Driver Eye-Height Trends and Sight Distance on Vertical Curves

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A review of trends in U.S. passenger-car eye height shows only a slight decrease in eye heights since the early 1960s. Eye heights in contemporary small cars fall on or within the lower eye-height boundary for U.S. sedans. Based on the trend of the past four or five years, passenger-car eye heights do not appear to be decreasing. Analyses were performed to determine the sensitivity of stopping sight distance on vertical curves to driver eye height and other parameters entering into the stopping-sight-distance equations. Sight distance was found to be relatively insensitive to eye height. On a given hill crest, the sight distance for a driver whose eye height is 6 in lower than the design eye height (3.75 ft) is only 5 percent less than the design sight distance. On the other hand, stopping distance is very sensitive to travel speed, pavement friction, and reaction time. For example, a 1.8-mph decrease in speed reduces stopping distance by the same amount that a 6-in decrease in eye height reduces sight distance. In addition, sight distance is about 2.5 times more sensitive to obstacle height than to eye height. It is argued that reductions in travel speed since the introduction of the 55-mph speed limit compensate for any recent or projected decreases in driver eye height. In addition, because the hazard posed by a 6-in-high obstacle has not been established, it is suggested that vertical curves designed for that obstacle height probably incorporate a considerable safety factor.

A current topic of interest in the highway safety community is the effect of the changing mix of vehicle sizes and types on the compatibility of highway and vehicle design practices. One frequently mentioned issue is the lowering of driver eye heights as a consequence of the recent and continuing trend toward smaller cars. Present highway engineering design practice to ensure adequate sight distance on hills is based on the driver eye heights that prevailed in the passenger-car fleets of the early 1960s. Several recent papers (1-4) have expressed the concern that these practices and the designs resulting from them will not provide adequate sight distance for small-car drivers.

The purpose of this paper is to analyze the role of driver eye height in determining sight distance on hill crests and, in particular, to evaluate the sensitivity of sight distance to eye height and other highway geometry and vehicle parameters. As we will see, the reductions in driver eye height that might be brought about by the advent of small cars are unimportant compared with other factors that determine sight distance and sight-distance requirements.

Much of the material presented here is based on a paper published by the Society of Automotive Engineers (SAE) (5).

VERTICAL CURVE GEOMETRY

Hill crests are called crest vertical curves in highway engineering parlance. A crest vertical curve is the transition curve, usually a parabola, that connects the up and down grades that define the two sides of a hill. For vehicles approaching the crest of a vertical curve, the hill obstructs the view of the road ahead. Current design practices for crest vertical curves are given in the American Association of State Highway Officials (AASHO) design guide (6). Design policy for crest vertical curves is based on the need to provide drivers with adequate "stopping sight distance"--that is, enough sight distance to permit drivers to see an obstacle soon enough to stop for it under some set of reasonable worst-case conditions.

The parameters that determine sight distance on crest vertical curves are shown in Figure 1. They are change of grade (A)--that is, the algebraic difference between the slopes of the up and down grades--the horizontal length of the curve (L), and the heights above the ground of the driver's eye (H_e) and the obstacle to be seen (H_0). The length of curve required to provide a given sight distance (S) is given by the following expression:

$$L = A\,S^2/[100(\sqrt{2H_e}+\sqrt{2H_0})^2] \quad L > S \tag{1}$$

Solving for sight distance gives

$$S = 10\sqrt{L/A}\,(\sqrt{2H_e}+\sqrt{2H_0}) \tag{2}$$

For a given change of grade, the longer the curve length, the milder is the curve and the greater is the sight distance. Design values for these parameters are specified in the AASHO design guide (6).

The criterion for setting sight distance on vertical curves is the distance required to stop for an obstacle in the road. The expression used in the AASHO design guide to calculate stopping distance is

$$D = 1.467\,(RT)\,V + V^2/30f \tag{3}$$

where

- D = stopping distance (ft),
- RT = reaction time (s),
- V = speed (mph), and
- f = tire-pavement coefficient of friction.

The constants translate miles per hour into feet per second. Current practice assumes relatively poor conditions for stopping: a 2.5-s reaction time and a locked-wheel, wet-pavement stop. The effective pavement friction values assumed in the AASHO design guide range from 0.36 for stops from 30 mph to 0.29 for stops from 70 mph.

From Figure 1, it is clear that, on a given crest vertical curve, the sight distance also depends on the driver eye height and on the height of the target obstacle. On a given hill, the sight distance will increase with both target height and eye height. Conversely, the length of curve required to provide a given sight distance depends on the eye height and target height. The greater the height of either eye or target, the shorter is the length of vertical curve required to provide a given sight distance. Thus, a vertical curve design based on a given eye height will provide less sight distance to drivers with lesser eye heights. In the AASHO design guide (6), the "design" eye height for vertical curve design is 45 in and the design obstacle height is 6 in. These figures are currently under review by highway agencies.

The central issue in the design of vertical curves is the trade-off between sight distance and the cost of excavation: On a given hill, the required length of curve increases with the square of the sight distance, and the volume of soil and rock that must be excavated so that length of curve

Figure 1. Hill-crest geometry and sight distance.

