may be expected that certain of these road features can create a greater vibration disturbance to trucks than to cars."

SUMMARY

The preceding overview of existing design standards, coupled with the stated concerns about the subtleties in designing for trucks, points to the need for a definitive highway design and maintenance guide to satisfy the unique safety-critical operational requirements of trucks.

It is hoped that this symposium will be of assistance to AASHTO's Subcommittee on Design in its efforts to update the green book to reflect the "large trucks" allowed under the STAA of 1982 (1,p.iv).

REFERENCES

1. A Policy on Geometric Design of Highways and Streets, 1984. AASHTO, Washington, D.C., 1984.
2. A Policy on Geometric Design of Rural Highways. AASHO, Washington, D.C., 1965.
3. A Policy on Design of Urban Highways and Arterial Streets. AASHO, Washington, D.C., 1973.
4. O.F. Gericke and C.M. Walton. Effect of Increased Truck Size and Weight on Rural Highway Geometric Design (and Redesign) Principles and Practices. In Transportation Research Record 806, TRB, National Research Council, Washington, D.C., 1981.
5. J.E. Leisch, R.C. Pfefer, and B.L. Smith. Dynamic Design for Safety Seminar Notes. Institute of Traffic Engineers, Washington, D.C.; FHWA, U.S. Department of Transportation, 1975.
6. J.E. Leisch and J.P. Leisch. New Concepts in Design Speed Application. In Transportation Research Record 631, TRB, National Research Council, Washington, D.C., 1977.
7. N.J. Rowan and J.H. Johnson. Safety Design and Operational Practices for Streets and Highways. Technology Sharing Report 80-228. FHWA, U.S. Department of Transportation, 1980.
8. J.W. Hutchinson and C.G. Shapley. Reconstruction of Truck Accidents. In Highway Collision Reconstruction, American Society of Mechanical Engineers, New York, 1980.
9. Guide for Selecting, Locating, and Designing Traffic Barriers. AASHTO, Washington, D.C., 1977.
10. The Influence of Roadway Surface Discontinuities--A State-of-the-Art Report. TRB, National Research Council, Washington, D.C., 1984.

Sight Distance Problems Related to Large Trucks

P. S. FANCHER

ABSTRACT

In this paper are discussed the influences of the properties of large trucks on (a) sight distances for accelerating across intersections, (b) passing sight distances on two-lane highways, and (c) stopping sight distances for crest vertical curves. The vehicle properties considered include power-to-weight ratios (acceleration capabilities), overall lengths, driver eye heights, and braking capabilities. The findings presented here indicate that (a) current policy of AASHTO may be used to obtain conservative estimates of the time required to accelerate across intersections, (b) longer periods of time in the left lane are needed for passing longer trucks, and (c) if controlled stops without jackknifing, trailer swinging, or vehicle spins are to be performed by truck drivers, the required stopping sight distances at high speeds are much longer than those recommended in the AASHTO policy.

The intent of this paper is to provide an understanding of how sight distance requirements are influenced by the properties of large trucks. Whether large trucks are involved in crossing intersections, passing situations on two-lane roads, or stopping to avoid objects on the highway, pertinent truck characteristics are enough different from those of automobiles that design policies based on automobile characteristics cannot be assumed to be appropriate. With regard to crossing intersections, there is a recommended AASHTO policy for heavy trucks (the WB-50 design vehicle) (1). However, AASHTO policy for passing sight distance is based on acceleration capabilities of automobiles. And, although trucks are mentioned, the policy for stopping sight distance on crest vertical curves is based on the

Transportation Research Institute, University of Michigan, Ann Arbor, Mich. 48109.

locked-wheel performance of automobile tires. In the following sections of this paper relationships between truck performance and sight distance policies based on AASHTO recommendations are examined. [The AASHTO policy recognizes that it is less than adequate for large trucks traveling at high speed (1, p.iv).]

SIGHT DISTANCE FOR ACCELERATING ACROSS INTERSECTIONS

The weight-to-power ratio of heavy trucks (up to 80,000 lb) has experienced a decreasing trend since 1949 (Figure 1). This means that modern trucks can cross an intersection from a stop in less time than was required previously. A recent study (2) has shown that the accelerating time for the assumed WB-50 design vehicles given in the AASHTO policy (1) for geometric design is conservative compared with (a) measured results for a 273-lb/hp truck and (b) calculated results for a 300-lb/hp truck. Given current trends toward vehicles with higher power-to-weight ratios and less rolling resistance, the AASHTO curve of accelerating time versus distance traveled (Figure 2) will provide reasonable estimates of vehicle performance until some unforeseen factor causes a major change in the power-to-weight ratios of heavy vehicles.

