Stopping Sight Distance Parameters

DONALD E. CLEVELAND, LIDIA P. KOSTYNIUK, GARY R. WAISSI,
PAUL L. OLSON, and PAUL S. FANCHER

ABSTRACT

A review of stopping sight distance parameters has recently been completed for NCHRP. AASHTO currently recommends a driver perception-response time of 2.5 sec and this value was found to be satisfactory. AASHTO currently uses braking distances based on locked-wheel skidding on poor-condition wet pavement surfaces. It was concluded that this is not appropriate for speeds above 30 mph if a vehicle with minimum legal tire tread is to be stopped in its own lane on a wet pavement of this type. For a vehicle to be able to make such a stop it was concluded that braking distances should be increased. At a speed of 40 mph, the distance increases to 360 ft and at 80 mph it increases to 1,630 ft. Examination of recently measured speed distributions showed that drivers continue to select the same speeds on wet pavements as they do on dry roads and that the AASHTO policy of using the same initial speed for both wet and dry conditions should be retained. Lowering the driver eye height to 40 in. from the current AASHTO value of 42 in. would accommodate more than 95 percent of the automobile driver-vehicle combinations expected to be in use late in this decade. Such a change was recommended because a 42-in. eye height would not accommodate 25 percent of the vehicles. No research on the appropriate height of the object was performed. Ten vertical curve locations at which there was less than AASHTO policy minimum available stopping sight distance were found to have an average of about 40 percent more accidents than nearby locations with adequate sight distance. Several horizontal- and vertical-curve geometric design aids based on derivations made in the research are presented.

Stopping sight distance (SSD) is one of the most important criteria in geometric design, affecting both operations and safety. It is defined as the minimum sight distance that will allow a vehicle traveling at or near the design speed to stop just before reaching an object in its path, and it is important that this design element be frequently reviewed in response to changing vehicle and driver characteristics. The University of Michigan's Transportation Research Institute (UMTRI) was selected to carry out such a study. The final report was recently published in the NCHRP series (1). This paper summarizes the research, emphasizing those findings believed to be of particular importance in highway design and traffic control.

SSD application involves considering two concepts, the stopping distance (STD) and the available sight distance (ASD). The ASD depends on the locations of the eye of the driver, the object to be seen on the road, and obstructions to the line of sight caused by the geometry of the road and roadside. SSD is adequate when ASD is greater than STD and inadequate when the opposite condition exists.

STD consists of a perception-response distance (PRD) added to the braking distance (BD). When the speed (V) of the vehicle is considered, PRD is derived from the perception-response time (PRT). The STD on a level road is expressed as follows:

$$STD = 1.47\ V\ PRT + V^2/30\ f \qquad (1)$$

where f is the average deceleration from V to a stop (g). Although every significant parameter in the STD model is stochastic, the model is treated deterministically and the parameters used are drawn from that end of the probability distribution that accommodates poorer performance and results in greater STD values.

This paper is organized into three sections. A study of the effects of ASD on safety is summarized first. Next the three STD elements--initial vehicle speed (V), PRT, and BD--are discussed. The effects of grade and horizontal curvature on BD are considered. The studies concerned with ASD elements, eye and object height and road geometry, are described in the last section. The effects of vertical curvature on ASD for passenger cars and trucks and the sensitivity of ASD to the location of the object and eye in the lane on both horizontal and vertical curves are treated. Night effects on ASD are also considered.

SAFETY STUDIES

It is accepted that SSD has impacts on highway safety but the relationship has not been identified or recently quantified with enough accuracy to be used in evaluation studies. A review of the several studies of the relationship between SSD and safety is included in NCHRP Report 270 (1).

The problem with most of these studies is that it is difficult to separate sight distance effects from other roadway design elements and to maintain proper controls. A limited study of the effects of ASD on safety on tangent sections was carried out as a part of the research.

The number of accidents over a 6-year period was compared at 10 pairs of two-lane rural road segments in close proximity. The sites are located in Oakland and Washtenaw counties in southeastern Michigan. They were matched for traffic characteristics, road design factors, roadside features, traffic control, and abutting land use. The two segments were within 1 mi of each other on the same road with no major intersections between them. One segment was on a vertical curve and had an ASD that was less than the 1965 AASHTO policy value, the current minimum value (2), whereas the other had an ASD exceeding this value. Each limited-ASD (LSD) site had a standard warning sign with a speed advisory plate. Table 1 presents a description of the sites and a summary of the accident data.

TABLE 1 Summary of Safety Study

Site Pair	Site Type	Length (mi)	Speed Limit (mph)	Advisory Speed at LSD Site (mph)	ASD (ft)	No. of Accidents
1	LSD	0.50	45	40	118	11
	Control	0.50	45		>700	3
2	LSD	0.23	50	40	276	1
	Control	0.23	50		536	0
3	LSD	0.40	50	25	188	2
	Control	0.40	50		>700	2
4	LSD	0.25	45	30	174	7
	Control	0.25	45		>700	6
5	LSD	0.22	45	30	118	11
	Control	0.22	45		>700	3
6	LSD	0.25	45	30	250	17
	Control	0.25	45		>700	26
7	LSD	0.24	45	35	262	24[a]
	Control	0.24	45		>700	13[a]
8	LSD	0.15	50	40	308	5
	Control	0.15	50		>700	2
9	LSD	0.17	50	40	280	2
	Control	0.17	50		>700	1
10	LSD	0.20	25	-	223	0
	Control	0.20	25		>700	0
Total	LSD					80
	Control					56

Note: LSD = limited sight distance.
[a]Only 4 yr of accident data were available.

There was a total of 136 accidents for 30.28 mi-years of exposure. Of these, 80 accidents occurred on the LSD sites and 56 occurred on their matched control sections. At seven of the site pairs there were fewer accidents on the control section; in two cases there was a tie; and at only one site were there more accidents on the section with greater ASD. No accident-type differences were apparent.

The group totals were analyzed by standard contingency table techniques. The hypothesis of no significant difference in accident frequency between the LSD sites and the control sites was rejected at the 0.05 level. Hence, it was concluded that the approximately 40 percent more accidents at the LSD sites were not due to chance. It is believed that a larger study of this type should be conducted to confirm and develop a more reliable quantification of the effect of vertical-curve ASD on safety. Studies should also be made on horizontal-curve pairs with only STD varying.

STD ELEMENTS

In this section studies of the three parameters of the STD equation--initial speed (V), perception-response time (PRT), and braking distance (BD)--are summarized. In addition, sensitivity analysis and some interactions with geometric design elements are explored. Recommended changes in AASHTO policies are presented and discussed.

