking distances presented in Table 5.

trucks with antilock brakes are essentially equivalent to the current AASHTO criteria. Thus, the possibility of future government requirements for truck antilock brake systems (or projected market penetration of such systems in the absence of government requirements) is critical to the assessment of stopping sight criteria. If antilock brake systems do come into fairly universal use and achieve the performance projected in Table 5, the current AASHTO stopping sight distance criteria should be adequate for trucks.

Crest Vertical Curve Lengths

Table 7 shows the minimum vertical curve lengths for a range of design speeds and algebraic differences in grade based on the stopping sight distance requirements for trucks in Table 6. The vertical curve lengths in Table 7 are based on a 6-in object height and truck driver eye heights of 75 and 93 in.

A comparison between the data in Tables 3 and 7 indicates that the minimum vertical curve lengths for the worst-performing driver in a truck with a conventional braking system are always longer than current AASHTO criteria—in some cases by a substantial margin. At the same time, the minimum vertical curve lengths for a truck with an antilock brake system or for the best-performing driver in a truck with a conven-

tional brake system are always shorter than the current AASHTO criteria. Stated another way, both the truck with the antilock brake system and the best-performing driver with a conventional brake system will always have enough stopping sight distance on a vertical curve designed in accordance with AASHTO criteria.

Finally, the data in Table 7 show that the minimum vertical curve lengths are not very sensitive to the difference between 75 and 93 in of driver eye height. The maximum difference in vertical curve lengths between these minimum and average driver eye heights is 600 ft in one extreme case, although most of the differences are substantially shorter.

Horizontal Sight Obstructions

The differences in stopping sight distance between passenger cars and trucks shown in Table 6 are generally not mitigated by increased driver eye height, as in the case of vertical sight restrictions. As shown in Equation 6, the sight distance requirements for horizontal curves should actually be somewhat higher—as a function of curve radius and superelevation—than for tangents.

CONCLUSIONS

A truck with a conventional brake system driven by a worst-performing driver requires up to 425 ft more stopping sight distance at 70 mph and requires longer crest vertical curves than current AASHTO policy recommends. Specific calculated values of stopping sight distance and crest vertical curve length are given in Tables 6 and 7.

In contrast, a truck with a conventional brake system and driven by a best-performing driver requires only slightly more stopping sight distance than current AASHTO policy and, because of increased driver eye height, requires shorter crest vertical curves than AASHTO recommends. This finding points to the critical role played by driver training and experience in emergency braking maneuvers. Unfortunately, current data do not provide any reliable estimates of the distribution of driver performance in the range between the extremes.

In the worst-case scenario, there may be a need to increase stopping sight distance requirements to accommodate trucks with conventional brake systems. The safety benefits of such a change are not known, however, and it has not been established whether revision of current design criteria would be cost-effective. Changes in current design criteria are not recommended unless a cost-effectiveness analysis indicates that longer vertical curves would produce safety benefits commensurate with the added construction cost.

Trucks with antilock brake systems require less stopping sight distance and significantly shorter crest vertical curves than current AASHTO policy recommends. It appears that trucks with antilock brake systems can stop in the same or less distance than a passenger car. Thus, future government policy and industry practice concerning the use of antilock brake systems have major implications for highway design policy, because it is likely that no changes in current stopping sight distance design policies would be needed to accommodate trucks if antilock brakes were required or widely used.

TABLE 7 MINIMUM VERTICAL CURVE LENGTHS (IN FEET) TO PROVIDE STOPPING SIGHT DISTANCE FOR PASSENGER CARS AND TRUCKS

Algebraic Difference in Percent Grade	Design Speed (mph)					
	20	30	40	50	60	70
<u>TRUCK (driver eye height = 75 in)</u>						
Conventional Brake System with Worst Performance Driver						
2	60	90	240	420	910	1,570
4	60	180	470	1,020	1,810	3,140
6	70	250	710	1,520	2,720	4,710
8	90	350	940	2,030	3,630	6,280
10	100	430	1,180	2,530	4,530	7,850
Conventional Brake System with Best Performance Driver						
2	60	90	130	260	340	750
4	60	100	210	520	910	1,530
6	60	110	380	780	1,360	2,300
8	60	200	450	1,040	1,810	3,050
10	80	250	630	1,300	2,261	3,820
Antilock Brake System						
2	60	90	120	200	350	510
4	60	90	130	400	700	1,150
6	60	120	300	600	1,040	1,720
8	60	140	400	800	1,400	2,300
10	60	200	500	1,000	1,730	2,870
<u>TRUCK (driver eye height = 93 in)</u>						
Conventional Brake System with Worst Performance Driver						
2	60	90	200	230	720	1,330
4	60	150	380	860	1,530	2,650
6	60	190	600	1,290	2,300	3,980
8	80	290	800	1,710	3,100	5,300
10	100	360	990	2,140	3,820	6,630
Conventional Brake System with Best Performance Driver						
2	60	90	120	220	390	560
4	60	90	220	430	770	1,290
6	60	130	320	660	1,150	1,930
8	60	150	430	880	1,530	2,580
10	60	210	540	1,080	1,910	3,220
Antilock Brake System						
2	60	90	120	190	320	390
4	60	90	190	340	640	1,060
6	60	110	260	560	960	1,590
8	60	120	370	740	1,270	2,120
10	60	180	460	920	1,590	2,650