Although accelerating time versus distance traveled during acceleration is not changing rapidly, there is a trend toward longer vehicles (e.g., the use of more doubles and longer semitrailers). The distance traveled for these longer vehicles to clear an intersection may increase by approximately 10 or 15 ft in some cases. At first approximation, the AASHTO recommendation (Figure 2) yields an additional accelerating time of 1 sec per each 15 ft of travel for distances of from 60 to 160 ft. If the cross traffic were traveling at 55 mph, this additional second of accelerating time would mean an additional intersection sight distance of approximately 80 ft. As long as future longer vehicles do not have lower power-to-weight ratios than current vehicles, the AASHTO design recommendations will apply with the added length being accounted for by using the appropriate distance traveled during acceleration when reading accelerating time from the design curves.

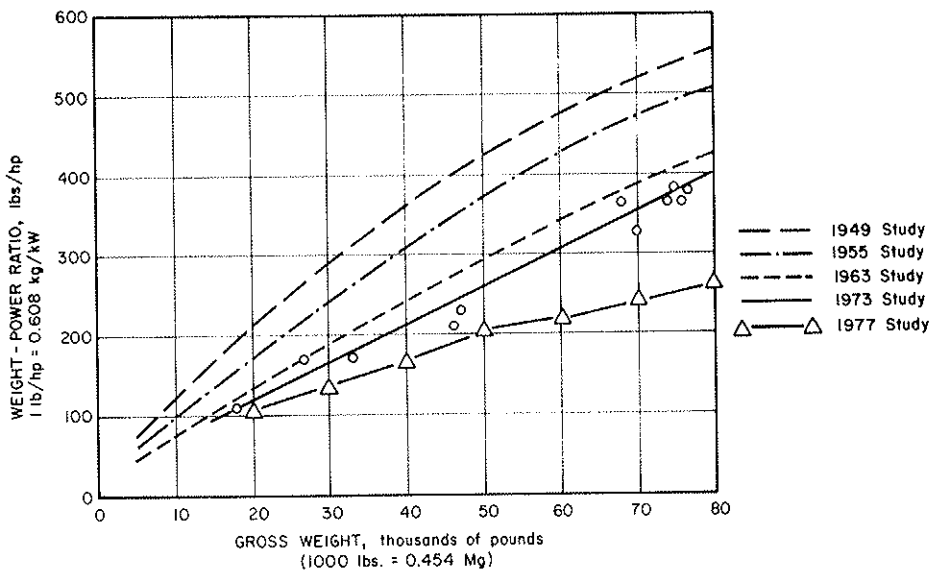


FIGURE 1 Trend in weight-to-power ratios from 1949 to 1977 (2).

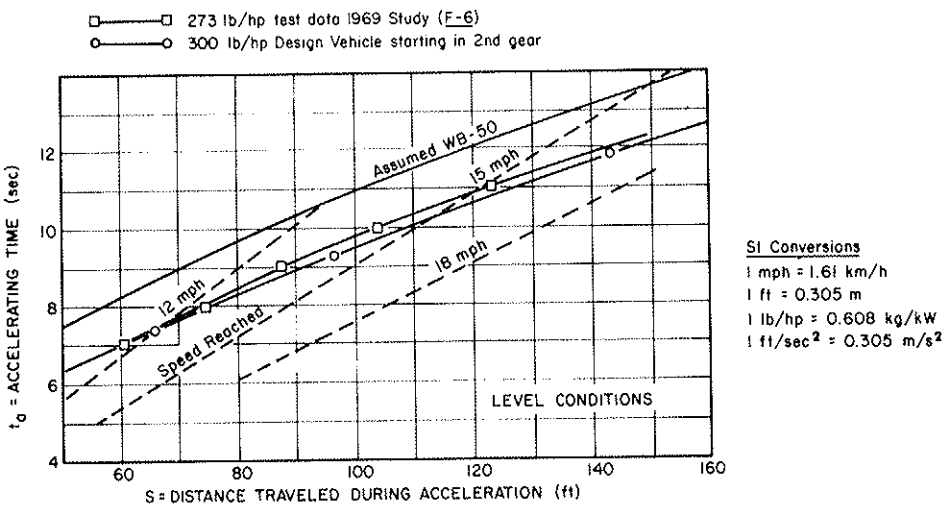


FIGURE 2 Accelerating time versus distance traveled during acceleration.