Initial Speed

It was once assumed that motorists travel at a slower speed, the operating speed, on wet pavements than they do on dry roads. The 1965 AASHTO policy (2) used the design speed for dry pavements and the operating speed was assumed for wet pavements for V in STD calculations. Since 1971 the policy (3) has been to use the same speed (the design speed) for both wet and dry conditions. A study of motorist speed behavior was conducted to test the current validity of this policy. Speed distributions were analyzed from 106 rural sites with 55-mph speed limits in five states. The data had been recently collected for the national speed-limit monitoring program (4) for rural Interstates, principal and minor arterials, and major collectors.

Statistical tests of a 10 percent sample of the available 900 daylight hourly distributions indicated that they could be treated as normally distributed at the 0.05 level of confidence. Visual inspection of cumulative plots of the remaining data confirmed this conclusion. This supported the finding that speeds on rural highway facilities are often normally distributed and in this case permitted the use of statistical techniques based on the assumption of normality.

The daylight speed distributions recorded at a set of 25 permanent Illinois speed-monitoring stations for which reliable weather information was also available were compared under wet and dry pavement conditions. Speed data were obtained for up to 3 days per site on days on which it was known to have rained for the whole day and for adjacent days when there had been no rain. An analysis of variance of the hourly speeds revealed no difference in the average and accordingly they were aggregated to provide a daylight total.

The daily cumulative speeds at a site were then compared for rainy and dry days. Generally, the differences between wet and dry pavements were not statistically significant and were never practically important. Figure 1 shows the distribution of the differences in 85th- and 95th-percentile speeds for wet and dry conditions at 25 sites. At these important higher speeds, those of most concern in the determination of STD, the wet and dry pavement speeds are practically indistinguishable. This confirmed the validity of the AASHTO policy not to treat wet and dry pavements differently.

Driver PRT

SSD PRT covers four steps. The driver must detect an obstacle, identify it as a significant hazard, decide to stop, and begin the stop. The case of particular interest in the STD context is the surprise situation in which the motorist is not aware of the presence of an object on the road ahead. In the primary PRT study, subjects drove an instrumented vehicle for several miles for familiarization. They then crested a sharp vertical curve on a tangent section and encountered a surprise in the form of a low-contrast obstacle shaped like a short railroad tie centered in the lane of travel on the reverse slope of the crest. Time and distance measurements were made from when the obstacle first became visible to when the subject removed his foot from the accelerator (perception time) and then from the accelerator release to brake pedal contact (response time). After the surprise encounter the test was repeated several times on the same subjects under "alerted" conditions. These trials required only

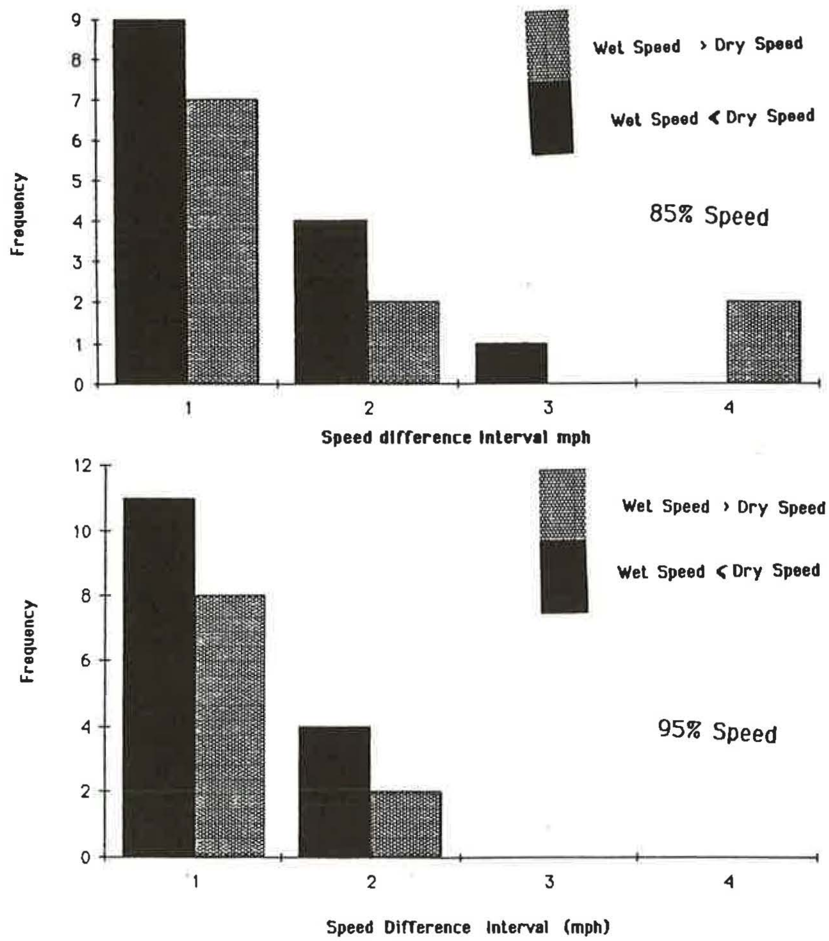

FIGURE 1 Speed differences under dry and wet conditions at the 85th and 95th speed percentiles.

that the subject tap the brake pedal. Finally, in a different driving environment, the subjects released the accelerator and tapped the brake pedal in response to the lighting of a red lamp mounted on the hood of the test car (brake trials).

A total of 64 subjects, 49 younger than 40 years of age and 15 older than 60, was studied. The data for the younger drivers from this study are presented in Figure 2 on a cumulative normal probability scale. The most relevant finding is that for the surprise condition, the 5th- and 95th-percentile values of the PRT were 0.85 and 1.6 sec, respectively. The PRT for the older drivers was substantially the same.

The subjects used in this study, however, were not fully representative of the normal driving population. Their driving times before the tests were short, they knew that they were involved in an experiment of some kind, and they did not appear fatigued or under the influence of alcohol or drugs. Such conditions would be expected to affect the PRT. Studies of the effects of drugs and alcohol indicate that a 50 percent increase in PRT is reasonable (5). Such a correction leads to a 95th-percentile value of 2.4 sec. This is a reasonable percentile for design and is so close to the current 2.5-sec AASHTO policy value that it was concluded that the current value should be retained.

