Stopping Sight Distance: Can We See Where We Now Stand?

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This paper examines the development of stopping sight distance (SSD) methodology over the past 75 years. Publications between 1914 and 1940 show that sight distance became increasingly important, but that it was not thoroughly understood. The emphasis during this period was on letting drivers see other vehicles in sufficient time to take evasive action. This concept changed drastically with the 1940 publication of AASHO's classic methodology, which made specific reference to objects, eye heights, and driver perception and reaction times. Evidence shows that the new procedures were gradually assimilated into the design process. Since 1940, emphasis has been on fine tuning the methodology by modifying its parameters. The paper discusses the prominent factors affecting SSD and traces their development over the past 75 years. The sensitivity of stopping sight distance to changes in the key parameters is examined. Characteristics and weaknesses of the methodology are discussed through a review of the recent technical literature. Five potential problems with the current AASHTO policies are discussed. Conclusions are drawn regarding the appropriateness of the current methodology and several specific recommendations are offered for additional research on this important topic.

Most highway and traffic engineers are familiar with the topic of stopping sight distance (SSD) as it is applied to the design and operation of streets and highways. They generally recognize that because of its dependence on human, vehicle, highway, and environmental factors, sight distance is a complicated issue. Although the publication of standards by AASHTO (*1*) might lead them to believe that this complex problem has been resolved, and that designs conforming to the standards will achieve the desired results, engineers are finding that it is expensive to comply with the current standards, especially in the reconstruction of existing highways. While this is a serious issue, with obvious financial and legal implications, its resolution may be hampered by our myopic view of the current sight distance standards. The intent of this paper is to examine the development of SSD methodology, to point out inconsistencies in the current procedures, and to pose topics for further research.

HISTORICAL DEVELOPMENT

Conventional wisdom has it that the origin of sight distance standards can be traced to a pair of 1940 AASHO publications (*2*, *3*). It would be inappropriate, however, to conclude that the issue was ignored at the state or national levels prior to that time. Early engineering textbooks, which typically emphasized the materials aspects of highway construction, devoted little attention to the subject. For example, the hazard of limited sight distance was recognized in a 1914 text (*4*, p. 97) by Blanchard:

> Sharp curves are points at which collisions are very liable to occur, particularly if the view is obstructed. Sometimes, if it is impossible to increase the radius of the curve, a great improvement can be obtained by clearing away obstructions so that the curve can be seen throughout its entire length when approached in any direction.

This was probably a good idea, but highway engineers of that era would argue that the suggested treatment was quite expensive. Two years later, coincident with the first Federal-aid Highway Act, a text (*5*, p. 45) by T. R. Agg advises:

> Safety Considerations. Steep grades, sharp curves and knolls that obstruct the view ahead should be avoided in the interest of safety. There should always be a clear view ahead for at least 250 ft and if a curve exists on a hill, the grade should be flattened around the curve if possible so as to permit a quick stop in case of emergency.

While Agg may have been correct, the engineer of today would feel uncomfortable with this statement. Why *250* ft? What about *speed*? What are the *object and eye heights*? And what kind of emergency is Agg talking about? There aren't any answers to these questions, because the statement above is the entire reference to sight distance in the text. But perhaps today's questions weren't appropriate then. Vehicles were taller and provided greater eye heights and ground clearance, while speeds were lower. By 1924, the third edition of Agg's text (*6*, p. 91) expanded on the issue of sight distance as follows:

> Curves. Horizontal and vertical curves, embankments, railroad crossings and intersections with other highways, constitute the dangerous portions of a public highway. . . . To minimize danger at curves it is desirable to provide ample sight distance and to construct horizontal curves with long radii and ample superelevation. The sight distance should be such as to permit a view of an approaching vehicle 400 ft away. That distance will permit both vehicles to be brought to a stop before colliding. Since the line of sight on a horizontal curve will depend upon whether the curve is in cut or not and upon the width of cleared right-of-way, no standard radius of curvature can be suggested that will provide the desired sight distance but it is easily computed in any case. . . . The radius of cur-

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> vature for vertical curves that will give a sight distance of 400 ft is about 3,500 ft and this applies regardless of the rate of grade if the algebraic difference in grades exceeds about 5 percent.

Agg's revised text clears up the vagueness in the 1916 version by identifying what has to be seen and what driver action is expected, and indicating that the principle applies to both horizontal and vertical curves. The reference to the *radius* of a vertical curve is appropriate because some engineers in those days recommended the use of circular vertical curves to minimize earthwork. The distance has increased to 400 ft because of a better understanding of the issue, an increase in vehicle speeds, or both.

Early references to sight distance are not limited to textbooks; Brightman (*7*, p. 114) indicates that Michigan's practice in 1926 was to provide 500 ft of sight distance:

> The subject of visibility is one that cannot be overlooked and it is related to both horizontal and vertical alignment. In order that the motorist may always see far enough ahead for safety, the road should be so aligned that a clear vision of 500 feet ahead is available. This is worked out by long curves and the cutting away of banks which may hide the view in horizontal alignment. The vertical alignment is solved by the use of vertical curves in the grades which allow a car to be seen at a point 500 feet distant at all times.

Two years later, AASHO adopted a standard of practice on road design (*8*, pp. 12–13) requiring that "horizontal and vertical curves be used which provide a sight distance of at least 500 feet."