PASSING SIGHT DISTANCE ON TWO-LANE HIGHWAYS

For passing on two-lane highways, the AASHTO design policy specifies the sight distances needed for one vehicle to pass another before encountering oncoming traffic. The total passing sight distance is divided into four parts: (a) initial acceleration distance including perception and reaction time, (b) distance traveled in the left lane, (c) clearance safety margin with respect to the opposing vehicle, and (d) distance traveled by the opposing vehicle during two-thirds of the time the passing vehicle occupies the left lane.

Vehicle acceleration performance is involved in this maneuver. For automobiles the contribution of the initial acceleration part of the maneuver is approximately 15 percent of the total passing sight distance. However, some heavy trucks have sustained speeds on level ground of no more than 60 mph when fully laden, and, at speeds near 40 mph, distances on the order of 2,500 to 3,000 ft may be needed to accelerate to 50 mph.

On the basis of these observations, the AASHTO passing sight distance model used for automobiles does not appear to be appropriate for heavy trucks. It might be better hypothesized that trucks pass when they have already attained passing speed before encountering a vehicle to be passed. Because of the height of their eyes, truck drivers can see over cars in front of them and decide, without slowing down or pulling out into the left lane, whether to pass. If this hypothesized scenario is accepted, the passing sight distance used for automobiles would be adequate for trucks that have not had to slow down. However, if trucks must slow down for slowly moving vehicles, they will require long distances to accelerate to speeds high enough to pass vehicles traveling at velocities above 40 mph.

Furthermore, researchers (3) have defined a critical point at which the passing vehicle comes abreast of the vehicle to be passed. At this point, the driver decides whether to complete the pass or to abort the maneuver. Under this model of the passing situation, the initial acceleration distance is not included in the minimum passing sight distance. Hence, the acceleration characteristics of trucks do not influence the passing sight distance required for heavy trucks if this model is used.

In addition to difficulties encountered in "seeing around" trucks, the distance traveled in the left lane by an automobile passing a long truck is longer than that needed to pass another automobile. This increase in passing distance and, consequently, passing time will increase the time during which approaching traffic will travel. An additional 30 ft of vehicle to be passed means that an additional 2 sec are needed for passing at a speed differential of 10 mph. An oncoming vehicle would travel approximately 160 ft during these 2 sec if it were traveling at 55 mph. The presence of long trucks could add more than 300 ft to the passing sight distance recommended for passing shorter vehicles, when allowance is made for (a) 2 more seconds of travel in the left lane and (b) 2 more seconds of travel for the oncoming vehicle. (Following this line of reasoning, a truck-passing-truck situation might require 4 additional seconds in the left lane and also 4 additional seconds for travel of the oncoming vehicle--perhaps 600 ft more than the distance recommended for automobiles passing automobiles.)

STOPPING SIGHT DISTANCE

Sight distance for passing and for crossing intersections depends on the acceleration capabilities of the vehicles involved. Clearly, the acceleration capabilities of heavy vehicles have little to do with stopping sight distance. Nevertheless, acceleration capabilities do influence a number of situations in which heavy trucks are able to travel at high speeds. For example, when climbing a long upgrade section before a crest vertical curve, a heavy truck may proceed slowly. Calculations, made for studying the stopping sight distance of trucks at those particular locations, might well consider the speed of approach of the vehicles involved.

Given an initial speed, the primary parameters that affect stopping sight distance include (a) perception and reaction time, (b) driver eye height, (c) height of the object in the roadway, and (d) braking distance. Values of these parameters are used to calculate the lengths of vertical curves that will not hide significant hazards from the driver until the driver is too close to be able to deal with them effectively.

In the United States, AASHTO recommends a perception and reaction time of 2.5 sec and an object height of 6 in. In this paper, it is assumed that these values apply to all vehicles, including heavy trucks. Matters related to eye height and braking distance will be examined in detail in the following discussions.