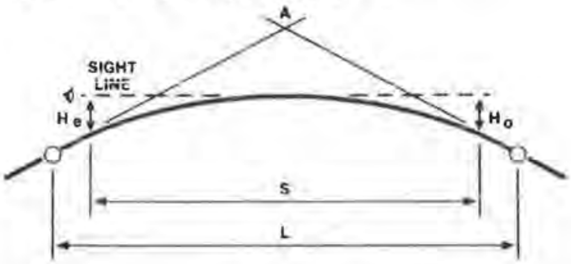


Figure 2. Length of vertical curve and associated excavation volume versus sight distance.

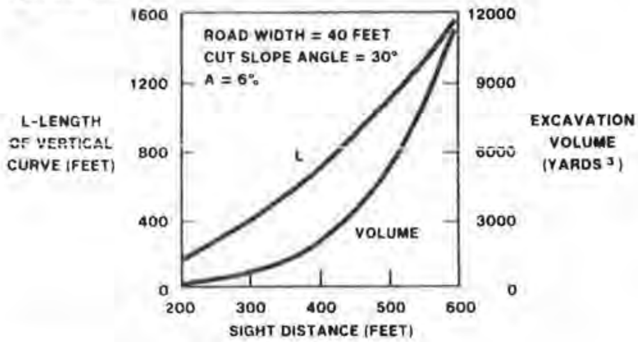
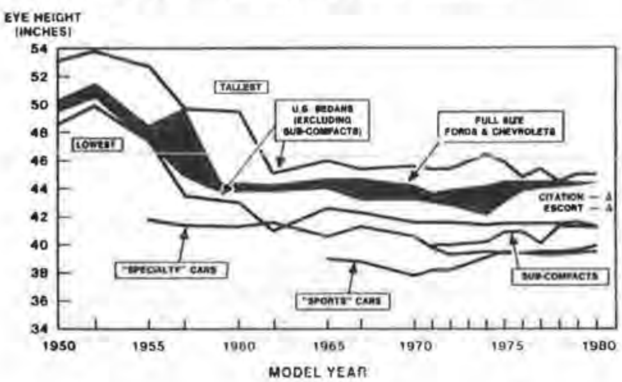


Figure 3. Eye-height trends in U.S. passenger cars: 1950-1980.



increases with the fourth power of the sight distance. These relations are illustrated in Figure 2.

EYE-HEIGHT TRENDS

Before the analysis is discussed, it will be useful to look at actual trends in U.S. passenger-car eye heights over the past three decades. Figure 3 shows a plot of the median driver eye height (i.e., the centroid of the SAE eye ellipse) of the major domestic passenger-car lines for selected model years between 1950 and 1980. The continuous top and bottom lines show, respectively, the highest and lowest U.S. passenger-sedan eye height in each model year, excluding subcompacts. Lowest eye heights for subcompacts are shown in a separate line. The cars that constitute the domestic subcompact class are the Pinto, Bobcat, Vega, and Chevette. Also shown are the eye heights for full-sized Fords and Chevrolets and the lowest eye heights for "specialty cars" and two-seater sports cars. The specialty-car class includes vehicles such as the Thunderbird, Mustang, Camaro, and Firebird. Note that these curves show boundary values and trends for certain car classes and are not based on sales-weighted averages.

Vehicle dimensioning and measuring systems have changed since the early 1960s, and it may be that the eye heights in the first part of the graph are not compatible with later data. Nevertheless, the trend that shows the decline in eye height through the 1950s parallels the changes in roof heights over that period and is probably correct.

In any event, it is apparent that most of the decrease in passenger-car eye height over the past 30 years took place in the 1950s. By the early 1960s, minimum passenger-car eye heights were on the order of 41 or 42 in, where they remain today. Since the late 1970s, subcompact eye heights have been greater than 41 in, and the newer small cars generally have design eye heights greater than 42 in. Note that it is the specialty cars and sports cars, not the new subcompacts, that have the lowest eye heights. Based on the trend of the past four or five years, passenger-car eye heights show no signs of further decreases.

The highway design eye height specified by AASHO in 1966 was 45 in. This was regarded by AASHO as an average value. Not since the model years of the late 1950s has an eye height of 45 in been representative (i.e., toward the bottom of the range) of U.S. cars. In the absence of sales-weighted data, there is no way to determine what fraction of passenger-car eye heights is above or below a given value. However, the data in Figure 3 suggest that a representative eye height might be 41 or 42 in, if variation among drivers in seated eye heights is considered.

