conducted for more levels of traffic volume, left-turn volume, and driveway density. Further studies should address unbalanced as well as balanced traffic flow conditions, and the effects of driveway configuration need to be evaluated.

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Functional Analysis of Stopping-Sight-Distance Requirements

TIMOTHY R. NEUMAN, JOHN C. GLENNON, AND JACK E. LEISCH

A basic highway design concept is that the driver should be provided a sufficient visible length of highway to enable collision avoidance. Translating this concept to appropriate standards and criteria is an important design consideration. The concept of safe stopping-sight distance (SSD) as developed by AASHTO is reviewed and discussed. A functional SSD model is offered as a means of demonstrating shortcomings and inconsistencies in AASHTO design policy. In addition, the geometry of SSD is evaluated through the use of sight-distance profiles. Significant conclusions are presented that relate to SSD design values on horizontal curves and special problems with trucks on horizontal curves. The functional SSD model is helpful in understanding accidents at locations that have inadequate SSD.

Stopping-sight distance (SSD) is an important highway design feature. The concept of providing a sufficient length of highway visible to the driver for collision avoidance is basic to the safe design of highways. However, translating this concept to design standards and criteria is not as simple as it may appear.

A critical review of current design practice for SSD is presented in this paper. The concepts and conclusions presented are drawn from a study of SSD conducted for FHWA as a part of a research project entitled, "Effectiveness of Design Criteria for Geometric Elements."

A concept of SSD that focuses on highway operational requirements has been developed. Shortcomings and inconsistencies in AASHTO design policy are revealed by applying this operational SSD concept. Also, by using sight-distance profiles, additional insights are gained on the relation between sight distance and highway safety.

OPERATIONAL AND SAFETY CONCEPT OF SSD

Analysis of the operational and safety aspects of SSD requires an understanding of the concept of SSD as it relates to highway operations. The geometric design policy published by AASHTO discusses the need for SSD (1-3):

> If safety is to be built into highways the designer must provide sight distance of sufficient length in which drivers can control the speed of their vehicles so as to avoid striking an unexpected obstacle on the traveled way....
>
> The minimum sight distance available on a highway should be sufficiently long to enable a vehicle traveling at or near the likely top speed to stop before reaching an object in its path. While greater length is desirable, sight distance at every point along the highway should be at least that required for a below average operator or vehicle to stop.

This short discussion alludes to many of the operational elements of SSD: vehicle performance, driver ability, and the roadway alignment. This AASHTO operational model of SSD provides a reasonable starting point for considering SSD and highway operations.

AASHTO SSD Operational Model

AASHTO defines minimum SSD requirements in terms of a passenger car encountering a stationary object in its path. This basic functional model has not changed since 1940. The following review of the evolution of AASHTO SSD policy illustrates the reasoning behind this model. It also demonstrates the need to go beyond this simple abstraction to gain insight on the safety relations of SSD.

In 1940 AASHO formally recognized the need for a sight-distance requirement to help drivers avoid collision circumstances other than passing encounters. Although AASHO recognized that a clear sight line to the pavement was desirable, analyses of how this requirement affected construction cost led to a compromise. A design object height of 4 in. was selected on the basis of optimizing the relation between object height and required vertical curve length. Although the object-height criterion is discussed in the AASHO policy as it relates to objects in the road, the selection of a 4-in. height was not based on the frequency or severity of such objects. This conclusion is further borne out by subsequent changes in AASHO policy to a 6-in. object height; exactly the same discussion was used in relating this height to roadway events.

Selection of other design parameters such as perception-reaction time, eye height, and pavement friction was rational; individual design values were selected based on the existing distributions of these physical values, which were periodically updated, as indicated by the data in Table 1. Yet the underlying methodology was by design an abstraction--a simplified set of elemental factors used to derive a distance--with only an indirect link to the functional needs for sight distance.

Functional Elements of Concern in SSD

It is suggested that attention should be focused on the functional requirements for SSD, which vary depending on a range of factors. SSD requirements are a function of more than a single object height, eye height, or pavement condition. There are many common types of collisions (rear-end, head-on, impacts with large animals, and so on) for which a 4- or 6-in. object bears little or no relation. In addition, accident experience strongly suggests links between geometry (independent of that which produces restricted SSD) and accident causation. Such links are not sufficiently treated in the current AASHTO SSD methodology.