Influence of Eye Height of Truck Drivers

The AASHTO policy for crest vertical curves is based on automobile characteristics (1). When trucks are compared with automobiles, the additional eye height of the truck driver is believed to compensate for the reduced braking capabilities of trucks.

Geometric relationships are available for calculating the length of crest vertical curves for given values of eye height (h_e), object height (h_o), and available (specified) sight distance (S_A). These relationships are derivable from the basic properties of parabolas and tangents to these parabolas (2, Appendix E). In this context, the vertical distance between a parabola and its tangent (as shown in Figure 3) is given by the following simple equation:

$$h = CS^2 \tag{1}$$

where

- h = vertical height,
- S = horizontal distance from a selected point of tangency, and
- C = coefficient of x^2 in the parabolic expression

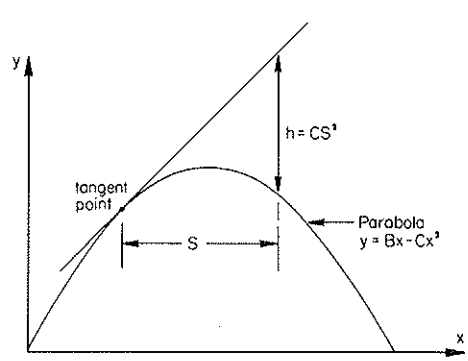


FIGURE 3 Sight distance with respect to a parabola.

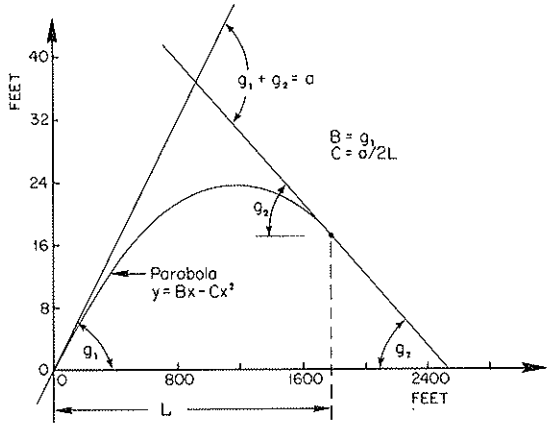


FIGURE 4 Geometric properties of crest vertical curves.

$$y = Bx - Cx^2 \tag{2}$$

The coefficients B and C in Equation 2 are related to the geometric properties of a crest vertical curve by the following equations that use the symbols shown in Figure 4.

$$B = g_1 \tag{3}$$

$$C = (g_1 + g_2)/2L = a/2L \tag{4}$$

Now consider the sight distance between a driver's eyes and an object when both the driver and the object are on the vertical curve; that is,

$$S_e = (h_e/C)^{0.5}$$

$$S_o = (h_o/C)^{0.5}$$

and

$$S_A = S_e + S_o = (h_e/C)^{0.5} + (h_o/C)^{0.5}$$

$$= (2L/a)^{0.5}(h_e^{0.5} + h_o^{0.5}) \tag{5}$$

However, the highway design problem is to find the length of the vertical curve (L) given the needed available sight distance (S_A). Solving Equation 5 for L yields the following design equation that applies when $L > S_A$:

$$L = S_A^2/[(2/a)(h_e^{0.5} + h_o^{0.5})^2] \tag{6}$$

For $L < S_A$, maximum L, corresponding to minimum sight distance, is obtained when both the object and the eye are on either side of the vertical curve. For this case, the following equation is used in design (2, Appendix E):

$$L = 2S_A - [(2/a)(h_e^{0.5} + h_o^{0.5})] \tag{7}$$

Either Equation 6 or Equation 7 can be used to examine the situation in which $L = S_A$. (Clearly, Equation 6 or Equation 7 will give the same result because they are equivalent for $S = L$.) Let L^* be the value of L if L were equal to S_A; specifically,

$$L^* = (2/a)(h_e^{0.5} + h_o^{0.5})^2 \tag{8}$$

The quantity L^* has at least three interesting properties: (a) it does not depend on sight distance, (b) it can be used to simplify Equations 6 and 7, and (c) it can be used conveniently to gain an understanding of the influence of differences in eye heights.