SENSITIVITY TO EYE-HEIGHT CHANGES

How is visibility over the crest of a hill affected for a driver whose eye height is other than the value assumed in the design of the curve? The sensitivity of sight distance to eye height is expressed by the partial derivative, $\partial S/\partial H_e$, which gives the rate of change of sight distance with respect to eye height. The expression for this partial derivative is as follows (the derivation of this and the other partial derivatives used in the analysis is shown in Figure 4):

$$\partial S/\partial H_e = S/2\,(H_e + \sqrt{H_e H_0}) \quad (4)$$

If this expression is normalized by dividing through by sight distance, the result gives the fractional change in sight distance per unit change in eye height:

$$\partial S/\partial H_e/S = 1/2\,(H_e + \sqrt{H_e H_0}) \quad (5)$$

For the design values of eye height and object height (45 and 6 in) currently in use, the result is constant at 0.81 percent change in sight distance per inch change in eye height. Figure 5 shows a graph of Equation 4 and the change in sight distance per inch change in eye height as a function of the design sight distance. Thus, for example, on a crest vertical curve where the design sight distance is 300 ft, an inch change in eye height will produce a 2.4-ft change in the sight distance. A vertical curve designed to accommodate 60-mph traffic will provide 634 ft of sight distance (Equation 3). On such a curve, an inch change in eye height will produce a 5-ft decrease in sight distance. A convenient generalization is that a 6-in change in eye height will produce about a 5 percent change in sight distance.

This relation is illustrated in Figure 6, which

Figure 4. Mathematical derivation of partial derivatives used in study.

Mathematical Derivations

Partial Derivatives

Expressions are numbered consecutively. Numbers in brackets are the numbers given the expressions in the main text.

I. $\partial S/\partial H_e$

$S = 10\,L/A\,(\sqrt{2H_e} + \sqrt{2H_o})$ (1) [1]

$\partial S/\partial H_e = 10\sqrt{L/A}/\sqrt{2H_e}$ (2)

From (1),

$10\sqrt{L/A} = S/(\sqrt{2H_e} + \sqrt{2H_o})$ (3)

Substituting (3) into (2) and simplifying,

$\partial S/\partial H_e = S/[\sqrt{2H_e}\,(\sqrt{2H_e} + \sqrt{2H_o})]$ (4)

$\partial S/\partial H_e = S/[2(H_e + \sqrt{H_e H_o})]$ (5) [4]

II. $\partial D/\partial V$

$D = 1.467(RT)V + V^2/30f$ (6) [3]

For RT = 2.5 s,

$\partial D/\partial V = (V/15f) + 3.67$ (7) [6]

III. $\partial V/\partial H_e$

Setting S = D [(1) and (6)] gives

$10\sqrt{L/A}(\sqrt{2H_e} + \sqrt{2H_o}) = 1.467\,(RT)\,V + V^2/30f$ (8)

and also

$\partial S/\partial H_e = \partial D/\partial H_e$

Recalling that

$\partial S/\partial H_e = S/2(H_e + \sqrt{H_e H_o})$ (5)

and differentiating implicitly with respect to H_e, while holding H_o and RT constant,

$S/2(H_e + \sqrt{H_e H_o}) = (1.467\,(RT) + V/15f)(\partial V/\partial H_e)$ (9)

Solving for $\partial V/\partial H_e$ and setting RT = 2.5,

$\partial V/\partial H_e = \{S/[2(H + \sqrt{H_e H_o})]\}$
$\times \{1/[1.467\,(RT) + V/15f]\}$ (10)

But, by assumption,

$S = D = 1.467\,(RT)V + V^2/30f$

Substituting D for S in (10) gives

$\partial V/\partial H_e = \{[1.467\,(RT)V + V^2/30f]$
$\div [1.467(RT)V + V/15f]\}$
$\times \{1/[2(H_e + \overline{H_e H_o})]\}$ (11)

For $H_e = 3.75$, $H_o = 0.5$, RT = 2.5,

$\partial V/\partial H_e = 0.1V[(110.1f + V)/(110.1f + 2V)]$ (12) [7]

IV. $\partial D/\partial (RT)$

$D = 1.467\,(RT)V + V^2/30f$ (6) [3]

$\partial D/\partial (RT) = 1.467V$ (13) [8]

V. $\partial(RT)/\partial(H_e)$

Setting S = D gives

$10\sqrt{L/A}\,(\sqrt{2H_e} + \sqrt{2H_o}) = 1.467(RT)V + V^2/30f$ (14)

Differentiating implicitly with respect to H_e while holding H_o, V, and f constant gives

$S/[2(H_e + \sqrt{H_e H_o})] = 1.467V\,[\partial(RT)/\partial H_e]$ (15)

$\partial(RT)/\partial(H_e) = \{S/[2(H_e + \sqrt{H_e H_o}]\} \cdot (1/1.467V)$ (16)

Substituting D for S,

$\partial(RT)/\partial(H_e) = \{[1.467(RT)V + V^2/30f]$
$\div [2(H_e + \sqrt{H_e H_o})]\} \cdot (1/1.467V)$ (17)

Setting $H_e = 3.75$ and $H_o = 0.5$,

$\partial(RT)/\partial(H_e) = (RT + V/44f)/10.24$ (18) [9]

VI. $\partial D/\partial f$

$D = 1.467(RT) + V^2/30f$ (6) [3]

$\partial D/\partial f = -(V^2/30f^2)$ (19) [10]

VII. $\partial f/\partial H_e$

Setting S = D,

$10\sqrt{L/A}\,(\sqrt{2H_e} + \sqrt{2H_o}) = 1.467\,(RT)V + V^2/30f$

Differentiating implicitly with respect to H_e while holding H_o, V, and RT constant gives