An important factor not considered quantitatively here is the object contrast. The foregoing data are based on a relatively low-contrast condition. However, worse values are possible and this would cause a further increase in the required PRT. There is no information on the distribution of contrasts for real obstacles encountered in actual driving situations, and hence no estimate of the magnitude of this additional correction was made. However, a limited field study of the response time to some object characteristics was made. Seven widely varying conditions with different obstacle height, width, and contrast were evaluated by using 26 observers. The difference in response time among the seven conditions had a range generally of about 0.2 sec, except that for the 95th-percentile observers the range was 0.4 sec and the 98th-percentile subjects had a range of about 0.5 sec. Where there was a great contrast between the obstacle and the background the response time was shorter. It was also observed that a high narrow object that was in poor contrast to the natural background foliage found at this study site required a longer response time.

BD

BD was viewed in the research as being made up of three parts--the basic capability of the tire-road interface to decelerate the vehicle, a measure of the efficiency of the vehicle's braking system under varying loads, and a driver control strategy, which may not use all of the available braking capability, depending both on driver skill as well as on choice. In stops from high speeds the contribution to the

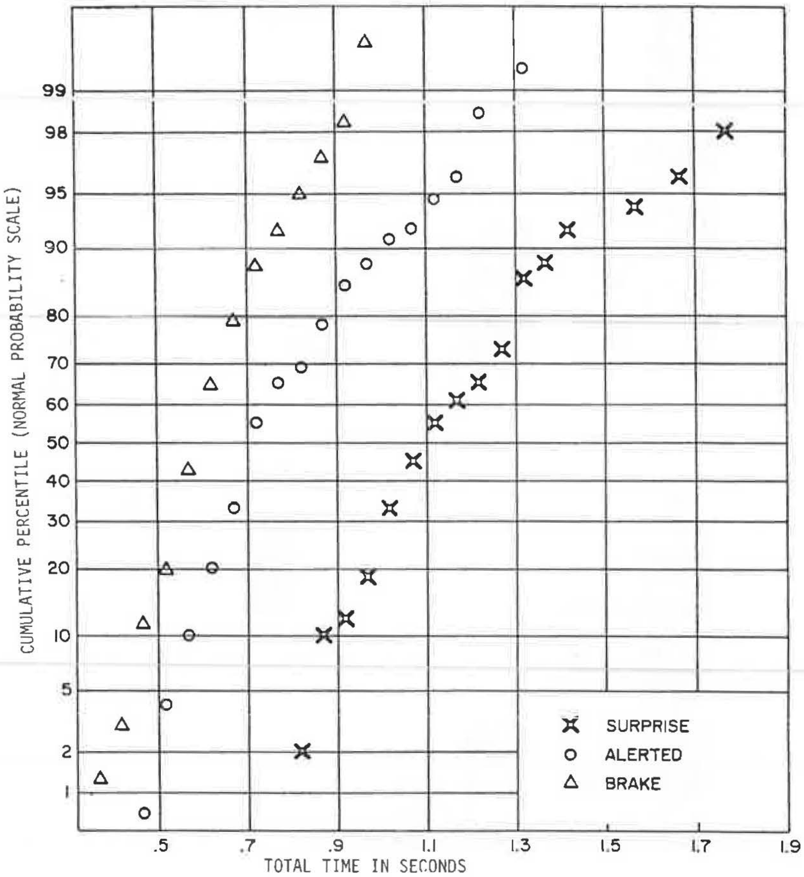

FIGURE 2 Perception-response times for younger drivers.

braking distance from aerodynamic drag also becomes important.

AASHTO policies view the driver as applying the brakes sufficiently hard to lock the wheels; the deceleration then depends only on the condition of the pavement and tires. The road condition is measured by the skid number, a function of the velocity and the pavement texture depth. The condition of the tires is measured by the depth of the treads. In a locked-wheel stop it is assumed that all the available friction is utilized for deceleration.

However, it has been found that drivers generally do not decelerate by locking the wheels but modulate their braking effort in an attempt to minimize BD and maintain directional control and stability. This appears to be particularly true at high speeds on wet pavements. The question then becomes one of determining how deceleration depends on the capability of the vehicle brake system to utilize the friction available at the interface among vehicle, tire, and pavement and the ability of the driver to modulate braking control.

The maximum friction available at the tire-pavement interface in controlled deceleration is greater than that available in the locked-wheel situation, but vehicle braking systems are not capable of utilizing all of the available friction. The term braking efficiency (BE) is used to express the percentage of tire-pavement friction that a perfect driver could achieve and yet maintain control over the vehicle. The braking capability of passenger vehicles has improved significantly over the last decade. The average BE of a 1982 model passenger car is 0.91 (6). The BE of heavy trucks is not as great as that attained by passenger cars. Because truck BE depends on the vehicle geometry, weight, and load distribution, it is best determined separately for each truck configuration.

The ability of a driver to bring the vehicle to a controlled stop is measured by the control efficiency (CE). Analysis of experimental data collected (7) shows that the CE for passenger car drivers decreases with increasing initial speed. In addition a limited set of experiments performed in this research indicates that professional drivers of heavy trucks do not achieve a CE of more than 0.62.

The relationships developed to calculate the instantaneous coefficient of friction (μ) between the road and tires for locked-wheel and controlled decelerations for passenger cars and trucks are given as follows. (The aerodynamic drag deceleration component, which is not shown, is a function of the vehicle velocity and its frontal area and weight.) For a locked-wheel stop, the coefficient for passenger cars is

$$\mu = 0.012 \ A \ SN_V \qquad (2)$$

For trucks it is

$$\mu = 0.0084 \ A \ SN_V \qquad (3)$$

where

$SN_V = SN_{40} \exp[-0.0016(MD^{-0.47})(V - 40)]$,
V = velocity (mph),
MD = mean pavement texture depth (in.) (sandpatch method), and
$A = 1 + (5.08MD - 0.008045V)[1 - (x/12)^{1/2}]$ where x is tire tread depth in 1/32 in. (except for tread depths > 12/32 in., x = 12).

For a controlled stop, the coefficient for passenger cars is

$$\mu = (0.2 + 0.01344SN_V)\ A\ BE_{car}\ CE_{car} \quad (4)$$

For trucks it is

$$\mu = 0.01218\ SN_V\ A\ BE_{truck}\ CE_{truck} \quad (5)$$

where

BE_{car} = 0.91,
BE_{truck} = BE (truck geometry, weight, load distribution) determined for each truck configuration,
CE_{car} = $0.267 + (0.0808 + 0.00543SN_{V_I})A_{V_I}$,
V_I = initial velocity,
A_{V_I} = value of A evaluated at V_I, and
CE_{truck} = 0.62.