An informative article by Baldock (*9*, pp. 732–34) shows that in 1935 the practice in Oregon was to design all trunk highways, except through mountains, for vehicular speeds of 75 to 100 mph. As indicated by the following excerpts from Baldock's article, Oregon was cognizant of the problems in designing for these high speeds.

> Early in the consideration of vehicular speeds it was determined that three speeds would have to be considered as follows:
>
> 1. Critical speed, the maximum that can be attained with the standards used and beyond which only the most skillful racing drivers can operate without extreme hazards.
> 2. Designed speed, 80 percent of the critical speed and a speed that is safe for skillful drivers.
> 3. Recommended safe speed, which takes into account normal traffic conditions and the limitations of the ordinary driver. Hence a speed somewhat less than the designed speed.
>
> The critical speed of an automobile on a highway is controlled by the following factors: (1) the ability of the operator to function properly—the human equation, particularly in emergencies; (2) the ability of the mechanism of the vehicle to operate at high speeds without undue hazard; (3) the stopping distance or the distance travelled during the reaction time of the operators plus the braking distance; (4) the curvature . . . ; (5) the horizontal sight distance on curves, which, of course, varies with the curvature, the position of the vehicle on the road and the distance from the line of travel to the sight distance obstruction; (6) the sight distance over vertical curves; (7) the sight distance required in passing vehicles at varying speeds; and (8) the gradient used in the mountain sections.

Baldock clearly shows an understanding of the relationship between speed and sight distance. He also presents Oregon's method of calculating stopping sight distance, which is similar to current methods except that it assumes a driver reaction time of 0.5 sec. The frictional values used in the stopping distance equation were 0.5 on wet pavement and 0.8 on dry pavement; the latter condition is comparatively rare in Oregon. For a designed speed of 80 mph, the stopping distance would be 740 ft, and a sight distance of 1,500 ft is specified for vertical curves.

At the national level, there was increasing awareness of the relationship between design and safety. In 1935, for the first time, the Annual Report (*10*, p. 6) of the Bureau of Public Roads (BPR) included a brief section entitled Highway Safety, which states in part:

> In approval of plans for highway construction it [the BPR] has constantly endeavored to effect a desirable widening of surfaces, straightening of alignment and reduction of grades to make the roads suitable for the increased speed of modern traffic.

Nevertheless, the BPR report does not specifically mention the issue of sight distance. A text (*11*, p. 417) published in this same year offers the following guidance on sight distance:

> On double-track paved roads, the sight distance should be such that a driver can observe an approaching vehicle without being startled when travelling at normal road speeds and with the corresponding degree of concentration of attention given the road. On account of increasing automobile speeds a minimum sight distance of 600 ft is desirable.

Another indication of state practice in the mid-1930s is provided by a report (*12*) from the Ohio Department of Highways, which indicates that

> One danger point of the highway which receives more consideration than previously is the abrupt change at the crest of a hill where the driver is unable to see a safe distance ahead. On new construction and on reconstruction projects on main roads the sight distance on vertical curves are [*sic*] kept at a minimum of 1,000 feet on two-lane, 1,500 feet on three-lane, and 800 feet on four-lane pavements, unless this is economically prohibitive.

The Ohio report also presents a graph for determining the length of a vertical curve based on the algebraic difference in grades and the desired visibility length (500 to 1,500 ft). The chart is very similar to Figure III-39 in the current AASHTO standards (*1*) except that it assumes a 4.5 ft eye height.

Concern with sight distance was not limited to engineers in the United States. A British textbook (*13*) derives sight distance formulas for summit vertical curves that are similar to those used in current standards. The model assumes that two vehicles approach the summit from opposite directions, and the recommended sight distance allows each vehicle to decelerate to a stop before colliding with the other. The text notes that "one of the lowest cars on the road has an eye height of approximately 3 ft 9 in," and this figure is used in the calculations. The calculated braking distance of 240 ft for trunk roads with 60 mph speeds is doubled and then rounded to 550 ft "which gives the drivers half a second each to spare."

Standards for the 5,000-mi Reichsautobahn system, with a design speed of 112 mph (180 kph), provided for stopping sight distance. According to one source (*14*, pp. 292–94), the German calculations were based on a 1-sec perception-reaction time, and frictional coefficients of 0.4–0.5. Furthermore,

> In computing sight distance along curves and at summits a standard car is assumed, 4.9 ft high, with the eye of the driver 3.9 ft above the ground and 4.3 ft from the vertical plane of the two right wheels of the car. Two kinds of obstacles are considered: (1) A standard car and (2) an object near the summit projecting 20 cm (about 8 in) from the ground surface upwards.

The use of a lower eye height presumably reflected the design of the vehicle fleet. The standards recognized the importance of considering objects other than vehicles. In level terrain, their designs often used horizontal curve radii greater than the 6,560 ft necessitated by these standards; however, design standards were lowered when topography made compliance uneconomical.

The BPR's 1936 Annual Report (*15*, p. 15) specifically recognized the importance of providing adequate sight distance in the interest of enhancing highway safety.

> One matter that confronts highway officials which is of great present importance and which will be of much concern in the future is the eradication of those conditions that are now or may be conducive to accident, injury, and death. . . . The greatly increased speed of motor-vehicle travel requires a general increase in sight distances and the elimination of obstructions to view at intersections.