$S/[2(H_e + \sqrt{H_e H_o})] = -(V^2/30f)(\partial f/\partial H_e)$ (20)

Substituting D for S and solving for $\partial f/\partial H_e$,

$\partial f/\partial H_e = -\{[1.467(RT)V + V^2/30f]/[2(H_e + \sqrt{H_e H_o})]\}$
$\times (30f/V^2)$ (21)

Setting RT = 2.5, $H_e = 3.75$, and $H_o = 0.5$,

$\partial f/\partial H_e = (30f/V^2)\,[(110V + V^2/f)/10.24]$ (22) [11]

VIII. $\partial S/\partial H_o$

The derivation for this partial derivative is the same as for $\partial S/\partial H_e$ (4).

Figure 5. Sensitivity of sight distance to eye height versus design sight distance.

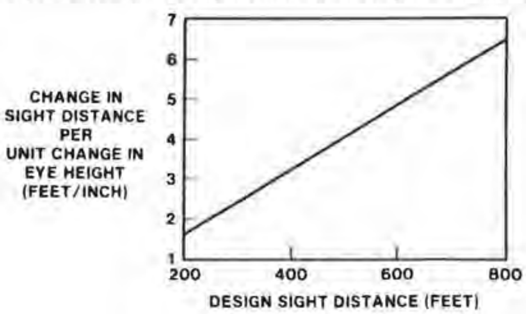
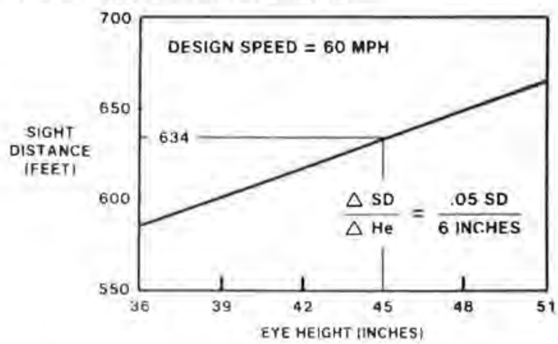


Figure 6. Sight distance versus eye height.



shows sight distance as a function of eye height on a 60-mph design speed vertical curve. For a driver with a 42-in eye height, the sight distance will be about 619 ft, 15 ft less than the design sight distance. With a 39-in eye height, the sight distance would be about 603 ft, 31 ft less than the design sight distance.

SENSITIVITY TO OTHER PARAMETERS

To help put these results in perspective, the sensitivity of stopping sight distance requirements on vertical curves to the other parameters entering into Equations 2 and 3 has been calculated. These analyses are summarized in the following paragraphs. Design eye and obstacle heights of 45 and 6 in, respectively, are assumed in the calculations.

Travel Speed

Travel speed is one of the factors entering into the expression for determining stopping distance (Equation 3), which in turn becomes the design sight distance. The partial derivative of stopping distance with respect to speed (assuming a constant f for simplicity) is given by

$$\partial D/\partial V = (V/15f) + 3.67 \quad (6)$$

This expression is plotted in Figure 7 and shows the rate of change of stopping distance per unit change in speed as a function of the travel speed. As the figure indicates, the stopping distance is quite sensitive to speed. For example, at 60 mph, each 1-mph change in speed results in a 17-ft change in stopping distance. This means that, on a vertical curve designed for 60-mph traffic, a 1-mph increase over the assumed speed will result in a sight-distance deficiency of 17 ft. From Figure 6, it can be determined that, for an eye 3.5 in lower than the design eye height, the sight distance will be 17 ft less than the design sight distance on a 60-mph vertical curve. Thus, a 1-mph increase in speed is equivalent to a 3.5-in decrease in eye height in that, in either case, the stopping distance will exceed the sight distance by 17 ft. Another way to put it is that a 1-mph decrease in speed will compensate for a 3.5-in decrease in eye height.

Figure 7. Sensitivity of stopping distance to speed versus travel speed.

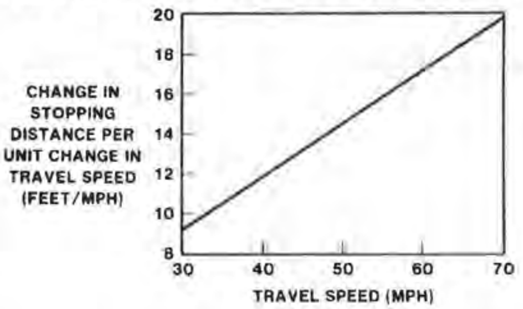


Figure 8. Design speed versus change in speed required per unit change in eye height for stopping distance to equal sight distance.

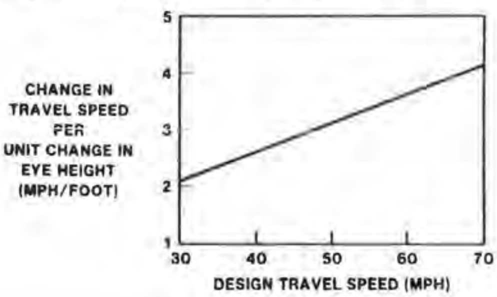


Figure 9. Travel speed versus eye height where stopping distance equals sight distance.