Using L^*, the design equations can be expressed as follows:

For $S_A < L^*$, $L = 2S_A - L^*$

(i.e., for $L < S_A < L^*$) (9)

For $S_A > L^*$, $L = S_A^2/L^*$

(i.e., for $L > S_A > L^*$) (10)

For either $S_A > L^*$ or $S_A < L^*$, the length of vertical curve (L) depends on two separable quantities: (a) S_A, the needed available sight distance, and (b) L^*, which is a function of eye height. The influence of eye height can be illustrated by comparing L_t^*, evaluated for eye heights typical of truck drivers, with L_c^*, evaluated for drivers of automobiles. For example, let the algebraic difference in grades a = 0.06 (6 percent) and h_{et} = 100 in. for trucks and h_{ec} = 40 in. and h_o = 6 in. for automobiles. Then, for the truck,

L_t^* = 431 ft,

and, for the car,

L_c^* = 214 ft.

In general, regardless of the algebraic difference in grades,

$$L_t^*/L_c^* = [(h_{et}^{0.5} + h_o^{0.5})/(h_{ec}^{0.5} + h_o^{0.5})]^2 \tag{11}$$

For h_{et} = 100 in., h_o = 6 in., and h_{ec} = 40 in.:

$L_t^*/L_c^* = 2.01$

For some heavy trucks and drivers, h_{et} might be as low as 90 in. In this case, $L_t^*/L_c^* = 1.85$. Clearly, the significant sight distance advantages of truck drivers (compared with automobile drivers) would greatly reduce the lengths of vertical curves needed for trucks if it were not for the longer stopping distances of trucks.

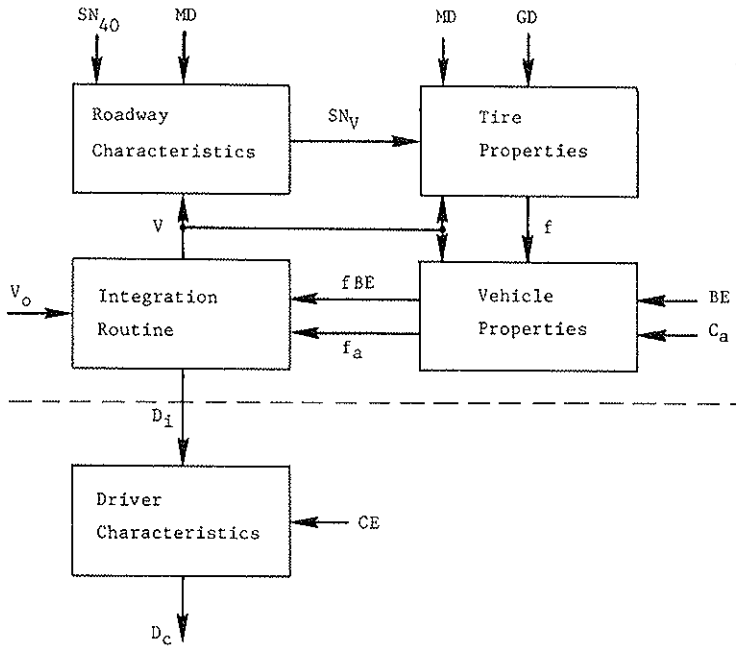
Stopping Distances for Trucks

In this section the significance of providing enough sight distance to allow trucks to make a controlled stop on a "poor, wet road" is addressed.

Stopping sight distance consists of (a) the distance traveled during the time required to perceive the object and to react by applying the brakes plus (b) the braking distance of the vehicle involved. Both the perception and reaction distance and the braking distance depend on the initial velocity of the vehicle. Perception and reaction distance is simply equal to the initial velocity multiplied by the perception and reaction time (i.e., 2.5 sec).

In addition to initial velocity, braking distance depends on the properties of the tire-road interface. Furthermore, for safe, controlled stops, braking distance depends on the braking efficiency of the vehicle and the control efficiency of the driver in modulating the brakes (2).

The following discussion outlines the elements of a procedure for predicting the braking distances of trucks operating on poor, wet roads (2,4). The items considered in this procedure are (a) roadway charac-



SYMBOLS

SN_{40}	-- pavement skid number at 40 mph
MD	-- mean texture depth
GD	-- tire groove depth
SN_V	-- skid number at velocity V
V	-- instantaneous velocity
V_o	-- initial velocity
f	-- tire road friction capability
BE	-- braking efficiency
CE	-- driver control efficiency
C_a	-- aerodynamic coefficients
f_a	-- aerodynamic drag divided by vehicle weight
D_i	-- ideal braking distance (perfect controller)
D_c	-- braking distance for a controlled stop

FIGURE 5 Diagram illustrating the calculation of braking distance.

teristics, (b) tire properties, (c) vehicle properties, and (d) driver control factors. The flow diagram shown in Figure 5 illustrates the sequence of calculations that are to be performed as speed decreases. Because the forces acting on the vehicle are functions of velocity, the equations of motion are solved using an integrative procedure [i.e., a numerical integration routine such as that given in Appendix B of Olson et al. (2)].