The literature of the day seemed to have difficulty in distinguishing among the various reasons for providing adequate sight distance. One author (*16*, pp. 21–24), however, appears to concisely identify two principal types of sight distance:

> The general feeling is that 1,000 ft is the shortest sight distance that may be regarded as reasonably safe on two-lane roads to be traveled at 60 miles per hour. In a distance of 1,000 ft a driver of a vehicle moving at 60 miles per hour can normally pass another vehicle moving at 40 miles per hour and avoid collision with an approaching vehicle traveling at 60 miles per hour.
>
> Sight distance on four-lane highways having parkways or median strips separating the opposing traffic lanes may be reduced appreciably below those on two-lane or three-lane roads because the possibility of accidents on them is limited largely to rear-end collisions. The safe sight distance for four-lane roads, therefore, should be at least that distance in which a moving car can be brought to a full stop. It will range from 300 to 700 feet depending on the speed and braking power of the vehicles involved. The American Association of State Highway Officials recommends a minimum sight distance of 500 feet for four-lane roads and 800 feet minimum on other Class A and B roads.

Elsewhere, the same article notes that AASHO *recommends* a minimum sight distance of 800 ft on horizontal curves; a reduction to 500 or 600 ft for design speeds of about 40 mph is permitted in mountainous terrain. This recommendation and the previously cited standard of practice (*8*) clearly show that AASHO was providing guidance on sight distance issues prior to the publication of its 1940 policy (*2*).

The first discussion on this topic by the Highway Research Board was in 1937, when the Proceedings (*17*) included a report from its Committee on Sight Distances. The report introduced the concept of nonpassing sight distance and identified several areas where additional research was needed to properly quantify the parameters involved. Several of the report's most significant conclusions are as follows:

> If safety is to be built into our highways, it is vitally necessary that the road be opened up to view for a sufficient distance to enable the driver . . . to control the speed of the vehicle to avoid encountering unexpected obstacles in its path [p. 111].
>
> The assumed design speed of a highway is considered to be the maximum approximately uniform speed which probably will be adopted by the faster group of drivers but not, necessarily, by the small percentage of reckless ones. . . . The length of highway visible to a driver at every point should be in excess of the distance required to bring the vehicle to a stop before reaching a stationary object in the same lane when travelling at the assumed design speed of the highway. This distance may be termed the safe stopping distance. Values for the factors entering into its determination should be chosen conservatively in order that drivers who normally drive faster than the assumed design speed and drivers who do so occasionally also may avoid encountering obstacles in the road [p. 112].
>
> For non-passing minimum sight distance two seconds for perception time, one second for brake reaction time, and 0.4 for the uniform coefficient of friction may be considered reasonable values. They result in non-passing minimum sight distances equal in feet to about ten times the assumed design speed in miles per hour. The variation is not uniform, being greater at high speeds and less at lower speeds. For four-lane and divided highways a greater margin of safety may be advisable. This may be secured by assuming a speed 10 miles per hour greater than the assumed design speed of the highway for sight distance purposes [p. 118].

Despite the extensive discussion of sight distances in the HRB paper, there is no mention of eye or object heights. For rural highways with a design speed of 60 mph, the stopping sight distance calculated using these HRB procedures is about 11 percent less than current AASHTO standards. But, if one accepts the admonition to assume a speed that is 10 mph greater than the actual design speed, the calculated sight distance is 13 percent greater than current AASHTO values.

The BPR's 1937 report (*18*, p. 2) again recognized the importance of sight distance and implied that a substantial portion of the highway system posed a hazard to motorists.

> Construction of through routes was begun some 15 or 20 years ago when the speed of vehicles was much slower and traffic considerably less in volume. The roads built were designed for conditions as they were then foreseen, and were influenced somewhat by the necessity of rapidly extending the mileage. Engineering standards in respect to sight distance, curvature, and grade have been steadily raised but much of the early construction reflects the earlier standards and is unsafe for modern traffic. . . . The condition of these highways cannot be considered satisfactory so long as many sections present unexpected dangers to the motorist.

In a section of its 1938 Annual Report (*19*, pp. 2–4) entitled Greatest Needs on Main Roads are Widening, Longer Sight Distances, and Reduction of Curvature, the BPR stated:

> Eliminating those curves that have become traffic hazards at the now normal driving speed and increasing sight distances by road straightening and by grading at the tops of hills are widespread needs on the existing main highways. These defects are found generally on roads in every part of the country and their danger to traffic is the consequence of an increase in vehicle speed far beyond what was visioned 15 or 20 years ago and far in excess of the legal limitations that existed in most states.

In the same report, however, the BPR blames drivers for accidents on roads it describes as hazardous. In a year when 32,000 persons died on the nation's highways, BPR reports:

> At the same time it must be recognized that accomplishment of all these things (e.g., sight distance improvements) will not constitute a solution of the accident problem. The present condition of main highways is not conducive to accidents except when rendered so by risk taking drivers. The data available on the causes of accidents indicate that improper acts by vehicle drivers are the element common to most accidents. . . . There is a relatively small group of definitely accident-prone drivers who experience a relatively large number of accidents.