The calculation of BD requires integration of the deceleration function over the appropriate range of velocity. The results of this integration can be satisfactorily approximated by using an appropriate average deceleration to solve for the BD. This average deceleration, f in Equation 1, is related to the coefficient of friction and aerodynamic drag by the following formula:

$$f = \mu(0.707V_I) + C_{aero}(0.5)(V_I)^2 \quad (6)$$

where C_{aero} for passenger cars is 10^{-5}. The instantaneous aerodynamic drag is approximately equivalent to a deceleration of only 0.004 g at 20 mph but increases to about 0.064 g at 80 mph. These relationships were used to estimate BD (1) and differ greatly from those in the recently published AASHTO policy (8).

A poor, wet road with a grade change of 15 percent (SN_{40} = 28) was selected for use in illustrating braking performance for both controlled and locked-wheel stops. Figure 3 shows the BD curves for this road for various initial speeds for new tires and for tires that are barely legal, with a 2/32-in. tread depth. It also shows the current AASHTO policy values (8), which can be seen to be very close to those for a locked-wheel stop with barely legal tires. New tires reduce BD by up to 100 ft, whereas controlled stops take up to twice as far as locked-wheel stops. These results make it clear that the current BD values should be increased from 275 to 360 ft at 40 mph and from 625 to 1,200 ft at 70 mph if passenger cars with worn tires are to make controlled stops on wet roads with a 15 percent grade change.

It is believed that the findings of the BD analysis are of the greatest significance among the findings of this research because they affect the STD so significantly. One alternative to lengthening the ASD to the required STD at critical locations is to improve the surface skid capability. For example, increasing the SN_{40} from 28 to 35 (approximately equivalent to a road with a 39 percent grade change) would yield a controlled-stop BD of 414 ft at a speed of 60 mph on a wet road with average partially worn tires (8/32-in. tread), a value consistent with current AASHTO policies. For such tires SN_{40} values from 32 to 37 would achieve desirable AASHTO STD values over the full range of important speeds used in highway design.

ROAD ELEMENTS AND STD

Grades, vertical curves, and horizontal curves all affect BD.

Grades

There are two effects of constant grades (G) on BD. Lengths are based on plane surveying practices that ignore gradients; the actual road extent is greater. On constant grades the additional distance per sta-

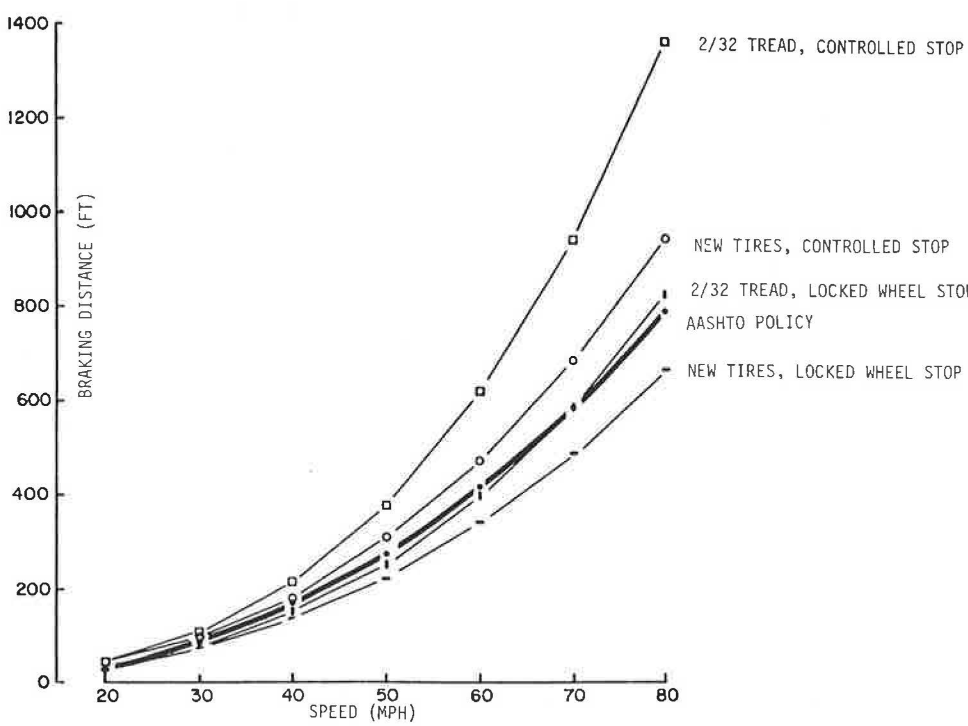

FIGURE 3 Passenger car braking distance on wet, poor road.

tion available with grades of 5 percent is only 0.1 ft/station, whereas for G = 10 percent the value is only 0.5 ft/station. This is clearly of no practical consequence. The second effect comes from the change in resistance to movement as the vehicle climbs or descends a constant grade. This effect can be important when grades exceed 3 percent, and when the increase in BD recommended earlier is taken into account, it should be incorporated into the calculations.

Vertical Curves

Vertical curves affect BD in three ways. In this research it was shown that the true length of a vertical curve (L) is greater than its horizontal projection by a factor of

$$(1 + A/100)^{1/2} \tag{7}$$

where A is the absolute value of the algebraic difference of grades expressed as a percentage. This value is about A/2 percent and therefore gives an increase in effective curve length; hence there is an ASD of about 3 percent for A = 6 percent and 5 percent for A = 10 percent.

A vehicle stopping on a vertical curve faces a continuously varying grade, and this can be taken into account in determining BD. The effect on BD can be substantial and lies between that of the two grades separately. A relation is provided in an NCHRP report (5) that makes a calculation of this value possible.

Finally a vehicle on a vertical curve experiences a centrifugal force that reduces its effective weight on crest curves and increases it on sags. This directly affects the BD because the effective weight affects the braking force, which in turn affects the deceleration and hence the BD. It is shown in an NCHRP report (5) that when a vehicle moves along a parabolic vertical curve, it follows a nearly circular path with a radius approximately equal to 100K, where K is the widely used number of feet along the curve for a 1 percent change in grade. This effect changes BD less than 1 percent for speeds of 50 mph or greater and only 2 percent at speeds of 30 mph. This small effect can be ignored in most applications.

Horizontal Curves

It is well known that the lateral acceleration experienced on a horizontal curve (f_e) decreases the available deceleration for stopping (f). The available total friction (f_t) is related approximately to the others, and by using the force equilibrium relationship for horizontal curves and the BD relationship, one obtains

$$f^2 = f_t^2 - [V^2/(15R) - e]^2 \tag{8}$$

where e is the superelevation of the curve with radius R. At high speeds this effect can be significant on curves with minimum radius designs, as has been recently documented by Neuman (9).