Four factors that contribute to the requirements for SSD are shown in Figure 1. These factors form the basis for a functional SSD model.

Highway Events

A range of common events on the highway creates the

Table 1. Evolution of AASHTO SSD policy.

Year	Design Parameters: Eye Height (ft)	Object Height (in.)	Perception-Reaction Time (sec)	Assumed Tire-Pavement Coefficient of Friction	Assumed Speed for Design	Effective Change from Previous Policy
1940	4.5	4	Variable—3.0 sec at 30 mph to 2.0 sec at 70 mph	Dry—f ranges from 0.50 at 30 mph to 0.40 at 70 mph	Design speed	
1954 (1)	4.5	4	2.5	Wet—f ranges from 0.36 at 30 mph to 0.29 at 70 mph	Lower than design speed (28 mph at 30 mph design speed; 59 mph at 70 mph design speed)	No net change in design distance
1965 (3)	3.75	6	2.5	Wet—f ranges from 0.36 at 30 mph to 0.27 at 80 mph	Lower than design speed (28 mph at 30 mph design speed; 64 mph at 80 mph design speed)	No net change in design distance
1970 (4)	3.75	6	2.5	Wet—f ranges from 0.35 at 30 mph to 0.27 at 80 mph	Minimum values—same as 1965; desirable values—design speed	Increase in SSD of up to 250 ft at 70 mph
1983, proposed (5)	3.50	6	2.5	Wet—f ranges from 0.35 at 30 mph to 0.27 at 80 mph	Minimum values—same as 1965; desirable values—design speed	No net change from 1970

Note: 1 ft = 0.305 m, 1 in. = 25.4 mm, and 1 mph = 1.609 km/h.

Figure 1. Functional relations of SSD.

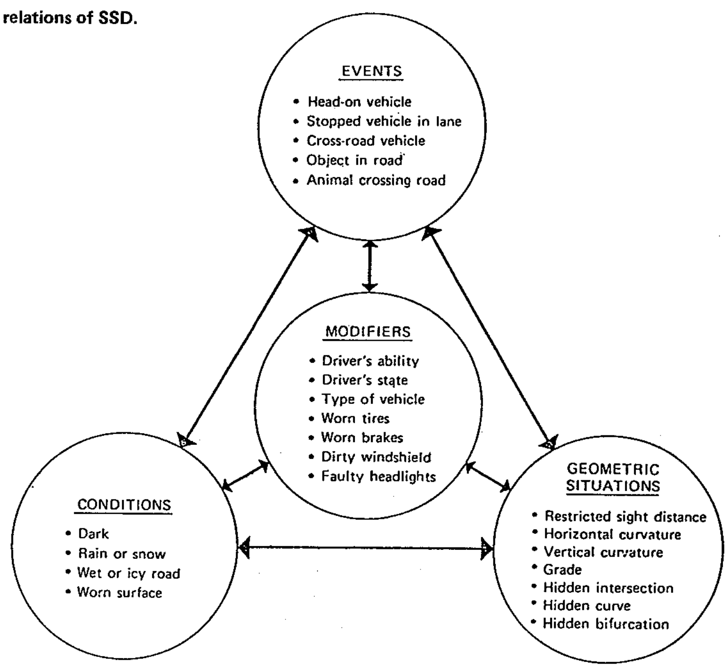


Table 2. Roadway events related to SSD conflicts.