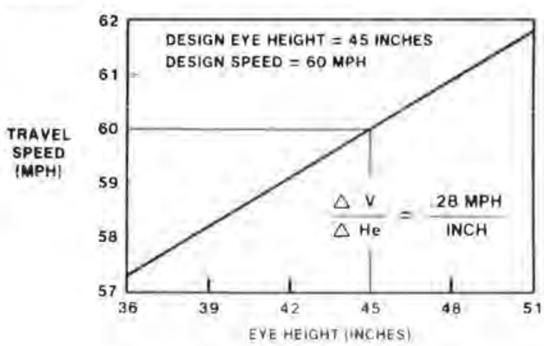
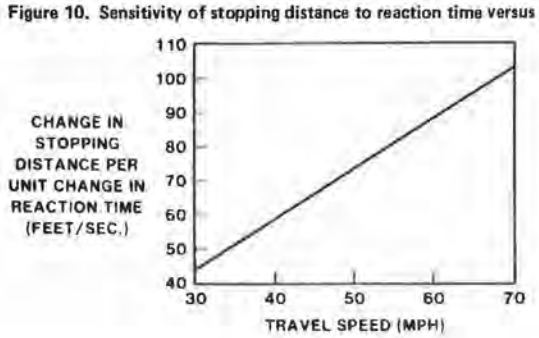


Figure 10. Sensitivity of stopping distance to reaction time versus travel speed.



The sensitivity of this trade-off between speed and eye height is made explicit by setting stopping distance equal to sight distance and finding the partial derivative of speed with respect to eye height:

$$\partial V/\partial H_e = 0.1V\,[(V + 110f)/(2V + 110f)] \quad (7)$$

This parameter is plotted in Figure 8 as a function of the speed assumed for the design of the vertical curve. Equation 7 indicates how much change in eye height up or down is required to compensate for an increase or decrease in speed so as to keep the sight distance equal to the stopping distance. For example, on a curve designed for 50 mph, a 1-ft drop in eye height would decrease the sight distance as much as a 3.1-mph reduction in speed would decrease the stopping distance. On a 60-mph vertical curve, the rate is 3.6 mph per foot of eye height.

Figure 9 shows the relation between speed and eye height on a 60-mph vertical curve, given that sight distance is held equal to stopping distance. The slope of the curve is the speed/eye-height partial derivative evaluated at 60 mph, 3.6 mph/ft, or 0.30 mph/in. This graph makes it very clear that small deviations from the design speed are equivalent to large deviations from the design eye height.

Reaction Time

Current highway engineering practice as set forth by the AASHO design guide (6) assumes a driver reaction time of 2.5 s. This is the value used to calculate stopping distance as given in Equation 3. Figure 10 shows a plot of the partial derivative of stopping distance with respect to reaction time:

$$\partial D/\partial (RT) = 1.47V \quad (8)$$

The figure shows the rate of change of stopping distance with respect to reaction time at different travel speeds. The slope is fairly steep, and at the higher speeds a small increase in reaction time has a substantial effect on stopping distance--e.g., 88 ft of stopping distance per second of reaction time at 60 mph.

Now the same procedure is followed as in the analysis of the trade-off between eye height and speed. First, it is noted that, on a given vertical curve, for any deviation from the design eye height there is a corresponding change from the design reaction time that will keep the stopping distance equal to the sight distance. For example, the sight distance on a 60-mph vertical curve for a 39-in eye height will be 31 ft less than the design sight distance (i.e., the stopping distance computed from Equation 3). The equivalent decrease in reaction time is 0.35 s because, by Equation 3, a 2.15-s reaction time results in a 603-ft stopping distance.

Figure 11 shows a plot of the partial derivative of reaction time with respect to eye height under the constraint that the stopping distance equals the sight distance. The expression for this derivative is

$$\partial RT/\partial H_e = (RT + V/44f)/10.24 \qquad (9)$$

The function is almost a straight line and shows that the reaction time required to compensate for a change in eye height increases as the travel speed assumed for design purposes increases. At 60 mph, a 0.7-s decrease in reaction time would decrease stopping distance as much as a 1-ft drop in eye height would decrease sight distance. Figure 12 shows the relation between reaction time and eye height on a 60-mph crest. At this design speed, the trade-off is about 0.06 s of reaction time per inch of eye height.