A 1939 textbook (*20*) notes that 5 ft is generally used as the height of the driver's eyes above the road surface. With respect to vertical curves, the text notes:

> The minimum length of vertical curves at summits will be governed by the distance within which two vehicles are within sight of each other, this distance being defined as the "sight distance." Proper sight distance varies for different conditions and should be greatest on roads having smooth pavements with no parking strips between opposing lanes of traffic. Recommended sight distances vary from 350 to 1,000 ft for rural highways, the maximum being applicable to high-speed through highways.

For horizontal curves, this text recommends minimum sight distances of 800 ft (measured along the roadway center line) on primary and heavily traveled secondary state highways, although 500 ft is a desirable minimum on local highways. The text also provides the following tabulation of stopping distances:

	Stopping Distance, Feet	
Speed	*Quick Thinker, Good Brakes*	*Slow Thinker, Fair Brakes*
20	30	55
40	100	170
60	200	330
80	325	550

Finally, in 1940, Agg published the fifth edition (*21*, p. 154) of his text; his discussion of sight distance at vertical curves suggests that the concern is drivers seeing each other.

> When two vehicles approach the top of a hill from opposite directions on a highway at least two lanes wide, there is no element of danger if each is held to its proper lane and the drivers are able to see each other while they are still a reasonable distance apart. The line of sight of an automobile driver is about 5 ft above the road surface. With that factor fixed, the curvature is readily computed for any desired sight distance. The problem then becomes one of determining what constitutes a reasonable sight distance, but upon this point it is not easy to be specific. Perhaps a good basis for preliminary computations is to determine how much distance is required to bring a vehicle to a stop from the extreme road speed to be expected (if there is any such thing as a limit to speed, which seems doubtful). If the road surface permits a reasonable application of the brakes without starting a skid, a vehicle with four-wheel brakes could be stopped in about 300 ft from a speed of 60 mph. To this must be added about 75 feet as the distance traveled during the "reaction time." This would indicate that about 800 feet is the minimum sight distance for summits on busy trunk-line highways. Many of the state highway departments are designing the trunk highways with a sight distance of 1000 ft or more.

This overview of sight distance prior to 1940 suggests that the issue was recognized as being important, but it was not thoroughly understood. The emphasis was to provide sufficient sight distance for the driver to see other vehicles in sufficient time to avoid them. In only one domestic reference (*17*) is the concept of avoiding obstacles in the road discussed. Only the foreign authors (*13*, *14*) used an eye height of less than 4.5 ft. In hindsight, AASHO's 1940 sight distance policy (*2*) represented a significant change from previous practice, although interestingly enough it received no notice in *Engineering News-Record*, which covered most of the highway developments of that era. The minimum sight distances based on the revised procedures ranged from 200 ft at 30 mph to 600 ft at 70 mph. Some highways designed according to previous criteria did not satisfy the new requirements.

Perhaps the most dramatic change introduced by the 1940 standards was the substitution of a small object as the feature that must be seen. AASHO's selection of a 4-inch-high object (*2*) was justified as follows:

> The stationary object may be a vehicle or some other high object, but it may be a very low object such as merchandise dropped from a truck or small rocks from side cuts. To be on the safe side the surface of the pavement should be visible to the driver for the entire length of the non-passing sight distance, but the necessity for it is questionable. Large holes rarely are encountered in modern pavements and very small objects generally can be avoided without the necessity for stopping. Therefore, a height of object of 4 inches is assumed in determining non-passing sight distance.

Table 1 summarizes the historical development, the 1940 standards, and the well-documented changes over the past 48 years. The 1940 policy established the fundamental methodology that is still in use today, but there has been a fairly continuous change in individual parameters toward safer values. For example, driver eye height has been reduced by a foot, whereas pavement friction values were reduced to approximately 70 percent of their original values. The only element that has not changed significantly is the driver; as a result, the assumed perception-reaction time has remained virtually constant.

REVIEW OF SELECTED RECENT RESEARCH

Glennon (*26*) performed a critical review of SSD literature for a Transportation Research Board report to Congress. He drew the following (paraphrased) conclusions:

1. Alignment changes performed to improve stopping sight distance appear to be safety-effective when very short portions of a roadway are improved to provide very long sight distances.
2. Alignment changes are normally cost-effective only on highways that have (a) very high traffic volumes and (b) major hazards that are hidden by a sight obstruction.
3. Highway agencies must be careful when making minor lengthening of extremely substandard crest vertical curves. Unless care is used, it is possible to provide better sight distance for a short length of highway while causing an increase in the total length of roadway with inadequate sight distance.