The roadway characteristics employed in the basic model are skid number and skid number gradient. The skid number at 40 mph and the skid number gradient are used in an exponential function to predict the skid number at the velocity of current interest in the iterative procedure; that is,

$$SN_V = SN_{40} \exp[P(V - 40)] \tag{12}$$

where

$$P = -0.0016(MD)^{-0.47} \tag{13}$$

V = velocity (mph), and
MD = mean texture depth in inches as determined by the sand-patch method (5).

For wet roads in the United States, the 15th percentile values (representing the poor, wet road) are given by the following equation (2,6):

$$SN_V = 28 \exp[-0.0115(V - 40)] \tag{14}$$

where SN_{40} = 28 and MD = 0.015 in. [Note that the poor, wet road used in the AASHTO design policy is indeed a slippery surface. A reasonable alternative to extreme changes in geometric design may be an improvement in pavement skid resistance (2).]

The equations given in Table 1 have been used for estimating the braking performance of a prototypical truck stopping on a poor, wet (15th percentile) road. The coefficients in these equations have been selected to represent (a) worn truck tires with 2/32 in. of groove depth, (b) the braking efficiency of an empty heavy vehicle with typical brake proportioning, and (c) the aerodynamic drag of a typical heavy truck. These selections correspond to a set of unfavorable conditions that reflects a conservative, safety-biased approach to design.

TABLE 1 Equations for Estimating Braking Distances

Equation	Explanation	Equation No.
$f_s = 0.0084\ SN_V$	f_s is the locked-wheel friction capability of a new truck tire	15
$f_s(2/32\ \text{in.}) = f_s - (0.5918)\ \Delta f$	$\Delta f = -0.0762 + 0.008045V$ and V is the instantaneous forward velocity in mph	16 17[a]
$f_p = 1.45\ f_s$	f_p is the maximum friction capability for a braked but unlocked tire	18[b]
Braking efficiency = BE = $(0.47)/(0.75 + 0.23 f_p)$	BE ≈ 0.55 to 0.59 for an empty truck. For locked-wheel calculations, BE is set equal to 1.0.	19
Control efficiency = CE = 0.62		
Aerodynamic drag = f_a = $0.00238\ A\ C_D\ V^2/W$	A = frontal area (100 ft²) CD = drag coefficient (0.8) W = weight (14,600 lb for an empty truck)	20

[a]Equations 16 and 17 are for estimating the influence of tread wear on friction (2, 7).
[b]Equation 18 is applied to either new or worn tires.

Figure 6 shows the influences of velocity, tire wear, and sliding and rolling friction on the estimated frictional capabilities of truck tires. When these frictional capabilities are combined with braking efficiencies and aerodynamic drag factors, the deceleration capabilities at various velocities may be predicted. Deceleration capabilities for new and worn tires and for the vehicle making locked-wheel and perfectly modulated stops (CE = 1.0) are shown in Figure 7.

Locked-wheel values can be used (as they are in the AASHTO procedure) to calculate locked-wheel stopping distances, but these values are not deemed appropriate for predicting stopping distances that allow drivers to control trucks during stops from highway speeds on poor, wet roads. Truck drivers will modulate their brakes to eliminate wheel lock in order to maintain directional control (2, Appendix B). However, professional truck drivers are not

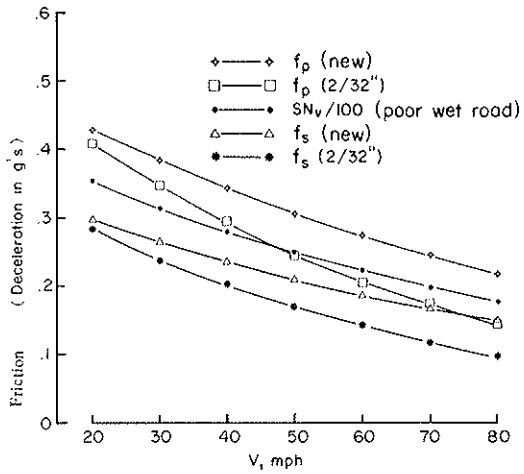


FIGURE 6 Friction capabilities of truck tires on poor, wet roads.