Pavement Friction

Tire-pavement friction is another parameter that enters into the stopping-distance equation (Equation 3) and thus helps determine sight-distance requirements. The sensitivity of stopping distance to pavement friction is given by the partial derivative of stopping distance with respect to the friction coefficient:

$$\partial D/\partial f = -V^2/30f^2 \qquad (10)$$

This function is plotted versus design travel speed in Figure 13. As the design travel speed increases, the sensitivity of stopping distance to pavement friction also increases. At 50 mph, an increase of 0.01 in friction coefficient will produce about a 9-ft drop in stopping distance. The trade-off between eye height and pavement friction is given by setting sight distance equal to stopping distance and finding the partial derivative of pavement friction with respect to eye height:

$$\partial f/\partial H_e = -(f/V)\,[(110f + V)/10.24] \qquad (11)$$

This parameter is plotted as a function of speed in Figure 14. The expression gives the change in pavement friction per unit change in eye height required to keep stopping distance equal to sight distance. The change in friction equivalent to a given eye-height change falls off rapidly with increasing speed. On a hill crest designed for 30 mph and a 45-in eye height, a 0.041 increase in pavement friction would compensate for a 6-in drop in eye height. On a 60-mph hill, the same decrease in eye height would require an increase in friction of only 0.022. The relation between eye height and pavement friction for a 60-mph vertical curve is plotted in Figure 15.

Obstacle Height

Of all the parameters that enter into the calculations of stopping sight distance, obstacle height is the most arbitrary. The other parameter values specified in the current design guide are based on studies conducted by various highway agencies and research organizations. The 6-in obstacle height appears to have been arrived at on the basis of a trade-off between practical cost considerations and the intuitive notion that, ideally, the driver should be able to see the road surface continuously up to the stopping-distance point.

Figure 16 shows a plot of the sensitivity of sight distance to obstacle height:

$$\partial S/\partial H_0 = S/2\,(H_0 + \sqrt{H_e H_0}) \qquad (12)$$

The expression is identical to Equation 4 except that H_o and H_e are interchanged. The eye-height/sight-distance line from Figure 5 is also plotted in Figure 16 for comparison purposes. It is obvious that sight distance is considerably more

Figure 11. Design speed versus change in reaction time per unit change in eye height required for stopping distance to equal sight distance.

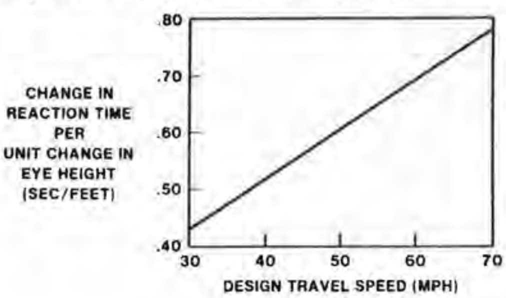


Figure 12. Reaction time versus eye height where stopping distance equals sight distance.

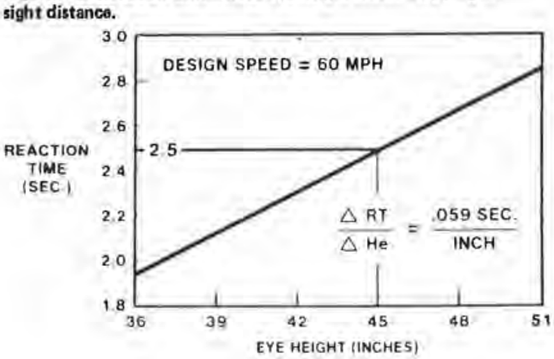


Figure 13. Sensitivity of stopping distance to coefficient of tire-pavement friction versus travel speed.

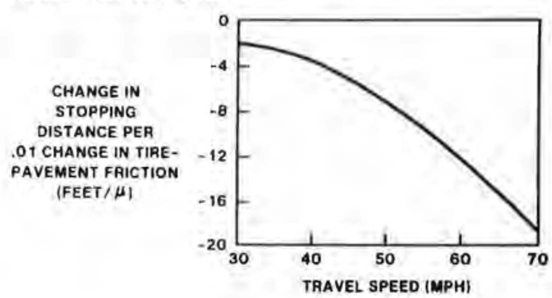


Figure 14. Change in tire-pavement friction per foot change in eye height required for stopping distance to equal sight distance.

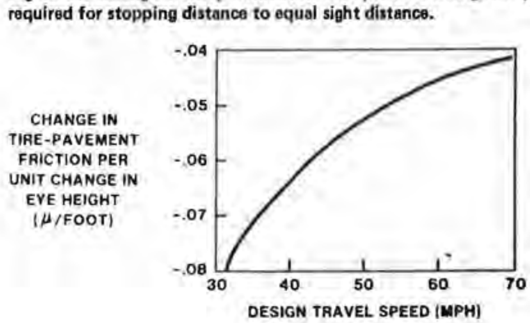


Figure 15. Tire-pavement friction versus eye height where stopping distance equals sight distance.

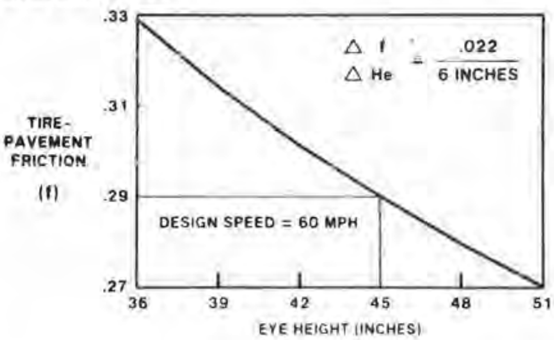


Figure 16. Sensitivity of sight distance to changes in eye height and obstacle height versus design sight distance.