TABLE 1 HISTORY OF STOPPING SIGHT DISTANCE PARAMETERS

Source	Reference No.	Pavement Condition	Stop Condition	Eye Height (ft)	Object Height	Friction Factors	Speed	Perception-Reaction Time (sec)	Sight Distance (ft)
Agg, 1916	5								At least 250
Harger, 1921	22			5.5	5.5 ft				
Agg, 1924	6				~5 ft				400
Michigan, 1926	7				~5 ft				500
Oregon, 1935	9	Wet, dry			~5 ft	0.5 wet 0.8 dry	80% of critical speed	0.5	1,500 @ 80 mph
Wiley, 1935	11				~5 ft		Normal road speeds		600
Ohio, 1937	12								1,000 (two lanes) 800 (four lanes)
Conner, 1937	16				~5 ft				500 (four lanes)
HRB, 1937	17				Unexpected obstacles	0.4	Maximum uniform speed	3	
Bateman, 1939	20			5	~5 ft				800 (Horiz C)
Agg, 1940	21			5	~5 ft	0.40 @ 60 mph		<1	
AASHO, 1940	2	Dry	Locked wheel	4.5	4 in.	0.50 @ 30 mph 0.40 @ 70 mph	Design speed	3 @ 30 mph 2 @ 70 mph	200 @ 30 mph 600 @ 70 mph
AASHO, 1954	23	Wet	Locked wheel	4.5	4 in.	0.36 @ 30 mph 0.29 @ 70 mph	85–95% of design speed	2.5	
AASHO, 1965	24	Wet	Locked wheel	3.75	6 in.	0.36 @ 30 mph 0.27 @ 70 mph	80–93% of design speed	2.5	
AASHTO, 1970	25	Wet	Locked wheel	3.75	6 in.	0.35 @ 30 mph 0.27 @ 70 mph	Min: 80–93% of design speed	2.5	
AASHTO, 1984	1	Wet	Locked wheel	3.5	6 in.	0.35 @ 30 mph 0.28 @ 70 mph	Design speed	2.5	200 @ 30 mph 850 @ 70 mph
NCHRP, 1984	29	Wet	Controlled	3.33	4 in.	By numerical integration	Design speed	2.5	

4. Treatments such as site-specific warning signs, advisory speed plates, and reduced speed zones should be encouraged at the locations where a crest vertical curve hides a hazard. The *Limited Sight Distance* sign has been ineffective in providing the proper warning to motorists.

5. Stopping sight distance on horizontal curves may be a particular problem. Cornering forces on the tires consume a portion of the friction force that might otherwise be used for deceleration. In addition, large trucks require longer SSDs than cars. For vertical curves, the truck driver's increased eye height offsets the required additional stopping distance; this advantage is not available for horizontal curves.

6. Low-cost treatments such as clearing vegetation or removing other minor obstacles on the inside of horizontal curves is a cost-effective technique to increase SSD on virtually all highways. Minor clearing on the inside of a curve can sometimes produce spectacular increases in SSD.

7. The skid resistance of pavement on the approaches to a limited sight distance roadway section might receive particular consideration.

Neuman et al. (*27*) examined the functional requirements of stopping sight distance. Their study identified several inconsistencies in the present AASHTO policy, including the following:

1. SSD accidents are event-oriented. The mere presence of a segment of highway with inadequate SSD does not guarantee that accidents will occur. Inadequate SSD is simply one item in a chain of events that leads to a collision. For example, a site with a minimally limited SSD on a low-volume, low-speed, rural route would rarely produce a critical linkage of events to cause a collision.

2. The probabilities of occurrence of SSD-related critical events define the relative hazard of any individual location. The joint probability of an accident is a function of traffic volumes, frequency of conflicts, and other factors.

3. The severity of SSD-related collisions may be more important than the frequency of such accidents. High-severity collisions may dominate cost-effectiveness studies of potential improvements.

4. There are many minor, uncontrollable factors that contribute to accidents at limited SSD locations. These minor factors (worn tire tread, deficient vehicle braking characteristics, irregular pavement, impaired driver, and the like) become more important when the driver enters a critical situation and tries to avoid an accident.

These researchers also report that at locations where deficient sight distance is caused by short vertical curves, lengthening the vertical curves could make the situation worse. Although the degree of SSD deficiency, as reflected by the safe speed, may be improved, the distance over which a driver experiences a deficiency may increase. In other words, an expensive reconstruction project might transform a short vertical curve with a seriously restricted sight distance into a longer vertical curve with only a marginally higher safe speed.

Neuman and Glennon (*28*), in an effort hampered by the lack of data, attempted to establish the cost-effectiveness of SSD improvements. They were able to establish upper limits on the effectiveness of sight distance improvements by constructing a model based on optimistic assumptions. Their model showed quite clearly that eliminating SSD deficiencies by making geometric changes to vertical or horizontal curves could only be justified in the presence of high traffic volumes or when significant hazards existed within the restricted sight area.

Olson et al. (*29*) performed a series of controlled roadway experiments to evaluate perception-reaction time, driver eye height, object height, and braking distances. Their findings caused a significant stir in the highway engineering community. Although they found that the 90th-percentile test driver had a perception-reaction time of 2.4 sec, they recommended retention of the traditional 2.5 sec because their test drivers probably had a heightened awareness and were not subject to factors (for example, fatigue) faced by normal drivers.

On the basis of their results, the researchers recommended changes to parameters in the AASHTO SSD equations. They proposed that the driver's eye height be reduced from 42 to 40 in, and that the object height be reduced from 6 to 4 in. In addition, they suggested another deviation from current AASHTO procedures. They contended that a driver will "modulate his braking control" so that he can decelerate without losing directional stability. They recommended a numerical integration technique for calculating braking distance, rather than relying on the AASHTO locked-wheel, skid-to-a-stop method.

The researchers also concluded that the higher eye height of truck drivers allowed them to initiate braking sooner at locations where sight distance is restricted by vertical curvature. As a result, stopping sight distance requirements for large trucks under these conditions are reasonably similar to those for passenger cars. Other researchers (Harwood et al., in this Record) report that this may not be the case because of variances in truck drivers' braking skills. In addition, the increased truck driver eye height provides no benefit when emergency stopping conditions exist within sharp horizontal curvature.