Discussion

The recommended STD distances can be compared with those associated with decision sight distance (DSD) (10). This research tends to bring these values closer together and may lead policymakers to use DSD in preference to STD in certain high-speed applications where alternatives to stopping are clearly available.

ASD ELEMENTS

In this section the geometric relationships developed for the engineer concerned with ASD are considered, with particular emphasis on crest vertical curves and the needed clearances for obstacles to the line of sight on horizontal curves.

Driver Eye Height

A study was made of the distribution of driver eye height for the near-term population of drivers and vehicles from which a desired percentile value could be selected to serve as a possible replacement for the current AASHTO policy of 42 in. (8). Driver eye height clearly varies with several factors, including the vehicle type, seat characteristics, and the size, position, and posture of the driver.

Experimental measurements were beyond the scope of this research and an approach based on recommendations of D. Hammond of the Ford Motor Company was used. This approach uses the Society of Automotive Engineers (SAE) eyellipse data, which provide vertical distances from the vehicle seating reference point (SgRP) to various population percentiles of eye height. In order to determine the driver eye height, SgRP-to-eyellipse distance must be added to the SgRP-to-ground distance, a vehicle-specific characteristic.

Ground-to-SgRP distances were determined for almost all domestic and foreign passenger vehicle models sold in the United States in 1981. Because the two distributions are approximately normal and it is assumed that driver and vehicle distributions are independent, the two distributions were added as shown in Figure 4.

Estimates of 1990 fleet sales by weight, as developed by NHTSA (11) with the assumption that the same weight vehicle would have the same SgRP-to-ground height as the 1981 vehicle did, were then used. The results were close enough to the 1981 values that no change was made. Accordingly, a change in the eye height value from 42 in., which is too high for 25 percent of the vehicles, to a value of 40 in., which will accommodate more than 95 percent of the passenger cars, is recommended.

Object Height

No original research was accomplished on object height. However, a good recent summary of ground clearance data for small cars has been provided by Woods (12). These data indicate that 30 percent of such vehicles would not clear a 6-in. obstacle. A 4-in. obstacle height is required to provide clearance for all these small vehicles. The research report shows the effects of such a value on vertical curve design.

Vertical Curves

SSD affects vertical alignment on tangent roadways on both crest and sag vertical curves. During the day the line of sight from the eye of the driver to the obstacle is broken by the road surface for the crest curve and by an overhead structure for the sag curve. After dark, headlamp illumination affects ASD on both types of curves. In this section the crest

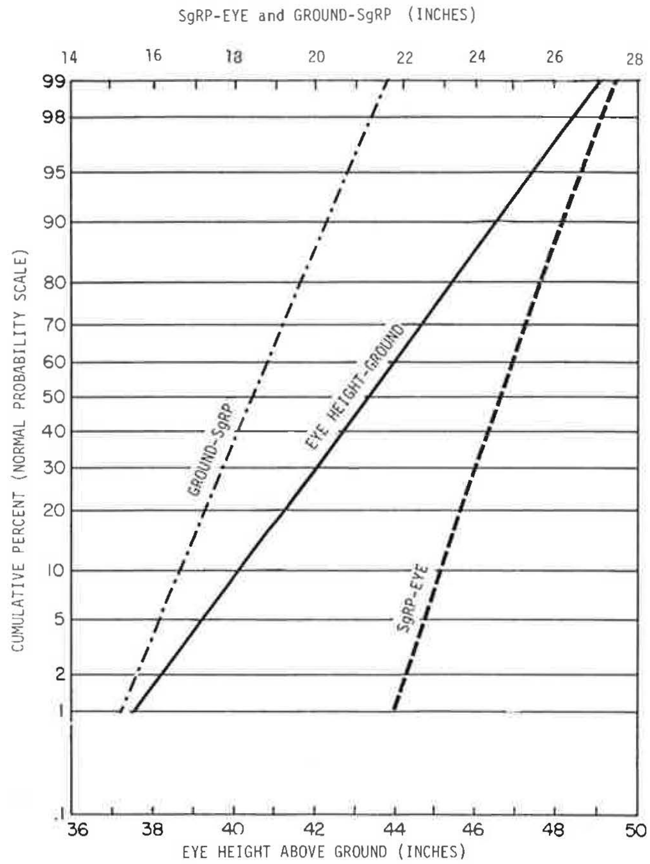

FIGURE 4 Cumulative distribution of eye-SgRP distance, SGRP-ground distance, and eye height above ground.

vertical-curve geometry and the results of an analysis of crest and sag vertical curves are given along with certain important truck and night vision elements.

Figure 5 shows the basic ASD elements for crest vertical curves. The ASD is divided into two components. S_e is the distance from the eye of the observer to the tangent point of the line of sight on the curve, and S_0 is the distance from the tangent point to the top of the object. The difference in grades, a = 0.01A, is here defined as $|0.01G_1 - 0.01G_2|$. The symmetry assumption shown in Figure 5 does not affect the final algebraic relationships developed.

In the general case the total sight distance can be expressed and simplified as follows, called the general sight distance formula:

$$\text{ASD} = L/2 + 100\{h_eL/(Ax) + h_0L/[A(L - x)]\} \qquad (9)$$

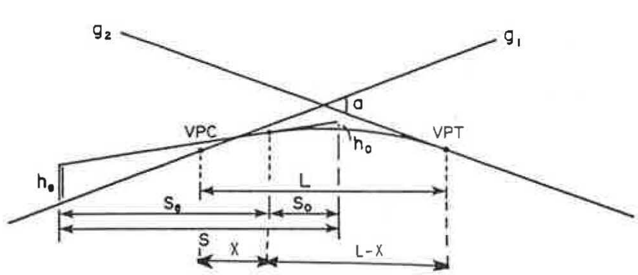

FIGURE 5 Basic elements of sight distance on crest vertical curves.

where

h_e = eye height (ft),
h_0 = object height (ft),
A = absolute value of the algebraic difference in grades (%),
L = curve length (ft), and
x = point of tangency of the line of sight measured from the point of vertical curvature (VPC).

Solutions for all cases can be obtained by using Equation 9 with the results given in Table 2.