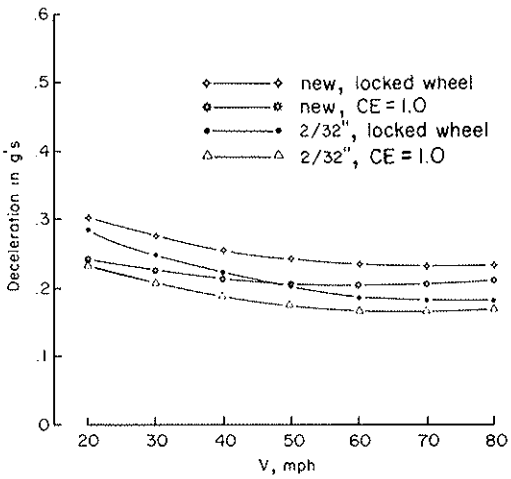


FIGURE 7 Truck deceleration on poor, wet roads.

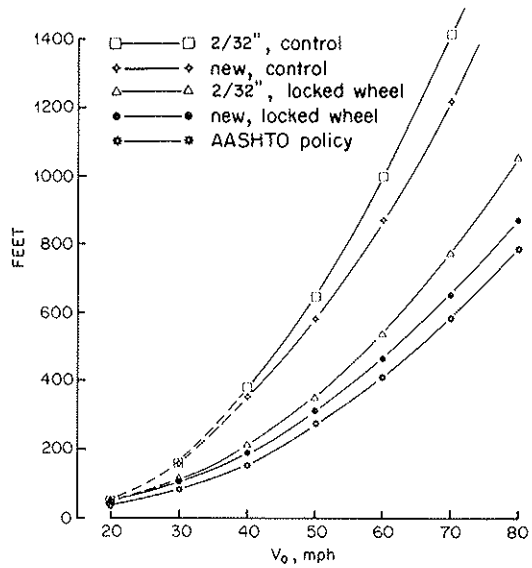


FIGURE 8 Truck braking distances on a poor, wet road.

able to perfectly modulate their brakes to obtain performance corresponding to the maximum capability of the road-tire-vehicle system. Experimental results have been used to estimate that truck drivers attain approximately 62 percent (CE = 0.62) of the performance capabilities of the road-tire-vehicle system (2).

The results of these considerations of truck performance show that trucks with worn tires will require stopping distances that are substantially longer than those recommended in the AASHTO policy. Furthermore, if spins, trailer swings, and jackknifing are to be avoided, controlled stops will require exceedingly long stopping distances at highway speeds (Figure 8).

The notion of attempting to design for trucks passing over crest vertical curves at 60 mph or faster may not be economically reasonable. At 60 mph the braking distances for controlled braking exceed the AASHTO policy for 80 mph (Figure 8). At 55 mph, controlled stops of trucks require braking distances that are approximately equal to the AASHTO policy for 80 mph (i.e., approximately 800 ft).

Consider the cost implications of restructuring a crest vertical curve to allow a braking distance of 800 ft for trucks instead of 340 ft for automobiles at 55 mph. Let the total difference in grade be 0.06 (6 percent) and the initial velocity be 55 mph. Under these circumstances, the controlled stopping sight distance (CSSD) for trucks is 1,002 ft and the AASHTO stopping sight distance for automobiles is 542 ft. From an earlier example, $L_t^* = 431$ ft and $L_c^* = 214$ ft and, applying Equation 10 with S_A = CSSD for the truck, it is found that $L_t = 2{,}329$ ft; for the automobile, $L_c = 1{,}373$ ft.

Another way to consider this situation is to evaluate the acceptable speed of trucks operating on crest vertical curves built for automobiles traveling at 80 mph. In this case (with a = 0.06 still), $L = 5{,}654 \text{ ft} = S_t^2/431$; or $S_t = 1{,}561$ ft. Using the braking distance for a 2/32-in. controlled stop, as shown in Figure 8, it is found that, at 67 mph, braking distance equals 1,315 ft and the perception and reaction distance equals 246 ft. Hence, trucks traveling at 67 mph will be able to make controlled stops on the vertical curve designed for automobiles traveling at 80 mph. Carrying out similar calculations for curves designed for 70 mph and 60 mph yields the results given in Table 2. From this point of view, crest vertical curves designed according to AASHTO recommendations for 70 or 80 mph will be more than adequate for trucks traveling at speeds of less than 59 mph.