MEASURING THE RELATIONSHIP BETWEEN ACCIDENTS AND STOPPING SIGHT DISTANCE

The primary reason for increasing SSD is to provide improved safety benefits to motorists. Unfortunately, it is difficult to know how much to improve SSD to obtain a given level of improvement because data are lacking on the relationship between SSD and accidents. Several studies have examined sight distance as one of many factors contributing to crashes; nevertheless, these general research efforts have failed to produce a realistic model to define the change in accident rates for specific treatments that change sight distance.

Two studies offer possible insight into the issue. Farber (*30*) employed a Monte Carlo simulation technique to investigate accident potential for a limited SSD situation. He investigated the hypothetical situation of left-turning vehicles just downstream from a sight-distance-limiting crest vertical curve. He was able to draw conclusions about accident potential as a function of traffic volume, sight distance, and related factors. Such simulation methods have previously been used in other types of research to gather realistic data on parameters such as conflicts, operating conditions, and accident potential. Continued development of Farber's model might be a useful way to develop a similar model describing the relationship between safety and stopping sight distance.

Olson et al. (*29*) performed a statistical analysis on ten pairs of sites that were matched for similarity—except for their sight distance. In seven of these pairs, the limited sight distance site had more accidents than its companion. In two cases, the limited and full sight distance pairs had approximately the same number of collisions, whereas in one case, the limited sight distance location actually had fewer accidents than its matching site. Overall, the limited SSD sites had a 50 percent higher accident rate than the locations with adequate SSD.

With the exception of these two studies, there does not appear to be any work that conclusively defines the relationship between limited SSD and accident rates. The absence of sufficient data on this issue limits our ability to predict the results of changes to the existing methodology.

SENSITIVITY OF STOPPING SIGHT DISTANCE PARAMETERS

The methodology for calculating SSD is found in the AASHTO Green Book (*1*). The basic equations to determine SSD at crest vertical curves utilize six variables:

1. Perception-reaction time,
2. Driver eye height,
3. Object height,
4. Vehicle operating speed,
5. Coefficient of pavement friction, and
6. Algebraic difference in grades.

If the basic SSD methodology is to be modified to improve roadway safety, an understanding of the role and sensitivity of each of these parameters is necessary. In other words, if any one of the parameters is to be changed, it is important to know the effect on other parameters and the resulting overall change in sight distance. Five of the parameters will be reviewed in the following discussion; the sixth parameter, algebraic difference in grades, is a product of local site conditions and is not specifically discussed. Because several of the references dealing with eye and object height changes also report the effect on crest vertical curve length, this latter characteristic is included in the comparisons.

Perception-Reaction Time

Recent research has confirmed that 2.5 sec is a reasonable perception-reaction time regardless of design speed (*29*). Woods (*30*) noted that any change in perception-reaction time was actually a change in the distance traveled at the design speed. Thus, the effect on SSD was highly speed dependent. Glennon (*32*) and Farber (*33*) indicated that for changes in perception-reaction time, the increase in SSD became significant at higher speeds. Hooper and McGee (*34*) reached the opposite conclusion, contending that at higher speeds the braking component of stopping sight distance became the dominant factor, even though a significant distance was traveled during the increased perception-reaction time.

Driver Eye Height

The sensitivity of eye height appears to have been thoroughly investigated and reported in the technical literature. As shown in Table 2, stopping sight distance has been found to be relatively insensitive to changes in driver eye height. The data

TABLE 2 EFFECT OF CHANGES IN EYE HEIGHT ON STOPPING SIGHT DISTANCE AND VERTICAL CURVE LENGTH

	Source					
	Farber (*33*)	Olson (*29*)	Khasnabis (*35*)	AASHTO (*1*)	Woods (*30*)	Woods (*30*)
ΔEye height (in.)	−6	−2	−3	−3	−1.2	−6
Percent change	(−15)	(−5)	(−7)	(−7)	(−3)	(−13)
ΔSSD (%)	+5	+1.5	+2.7	+2.5	—	—
ΔCurve length (%)	—	+3	+5.3	+5.0	+2.3	+11.5

TABLE 3 EFFECT OF CHANGES IN OBJECT HEIGHT ON VERTICAL CURVE LENGTH

	Source					
	Khasnabis (*36*)	AASHTO (*1*)	Woods (*32*)	Khasnabis (*36*)	Olson (*29*)	Woods (*32*)
ΔObject height (in.)	6 to 0	6 to 0	6 to 2	6 to 3	6 to 3	6 to 4
Percent change	(−100)	(−100)	(−67)	(−50)	(−50)	(−33)
ΔCurve length (%)	+79	+85	+24–30	+18	+10	+12–16

in the Table regarding vertical curve length changes are based on the specific set of assumptions employed by the researchers, so an absolute comparison is not possible.

Even with the inherent differences between the studies, Table 2 still shows that a 3-in decrease in eye height only produces a 3 percent increase in the necessary SSD, while a 6-in decrease requires a 5 percent increase in SSD. There is a relatively strong consensus among these researchers that a moderate reduction in driver eye height produces a small resultant change in vertical curve length and stopping sight distance.

Object Height

Considerable research has been devoted to the role of object height in determining SSD. Four studies, summarized in Table 3, indicate that stopping sight distance is more sensitive to object height than to driver eye height. For example, moving from a 6-in object to a 0-in object increases crest vertical curve length by approximately 80 percent. Smaller reductions in object height have a less drastic effect; halving the object height to 3 in increases the vertical curve length by 10–18 percent, depending on assumptions.