With these relationships SD graphs for crest vertical curves can be generated and plotted by computer. Figure 6 shows an example of such an SD graph [see also the paper by Neuman and Glennon (13)]. Such graphs can be used to evaluate the variation in ASD and to compare the STD with the ASD, the time a driver spends on the curve with minimum ASD available, and the locations on the crest vertical curve where the minimum ASD occurs. Computer programs were prepared to generate the data and plot these SD graphs.

Night Visibility

The ASD in the case of a sag vertical curve has been defined by AASHTO as the distance from the eye of the driver to the point on the road where a headlamp beam with an upward divergence of 1 degree from the vehicle axis strikes the road surface (2). The study showed that this model is useful only when the object to be seen has retroreflective properties, because the headlamp illumination above the vehicle's axis is too weak for the driver to see any other object at these distances.

The problem of night visibility on crest vertical curves was also considered. An object beyond a crest vertical curve that would be visible under daytime conditions is shadowed by the road crest at night. The effect of a typical headlamp mounting height on ASD at night was analyzed. Data on the visibility of small, low-contrast objects under headlamp illumination with high beams were used. This effect was concluded to be important only for speeds of 30 mph or less.

Trucks

Experiments were conducted in which the performance of professional truck drivers in stopping their vehicles on wet pavements under various load conditions was studied. For locked-wheel stops on poor, wet roads, trucks require from 1.20 to 1.22 the STD of passenger cars for speeds from 40 to 70 mph. For controlled stops the ratio is from 1.39 to 1.47. With typical values of eye heights for conventional truck and passenger cars of 93 and 40 in., respectively, and a 6-in. object height, calculations show that the required truck STD should be less than 1.35 times that for cars if trucks are to be able to stop within the ASD on crest vertical curves designed for cars. It can be concluded that the greater ASD for trucks compensates fully for the disadvantage in STD in locked-wheel stops. However, trucks require about a 7 percent greater ASD than do passenger cars for controlled stops.

Horizontal Curves

The ASD on horizontal curves is concerned with lines of sight across the inside of such curves as well as

TABLE 2 Formulas for Crest Vertical Curves

Case	Location of Observer/Object	Point of Tangency (x)	Sight Distance Formula[a]
$S < L$	Grade/curve	$0 < x < X_1$	$S = h_e L/(ax) + x/2 + (2h_0 L/a)^{1/2}$
	Curve/curve	$X_1 < x < X_2$	$S = (2h_e L/a)^{1/2} + (2h_0 L/a)^{1/2}$
	Curve/grade	$X_2 < x < L$	$S = (2h_e L/a)^{1/2} + (L - x)/2 + h_0 L/[a(L - x)]$
$S > L$	Grade/curve	$0 < x < X_2$	$S = h_e L/(ax) + x/2 + (2h_0 L/a)^{1/2}$
$S_0 < L$	Grade/grade	$X_2 < x < X_1$	$S = h_e L/(ax) + x/2 + (L - x)/2 + h_0 L/[a(L - x)]$
	Curve/grade	$X_1 < x < L$	$S = (2h_e L/a)^{1/2} + (L - x)/2 + h_0 L/[a(L - x)]$
$S_0 > L$	Grade/grade	$0 < x < L$	$S = h_e L/(ax) + x/2 + (L - x)/2 + h_0 L/[a(L - x)]$

[a] $X_1 = (2h_e L/a)^{1/2}$ and $X_2 = L - (2h_0 L/a)^{1/2}$.

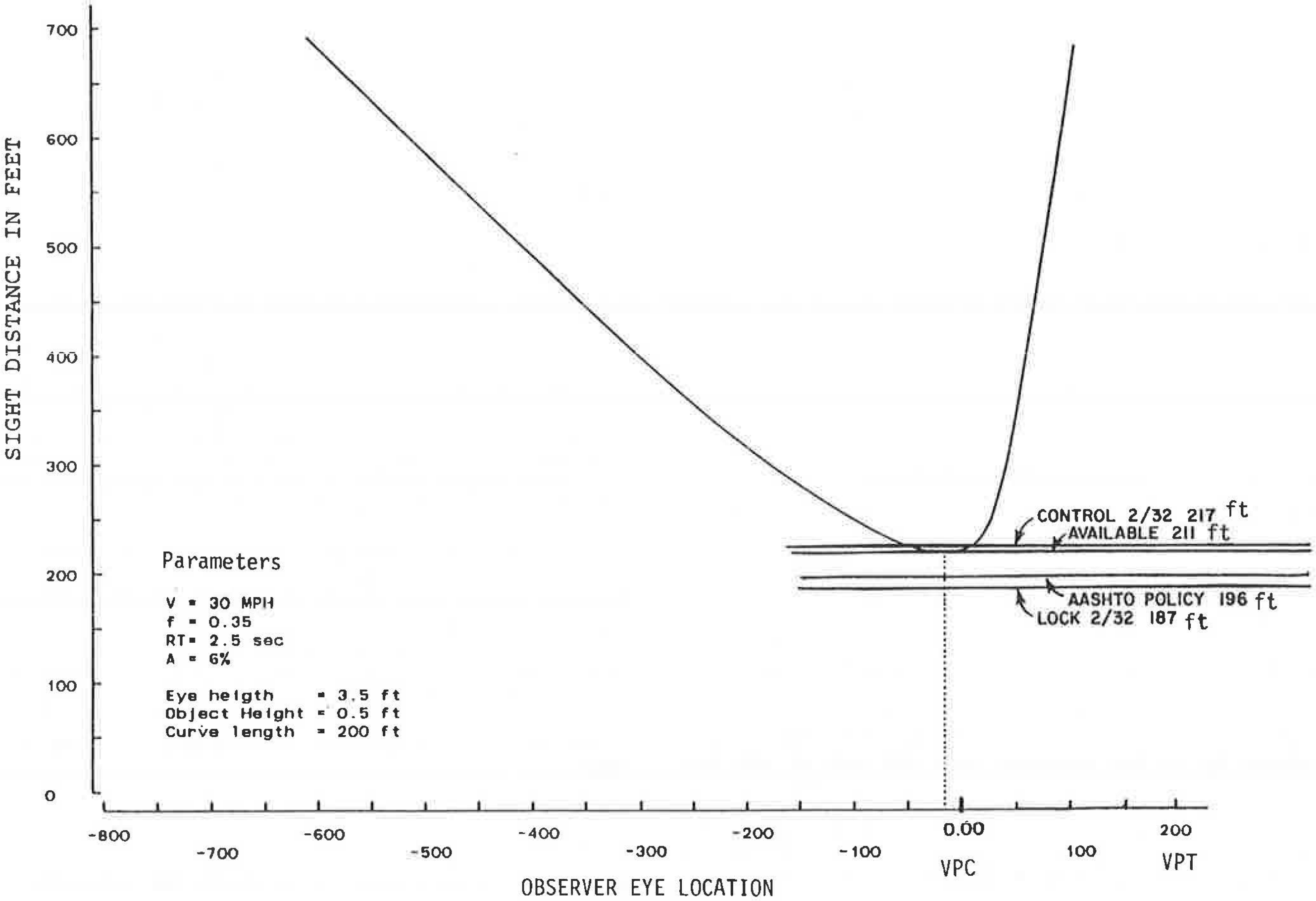

FIGURE 6 SD graph for crest vertical curve.