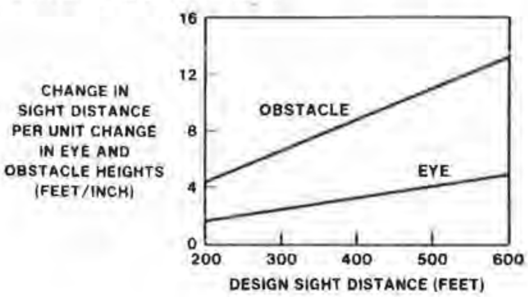
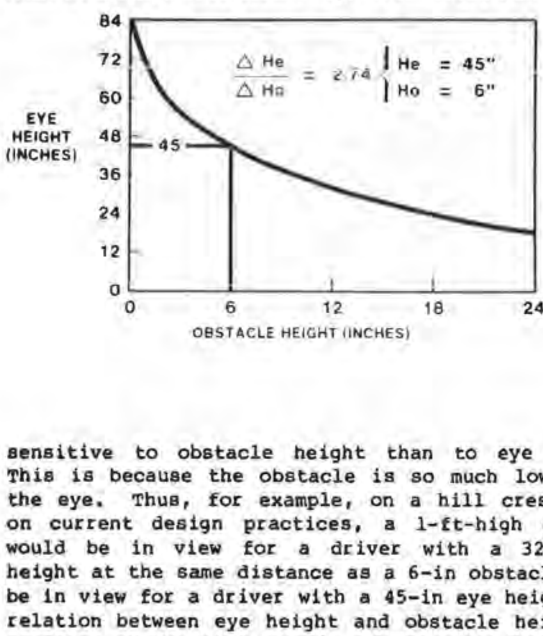


Figure 17. Eye height versus obstacle height for constant sight distance.



sensitive to obstacle height than to eye height. This is because the obstacle is so much lower than the eye. Thus, for example, on a hill crest based on current design practices, a 1-ft-high obstacle would be in view for a driver with a 32-in eye height at the same distance as a 6-in obstacle would be in view for a driver with a 45-in eye height. The relation between eye height and obstacle height for constant sight distance is plotted in Figure 17. This relation is independent of design speed. For eyeand obstacle-height values close to nominal, the rate of change is about 2.74 in of eye height per inch of obstacle height.

Summary of Sensitivity Analysis

The results of the sensitivity analysis are summarized in the following table:

Parameter	Reference Value	Value by Eye-Height Change: 3 Inches	Value by Eye-Height Change: 6 Inches
Speed	60 mph	0.9 mph	1.8 mph
Friction	0.3μ	-0.011μ	-0.023μ
Reaction time	2.5 s	0.16 s	0.32 s
Obstacle height	6 in	-1.1 in	-2.41 in

The table shows the changes in the several parameters that are equivalent to a 3- or 6-in change in eye height. In the cases of speed, reaction time, and tire-pavement friction, an "equivalent" change is the increase or decrease in the parameter required for stopping distance to equal sight distance. In the case of obstacle height, an equivalent change is the increase or decrease in obstacle height required for sight distance to remain unchanged. The sign indicates whether the change in the parameter must be in the same or opposite (-) direction as the change in eye height. The reference values are those assumed for the computation of design stopping sight distance.

DISCUSSION OF DESIGN EYE HEIGHT

Recent Federal Highway Administration (FHWA) studies suggest that the design eye height should be lowered by from 3 to 6 in to accommodate the trend toward smaller cars (3,6,7). Our analyses have shown that sight distance on hill crests is not very sensitive to changes in eye height in this range. The effect of a 3-in drop in eye height is less than the loss of sight distance that can result from the AASHO practice (6) of rounding off calculated values of stopping sight distance to provide even numbers for design purposes--e.g., 491-475 ft.

On the other hand, the sensitivity of stopping distance to speed, reaction time, and pavement friction is so great that normal variations in these parameters simply overwhelm the effect of eye-height variation. For example, eye height would have to be more than doubled to provide adequate sight distance for a driver traveling at 65 mph on a hill crest designed for 55 mph. It thus seems likely that the decreases in travel speeds brought about by the 55-mph speed limit, and possibly also pavement friction improvements over the past decade, more than compensate for any recent or projected decreases in passenger-car eye height.

Earlier, it was observed that the AASHO design obstacle height of 6 in seems somewhat arbitrary. The authors of the AASHO design guide considered 6 in to be a reasonable minimum that would ensure the visibility of objects perhaps 1 ft in height, such as fallen trees or boulders. However, this criterion was based on intuition and engineering judgment rather than any systematic analysis of the hazard. In fact, I am not aware of any data indicating that small obstacles in the road are an important cause of accidents.

Consideration of the hazard aside, it is by no means clear that a low-criterion obstacle can ensure the visibility of small obstacles at the design sight distance. The fact that the top 6 in of an obstacle is within view at 500 ft does not mean that it can or will be seen at that distance. Six inches represents only about 3.4 min of arc at 500 ft. An object that size might not be seen for some time after it comes into view unless it contrasts strongly with the road surface. There is not much point in requiring that an obstacle be within view at a given distance if it is unlikely to be seen or noticed at that distance.