Note: Based on stopping sight distances shown in Table 6.

ACKNOWLEDGMENT

The work reported in this paper was conducted under sponsorship of the Federal Highway Administration.

REFERENCES

1. *A Policy on Geometric Design of Highways and Streets*. AASHTO, Washington, D.C., 1984.
2. J. C. Glennon. Effect of Sight Distance on Highway Safety. In *State-of-the Art Report 6*. TRB, National Research Council, Washington, D.C., 1987.
3. *A Policy on Sight Distance for Highways*. AASHO, Washington, D.C., 1940.
4. *A Policy on Geometric Design of Rural Highways*. AASHO, Washington, D.C., 1954.
5. *A Policy on Geometric Design of Rural Highways*. AASHO, Washington, D.C., 1965.
6. *A Policy on Design Standards for Stopping Sight Distance*. AASHTO, Washington, D.C., 1971.
7. G. Johansson and K. Rumar. Drivers' Brake Reaction Times. *Human Factors*. Vol. 13, No. 1, February 1971.
8. P. L. Olson, D. E. Cleveland, P. S. Fancher, L. P. Kostyniuk, and L. W. Schneider. *NCHRP Report 270: Parameters Affecting Stopping Sight Distance*. HRB, National Research Council, Washington, D.C., June 1984.
9. P. S. Fancher, R. D. Ervin, C. B. Winkler, and T. D. Gillespie. *A Factbook of the Mechanical Properties of the Components of Single-Unit and Articulated Heavy Vehicles*. Report DOT-HS-807-125. NHTSA, U.S. Department of Transportation, December 1986.
10. R. A. Moyer and J. W. Shupe. Roughness and Skid Resistance Measurements in California. *Bulletin 37*. HRB, National Research Council, Washington, D.C., 1951.
11. P. B. Middleton, M. Y. Wong, J. Taylor, H. Thompson, and J. Bennett. *Analysis of Truck Safety on Crest Vertical Curves*. Report FHWA/RD-86/060. FHWA, U.S. Department of Transportation, 1983.
12. W. J. Burger and M. U. Mulholland. *Plane and Convex Mirror Sizes for Small to Large Trucks*. Report DOT-HS-7-01721. NHTSA, U.S. Department of Transportation, 1982.
13. Urban Behavioral Research Associates. *The Investigation of Driver Eye Height and Field of Vision*. Report DOT-FH-11-9141. FHWA, U.S. Department of Transportation, 1978 (cited in Reference 39).
14. D. L. Woods. Small Car Impacts on Highway Design, *ITE Journal*. April 1983.
15. T. R. Neuman, J. C. Glennon, and J. E. Leisch. *Stopping Sight Distance—An Operational and Cost Effectiveness Analysis*. Report FHWA/RD-83/067. FHWA, U.S. Department of Transportation, 1982.
16. R. M. Clarke, W. A. Leasure, R. W. Radlinski, and M. Smith. *Heavy Truck Safety Study*. Report DOT-HS-807-109. NHTSA, U.S. Department of Transportation, March 1987.
17. P. S. Fancher. Sight Distance Problems Related to Large Trucks. In *Transportation Research Record 1052*, TRB, National Research Council, Washington, D.C., 1986.
18. R. W. Radlinski and S. C. Bell. *NHTSA's Heavy Vehicle Brake Research Program—Report No. 6: Performance Evaluation of a Production Antilock System Installed on a Two-Axle Straight Truck*. Report DOT-HS-807-046. NHTSA, U.S. Department of Transportation, 1986.

The findings and conclusions of the paper are those of the authors and do not necessarily represent the views of the Federal Highway Administration.

Publication of this paper sponsored by Committee on Geometric Design and Committee on Operational Effects of Geometrics.