the location of the eye and object. Of particular importance is the location of the critical obstacle to vision, expressed typically as the clearance (m) along a radial direction from the path of the driver's eye as shown in Figures 7 and 8. Where this clearance is a maximum, which occurs when the STD is less than the length of the curve, M is used in the formulas. Elements that were considered include the changing values of m near the end of the curve as well as the effect of designs using spiral transition curves linking the tangents with the circular portion of the curve.

AASHTO presents clearance requirements for sight obstructions inside horizontal curves only for the case when STD < L and both observer and object are on the curve (2). The other cases all require less clearance for a given STD. This is of particular importance if the longer STD values recommended in this research are used in place of current AASHTO policy values.

Table 3 gives chord approximation relationships for determining the maximum needed clearance M. The chord approximation has less than 0.5 ft error in M for radii of 400 ft or more and is easier to use than the trigonometric relationship commonly encountered.

The case when STD > L has not been treated analytically or summarized in current AASHTO publications. It was found that this value of m can be expressed as a simple function of M for the case when STD < L. The results are shown in Figure 9.

Figure 10 was prepared as a design aid to relate ASD to m when STD > L. It can be used to determine the critical value of any parameter--m, R, I, or ASD--when the other three are given.

When the observer is on the tangent within a distance STD or less from the point of curvature (PC), there is also a required clearance (m) on the tangent section. It varies approximately as a quadratic

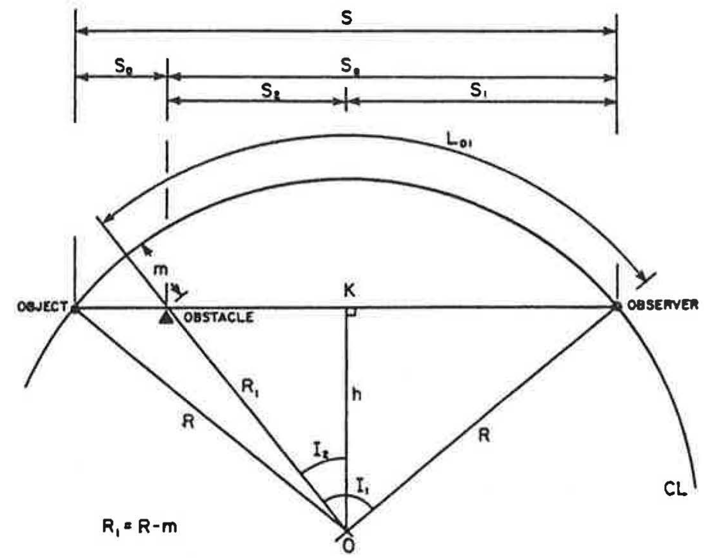

FIGURE 7 Observer and object in the horizontal curve.

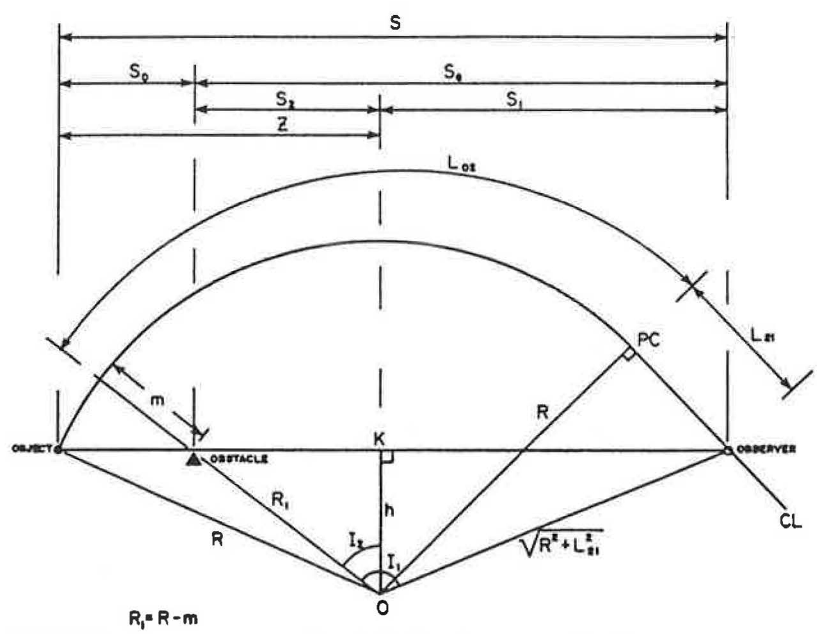

FIGURE 8 Observer on tangent and object in the horizontal curve.

TABLE 3 Horizontal Curve Clearance M (STD < L)

Case	Exact Solution	Chord Approximation
ASD < L	M = R[1 - cos(I*/2)]	$M = (STD)^2/(8R)$
ASD = L	M = R[1 - cos(I*/2)]	$M = L^2/(8R)$
ASD > L	M = R sin(I/2)tan[(I* - I)/2]	M = L(2STD - L)/(8R)

Note: I = central angle of horizontal curve; I* = central angle subtended by STD.

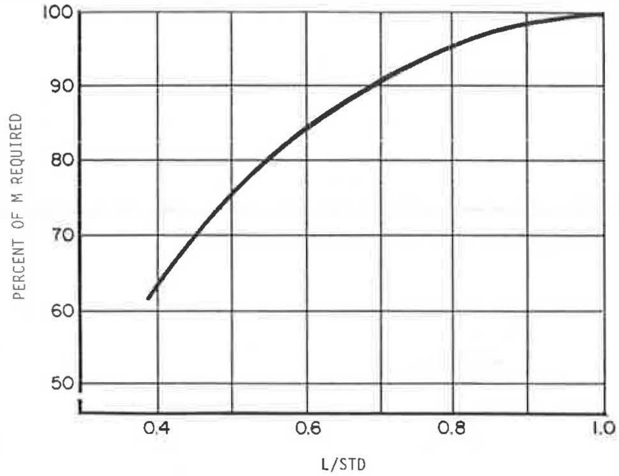

FIGURE 9 Required horizontal curve clearance as percentage of M when STD > L for ASD < L.