Vehicle Speed

At least three investigators have determined that travel speed is an extremely sensitive parameter. Woods (*30*) showed that a 10 percent increase in vehicle operating speed yielded an increase of approximately 40 percent in crest vertical curve length for speeds between 40 and 65 mph. Farber (*33*) found that "small deviations in speed are equivalent to large deviations in stopping sight distance." This same conclusion is supported by others (*35*).

Pavement Friction

The most sensitive parameter in determining SSD appears to be the pavement friction value. Farber (*33*) found a noticeable relationship between friction effects and design travel speed, and he observed that SSD sensitivity to pavement friction increased with speed. Woods (*30*) states that "pavement friction is the most sensitive parameter in crest vertical curve design." He showed that for *f* values near 0.35 (a fairly low value, comparable to the 15th percentile of a typical state's total friction measurements), crest vertical curve length increased about 4 percent for each 0.01 change in pavement friction. As friction values dropped lower, curve lengths increased at an even greater rate. For very low *f* values (around 0.10), a change of only 0.01 caused a 20 percent change in vertical curve length.

The highest level of sensitivity is at the lower end of the pavement friction scale. This is also the region in which braking characteristics are poorest. Thus, at locations where a high degree of hazard already exists because of low *f* values and marginal sight distance, relatively minor changes in *f* produce drastic changes in SSD. The worst possible effect occurs at the worst possible location.

Pavement friction values are partially dependent on environmental conditions. Hill and Henry (*36*) report that a pavement's *f* value will decrease by more than 0.01 for a temperature increase of 10°C. In some parts of the country, daily temperature swings are twice this much, resulting in friction changes of 0.02–0.03. Based on the 15th-percentile *f* value of 0.35 reported by Woods, this change in temperature could increase the necessary SSD 8 to 12 percent.

Summary of Parameter Sensitivities

Of the five parameters reviewed, the most sensitive is pavement friction, followed by vehicle operating speed. The least sensitive appears to be driver eye height. It is interesting, however, that most recent research and discussions have focused on driver eye and object heights, two of the less sensitive parameters in determining stopping sight distance. The potential daily change in ambient temperature at sites with low friction values has a significant affect on SSD, yet the issue has received relatively little attention.

POTENTIAL PROBLEMS WITH THE CURRENT METHODOLOGY

A review of the historical development of SSD demonstrates that the early highway engineers did not have a thorough understanding of the issue. In 1940, AASHO set up a plausible model with the potential to at least standardize this design parameter. Efforts during the past half-century have focused on adjustments to this model, although comparatively little attention has been directed to its validity. From a macroscopic view, the basic model possesses certain difficulties that warrant further attention.

Driver Vision Requirements

Considerable attention has been directed to the subject of object height, and in the last decade it has been reported that the undercarriages of many passenger vehicles cannot clear an object 6 in high. This has led to suggestions that the object height should be lowered. A reduction, however, may be unrealistic. Consider the situation where 600 ft of sight distance is required. The current model assumes that on a tangent, level road, the normal driver should not have a problem seeing a 6-in-high object at this distance; in the absence of atmospheric interference, this corresponds to seeing a 0.2-in-high object at 20 ft. By comparison, the standard letters on a 20/20 eye chart are 0.35 in high, whereas the 20/40 letters are 0.70 in high. Because of variations in driver licensing requirements and the general deterioration of a driver's visual abilities with age, the prudent highway engineer might plan for drivers with a static visual acuity of 20/40. In other words, the design driver must only be able to distinguish among objects that are 3.5 times as large as the object assumed for sight distance purposes. Granted, the driver does not have to *read* the object. On the other hand, the object need not have the contrast, either with itself or with the roadway, that is provided by a black-and-white eye chart. In addition, the static acuity measured in a standard vision test imposes a less demanding requirement than the dynamic acuity required in the driving task.

Furthermore, in the case of a vertical curve, the driver is faced with an additional problem: the entire object (either 6 or 4 in high) doesn't suddenly become visible. Rather, the driver initially has a line of sight to the very top of the object; as he approaches the object, there comes a point where he has a line of sight to the bottom of the object. Consider a 1,600-ft vertical curve with an algebraic difference in grades of 5.9 percent; with this design, a driver with an eye height of 3.5 ft will have a line of sight to the top of a 6-in-high object at a distance of 600 ft. Nevertheless, the driver will not have a line of sight to the entire object until he has approached to within 435 ft. The separation between where the driver might first see the top and the bottom of the object corresponds to approximately 1.9 sec at 60 mph, or 75 percent of the assumed conservative perception-reaction time.

Probability of an Accident with a 6-Inch-High Object

The previous section made the point that a typical driver will have difficulty in seeing a 6-in-high object at rural highway speeds. But it is also appropriate to consider how frequently an object of this kind is actually struck in an accident. Analysis by Woods (*30*) found that the collision rate for objects of this size or smaller was only 0.02 per million vehicle miles. This is at least two orders of magnitude smaller than the collision between pairs of multiple vehicles. The small probability of a collision with objects of this size suggests that we may be designing for an event that almost never occurs. In addition, a change to a 0-in object height, however desirable from a theoretical viewpoint, would appear to have a negligible effect on accident rates; it is questionable whether drivers can discern such small objects at the distances required for rural highway speeds.