SUMMARY AND CONCLUSIONS

This short review of sight distance issues related to the characteristics of heavy trucks has presented technical arguments supporting the following positions:

- The AASHTO curve (1) displaying accelerating time as a function of distance traveled for the WB-50 design vehicle is applicable to current longer trucks as long as the additional length of the truck is included in the distance traveled.
- The initial acceleration distance employed in estimating passing sight distance does not apply to heavy trucks. This portion of the conceptual framework used for determining passing sight distance needs to be revised. Nevertheless, automobiles passing long trucks will spend more time in the left lane than is required for passing another automobile. If the average relative passing speed is 15 ft

TABLE 2 Truck Control Speeds

Car Speed (mph)	AASHTO SSD (ft)	L_c (ft)	S_t (ft)	Controlled Truck Speed (mph)
For a = 0.06 (6%), $L_c^* = 214$ ft, $L_t^* = 431$ ft				
60	650	1,974	922	52
70	850	3,376	1,206	59
80	1,100	5,654	1,561	67
For a = 0.12 (12%), $L_c^* = 107$ ft, $L_t^* = 215$ ft				
60	650	3,949	922	52
70	850	6,752	1,206	59
80	1,100	11,308	1,561	67

Note: L_c = length of vertical curve based on the AASHTO SSD (h_e = 40 in.) and S_t = available sight distance for a truck driver (h_e = 100 in.) operating on a vertical curve of length L_c.

per second, the additional time in the left lane can be readily estimated using the additional length of the larger vehicle.

• The stopping sight distances given in the AASHTO policy for crest vertical curves are much shorter than those needed for stopping trucks while maintaining directional control. The primary factors that contribute to the longer stopping distances estimated for heavy trucks are (a) truck tire properties on poor, wet roads; (b) braking efficiencies of heavy trucks; and (c) driver control efficiencies in modulating the brakes to avoid wheel lock. It is concluded that vertical curves designed for design speeds of more than 60 mph in accord with the AASHTO policy are adequate for trucks traveling at speeds of less than 52 mph. A vertical curve designed in accord with the AASHTO policy for a design speed of 70 mph is adequate for trucks traveling 59 mph.

Although stopping sight distances for horizontal curves were not considered in the body of this paper, the braking distance material presented here is applicable to that situation. For many horizontal curves, the additional eye height of the truck driver will not be an advantage. In those cases, the longer braking distances of trucks will greatly increase the width of the zone to be kept free of sight obstructions, if the heavy truck is used as the design vehicle. [See Appendix E of Olson et al. (2) for a calculation procedure for sight distances on horizontal curves.]

ACKNOWLEDGMENTS

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REFERENCES

1. A Policy on Geometric Design of Highways and Streets, 1984. AASHTO, Washington, D.C., 1984.
2. P.L. Olson et al. Parameters Affecting Stopping Sight Distance. NCHRP Report 270. TRB, National Research Council, Washington, D.C., June 1984.
3. G.D. Weaver and D.L. Woods. Passing and No-Passing Zones: Signs, Markings, and Warrants. Report FHWA-RD-79-5 (PB 80 11 4564). FHWA, U.S. Department of Transportation, Sept. 1978.
4. D.E. Cleveland et al. Stopping Sight Distance Parameters. In Transportation Research Record 1026, TRB, National Research Council, Washington, D.C., 1985, pp. 13-23.
5. M.C. Leu and J.J. Henry. Prediction of Skid Resistance as a Function of Speed from Pavement and Texture Measurements. In Transportation Research Record 666, TRB, National Research Council, Washington, D.C., 1978, pp. 7-18.
6. G.T. Taoka. System Identification of Safe Stopping Distance Parameters. Department of Civil Engineering, University of Hawaii, Honolulu, Sept. 1980.
7. A. Dijks. Influence of Tread Depth on Wet Skid Resistance of Tires. In Transportation Research Record 621, TRB, National Research Council, Washington, D.C., 1976, pp. 136-147.