These considerations suggest the possibility that the AASHO 6-in design obstacle may be overconservative. Sight distance is much more sensitive to deviations from the design obstacle height than to deviations from the design eye height. Thus, objects larger than the design obstacle will come into view at the AASHO stopping distance for drivers whose eyes may be considerably lower than the design eye. For example, on a hill crest designed to the current AASHO practices (i.e., a 45-in-high eye and a 6-in obstacle), an 8.5-in obstacle will come into the view of a 39-in-high eye at the design sight distance; and a 15-in obstacle (e.g., the federally mandated minimum height for tail lamps) would be in view at the design sight distance for an eye only 28 in above the pavement. Accident studies or considerations of driver visual performance limitations could very well show that a 12- or 15-in-high design obstacle is more representative of real-world objects that drivers can see and need to avoid. If so, the sight distances designed to the 6-in-high target provide a considerable safety margin, and traffic safety on hill crests is not likely to be very sensitive to the changes in eye height associated with the downsizing of the passenger-car fleet.

REFERENCES

1. H.L. Anderson. Incompatibility Between Highway, Vehicles, and Drivers. Proc., American Assn. for Automotive Medicine, Oct. 1980.
2. J.J. Stapleton. Tort Liability Implications of Small Car Incompatibility with Highway Design. Proc., American Assn. for Automotive Medicine, Oct. 1980.
3. M.W. Boyd, A.C. Littleton, R.E. Boenau, and G.B. Pilkington. Determination of Motor Vehicle Eye Height for Highway Design. FHWA, Rept. FHWA-RD-78-66, April 1978.
4. G.B. Pilkington. Decision Sight Distance Requirements for the Small Car Driver. Presented at Annual Congress, Society of Automotive Engineers, Detroit, 1979.
5. E.I. Farber. Driver Eye Height and Sight Distance on Vertical Curves. Society of Automotive Engineers, Warrendale, PA, Paper 811286, 1981.
6. A Policy on the Geometric Design of Rural Highways: 1965. AASHO, Washington, DC, 1966.
7. R.L. Lee and C.P. Scott. Driver Eye Height and Vehicle Sales Trends. Office of Highway Safety, FHWA, Jan. 1981.

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Shoulder Upgrading Alternatives to Improve Operational Characteristics of Two-Lane Highways

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A research project was undertaken to develop upgrading warrants for use in determining when to add paved shoulders to rural two-lane roadways or when to convert two-lane roadways with paved shoulders into four-lane undivided roadways by low-cost treatments such as remarking the shoulder to indicate that it is a travel lane. The latter treatment is known as a "poor-boy" highway in Texas. The findings of one portion of the research—the effects of paved shoulders on vehicle operating characteristics—are described. Field studies were performed at 18 sites around Texas for three types of highways: (a) two-lane roadways without shoulders, (b) two-lane roadways with shoulders, and (c) four-lane, undivided roadways. Operational characteristics were recorded for more than 21 000 vehicles. Data were gathered on speed, platooning, shoulder use, and vehicle type. The findings indicate that operational benefits derived from a full-width paved shoulder increase as traffic volumes increase. These benefits are minimal at low and moderate volumes, but they become significant at volumes greater than about 200 vehicles/h. Above this volume, paved shoulders appear to increase the average speed on the roadway by at least 10 percent. They also limit the number of vehicles in platoons to less than 20 percent. No more than 5 percent of all vehicles used the shoulder at any of the sites. Conversion of the shoulder to an additional travel lane offers no apparent operational benefits until the volume reaches 150 vehicles/h. On higher-volume roads, this modification could be expected to cause average roadway speeds to increase by approximately 5 percent and limit platooning to 5 percent. Significantly, such a conversion results in more than two-thirds of the traffic using the outside (shoulder) lane.

There are thousands of miles of existing two-lane rural roadways that are providing adequate service at low levels of vehicle flow. But, as traffic volumes grow and other characteristics change, these highways experience serious safety and operational deficiencies. It frequently becomes necessary to upgrade them to provide increased service to the higher traffic volumes.

A study was conducted in Texas to consider two improvement alternatives involving paved shoulders on rural roads: (a) adding paved shoulders to two-lane roads that previously did not have them and (b) converting two-lane highways with full-width paved shoulders into four-lane "poor-boy" roadways. The latter option is accomplished at low cost by remarking the roadway surface to indicate that the shoulder has become a travel lane. This upgrading treatment produces an undivided four-lane roadway without shoulders.

The research project was undertaken to develop upgrading warrants by quantifying the safety and operational characteristics associated with paved shoulders and by establishing the driver's understanding of the legality of driving on paved shoulders. This paper documents the findings of one portion of the research: the effects of paved shoulders on vehicle operating characteristics.

PREVIOUS RESEARCH

Many previous studies have dealt with the basic questions of shoulder design, field performance, and safety improvement; however, very few have looked at operational considerations. Several of these are reviewed below.