Liability Trends

State highway agencies paid an estimated $120 million in judgments and settlements from tort liability claims in 1986, and spent at least another $20 million in defending these cases [Turner et al. (*37*)]. Engineers are properly concerned about this issue, especially since the number of suits is growing at an annual rate of 17 percent. Data are not readily available to show what share of these suits involve contentions of inadequate stopping sight distance, but the previously cited accident data imply that the number would be small. Although it would take additional research to reach a definitive conclusion, it appears that the extensive financial resources required to upgrade older roads to current SSD standards might be better spent on alternative improvements.

Vehicle Characteristics

There is no doubt that the current methodology does not provide adequate SSD for trucks on horizontal curves, regardless of object size (*26*). A current study (*30*) has found that a truck driver's ability and efficiency are major factors in assessing whether current standards are sufficient for large trucks in individual SSD maneuvers. Potential changes in braking systems might reduce the disparity between trucks and passenger vehicles, but as with any change to the vehicle fleet, this would be a longer-term solution. In the meantime, truck accident experience related to SSD warrants further examination.

Another vehicle characteristic, the lighting system, has not been given proper attention in the development of the SSD model. Previous discussion has noted that the driver may have difficulty detecting a 6-in-high object during the daylight at highway speeds. With properly aligned low-beam headlights, the driver on a typical rural road at nighttime will not be able to see an object in the road at these same speeds.

Pavement Friction

AASHTO (*1*) describes the frictional coefficients used in the model as *generally conservative*. Although there is a general consensus that designing for adequate stopping sight distance on an icy road is inappropriate, it is proper to recognize that pavement friction can change significantly in response to environmental factors. The variation of friction with increasing temperature was previously noted. In addition, the frequency and intensity of rainfall that serves to cleanse the pavement, as well as the quality of materials used in the pavement, can have a significant effect. Even if the SSD model had no other faults, its application to a specific location using an assumed nearly all-inclusive frictional coefficient may produce a substandard design.

CONCLUSIONS

Prior to the 1937 report by the HRB Committee on Sight Distances, the rationale for a policy on stopping sight distance was poorly understood. Emphasis was placed on providing sufficient distance for a driver to see and avoid other vehicles, but the distances were not analytically related to driver, vehicle, or roadway characteristics. Roadbeds and roadsides designed in compliance with these minimum recommended sight distances became substandard as vehicle speeds continued to increase. The methodology described in the 1940 AASHO policy sought to incorporate the factors that influence a driver's ability to respond to obstacles in the roadway. Since that time, the methodology has remained unchanged, although the individual parameters have been fine-tuned in an effort to account for changes in roads, vehicles, and driver behavior.

Stopping sight distance has become a topical issue for several reasons. Designers argue, for example, that recent adjustments to individual parameters in the model have had two effects:

1. Highways designed in accord with previous policies have suddenly become substandard, thus creating potential liability problems.
2. The expense of meeting the revised standards in the construction of new highways, and especially in the reconstruction of older alignments, adds significantly to project cost. This issue is critical because the benefits of the revisions have not been demonstrated.

If the highway engineering community had faith that the current SSD model reflected the needs in actual driving conditions, the foregoing effects could probably be accepted. There is growing concern that the 1940 model does not, and perhaps cannot, reflect the realities of driving. On one hand, it does not properly account for driver vision limitations, large trucks, nighttime driving, and realistic variations in pavement friction. On the other hand, further model adjustments to resolve these theoretical shortcomings may not be justified because

1. Available accident data fail to support the contention that the type of incident that the SSD model is intended to guard against is even a minor problem on existing rural highways.
2. The significant extra costs of highway construction and reconstruction occasioned by adjusting model parameters to reflect the extremes of current or projected driver, vehicle, or highway conditions could prove detrimental to overall highway system safety if the limited funds for improvement are used to provide an optimal, rather than a realistic, level of highway safety.

RECOMMENDATIONS

There is clearly a need to reexamine the role and importance of stopping sight distance in the safe operation of streets and highways. Although several ongoing and recently completed studies have examined individual components of this issue, and have made valuable contributions to the state of the art, there is a need for a more thorough study that would address the following issues:

1. Does the current model for stopping sight distance address a real problem, as exemplified by actual accident experience on sections of road that do not meet current standards, or is it a theoretical aberration that does not properly reflect actual operating conditions?
    a. If the model properly portrays realistic hazards on the highway system, what, if any, modifications are needed to better accommodate these conditions?
    b. If the model does not adequately represent the conditions experienced by the average, reasonably prudent driver, what methodology is required to reflect realistic conditions?
2. Since compliance with current SSD standards on reconstructed highway segments limits the number of projects that can be undertaken within budgetary constraints, what is the systemwide tradeoff among SSD, highway safety, safe roadsides, and other design and operational factors that influence safe roadway operation?
3. Other transient hazards on the roadway, most notably animals but also stalled vehicles in a traffic lane, create hazards for the motorist. Has too much attention been devoted to the *theoretical* 6-in-high object in the roadway?
4. Although AASHTO standards are developed and accepted by state highway agencies, and are applicable to rural highways under their control, they are often imposed in a *de facto* manner on local roads administered by counties and cities. There is a need to establish the relevancy of AASHTO's design standards in general, and SSD standards in particular, to local roads.

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