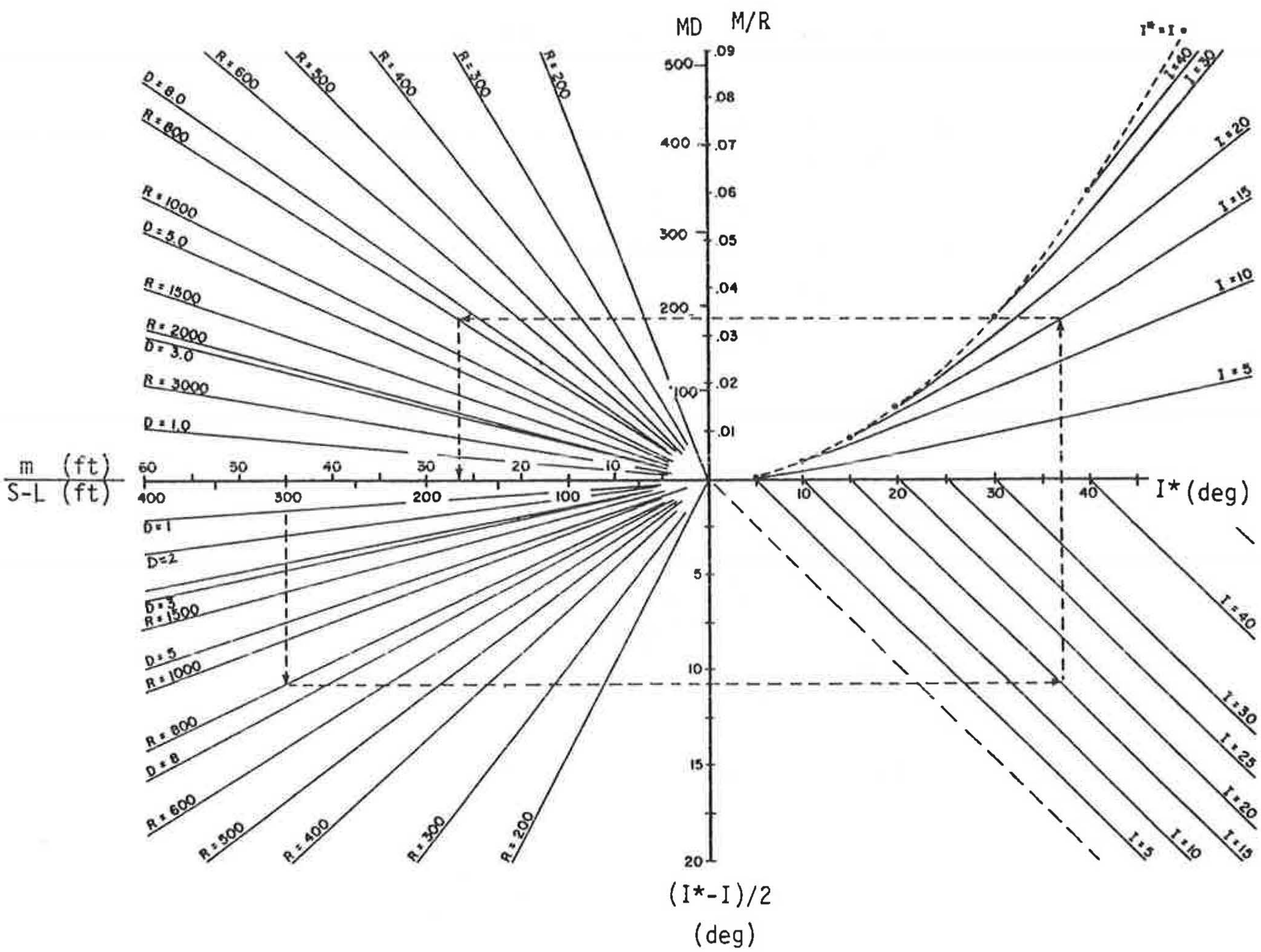

FIGURE 10 Critical lateral clearance on horizontal curves.

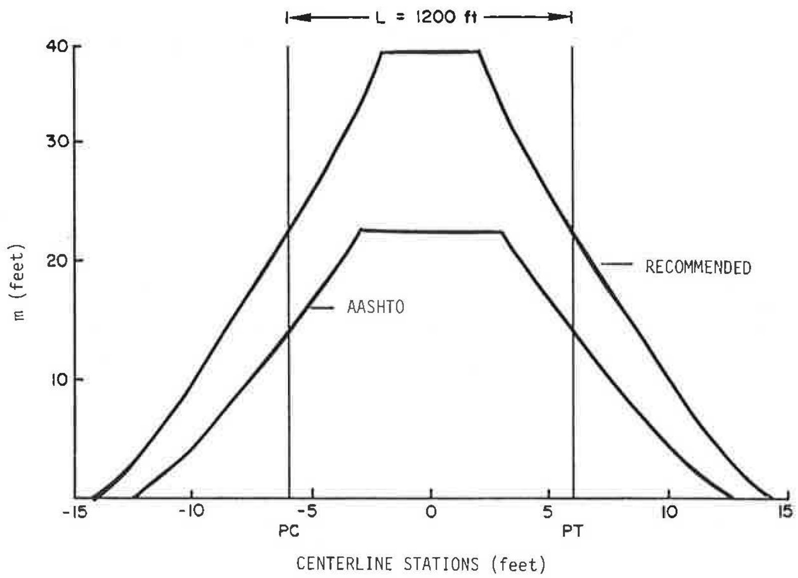

FIGURE 11 Example of needed horizontal curve clearance.

from zero at a point STD in advance of the PC to the full M required on the curve when the observer reaches the PC. Examples of this effect for STD values found in this research and AASHTO recommendations for a 1,200-ft curve with a design speed of 60 mph are shown in Figure 11.

Spiral Transition Curve

A spiral transition curve reduces the needed m while the driver is on the tangent and on the spiral. The magnitude of this effect was studied for typical spirals and it was found that this decrease in the needed m-value would range from about 1 to 4 ft as design speeds increase from 50 to 80 mph.

Position of Eye and Object

Current design practice places the eye and object on the centerline of the critical lane of travel. A sensitivity analysis showed that other reasonable positions of eye and object have no important effect on ASD.

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