Type of Event	Frequency of Occurrence	Severity of Conflict or Impact	Type of Event	Frequency of Occurrence	Severity of Conflict or Impact
Two-lane rural highway			Urban arterial		
Object in road			Object in road		
Large animal	Variable; generally infrequent	Severe	Large animal	Very infrequent	Severe
Road debris	Infrequent	Minor to moderate	Road debris	Infrequent	Minor
Rocks	Infrequent	Minor	Rocks	Very infrequent	Minor
Small animal	Occasional	Minor to moderate	Small animal	Infrequent	Minor
Icepatch	Infrequent	Minor to moderate	Icepatch	Infrequent to occasional	Moderate
Pothole, washout	Infrequent	Minor	Pothole, washout	Occasional	Minor to moderate
Vehicle in road			Vehicle in road		
Head-on	Very infrequent	Very severe	Head-on	Infrequent	Very severe
Rear-end	Frequent	Severe	Rear-end	Frequent	Moderate to severe
Crossing	Occasional	Severe	Crossing	Frequent	Severe
Pedestrian or bicyclist	Very infrequent	Very severe	Pedestrian or bicyclist	Frequent	Very severe
Rural freeway			Urban freeway		
Object in road			Object in road		
Large animal	Variable; generally infrequent	Severe	Road debris	Frequent	Moderate
Road debris	Infrequent	Moderate	Small animal	Very infrequent	Moderate
Rocks	Infrequent	Moderate	Icepatch	Infrequent	Moderate to severe
Small animal	Infrequent	Moderate	Pothole, washout	Infrequent	Moderate to severe
Icepatch	Infrequent	Minor to moderate	Vehicle in road, rear-end	Frequent	Moderate to severe
Pothole, washout	Infrequent	Minor to moderate	Pedestrian	Very infrequent	Very severe
Vehicle in road, rear-end	Infrequent	Very severe			
Pedestrian or bicyclist	Infrequent	Very severe			

need for sight distance in order to avoid an accident. These events include the AASHTO stationary object in road as well as moving objects (head-on vehicles, crossing vehicles, large animals). The significance of these events with respect to sight distance and safety can be judged by (a) the frequency of occurrence, and (b) the criticality of a potential collision or accident given the event.

The data in Table 2, which summarize common critical events that occur on rural and urban highways, reveal two important concepts. One is that the frequency (and, in some cases, severity) of an event is related to the type of highway. Vehicle-crossing conflicts are clearly a serious problem on two-lane rural highways, but not on freeways. Similarly, the higher speeds prevalent on freeways result in more serious consequences given an encounter with potholes or road debris than is expected on urban arterials. The data in Table 2 also indicate that the proper focus is on frequent or severe events in designing for adequate SSD.

Highway Geometry

The geometry of the highway has a clearly definable effect on SSD requirements. Its primary effect relates to vehicle braking requirements. The following sections discuss the effect of both grades and horizontal curvature on vehicle braking.

Effect of Grades on Stopping Distance

AASHTO policy currently recognizes the effect of grades on vehicle braking distance and, ultimately, the required SSD, as follows:

$$SSD = d_{P/R} + d_B = 0.278\,Vt_{P/R} + \{V^2/[255(f_B \pm G]\} \quad (1)$$

where

$d_{P/R}$ = distance traveled during perception reaction time by the driver (m),
d_B = distance traveled while vehicle is braking (m),
V = design speed (km/h),
$t_{P/R}$ = perception-reaction time (sec),
f_B = AASHTO coefficient of braking friction, and
G = percent grade ÷ 100.

The incremental effect that steeper downgrades have on required braking distances is substantial at high speeds. A vehicle traveling on a 6-percent downgrade at 80 km/h requires 21 m of additional braking distance; at 115 km/h, 49 m of additional distance is required.

Effect of Horizontal Curvature on Stopping Distance

AASHTO SSD policy currently does not recognize the complications to vehicle stopping ability caused by horizontal curvature. Such complications result from the AASHTO assumption that full (design) pavement friction is available to a vehicle forced to brake in an emergency situation. (Recall that design values for braking friction were selected by AASHTO from actual pavement friction values measured from skid tests.) Vehicles traveling on horizontal curves, however, do not have full friction available for braking, but instead have a reduced amount because of the friction already used by the vehicle in cornering.

The data in Figure 2 demonstrate that the friction available for braking on curves is that vector resultant of both available friction and cornering demand. Mathematically, this is given as

$$f_B' = \sqrt{f_B^2 - f_C^2} \quad (2)$$

where

f_B' = coefficient of braking friction available on curve,
f_B = coefficient of braking friction on tangent (AASHTO design values), and
f_C = coefficient of side friction demand on curve (AASHTO design values).

Obviously, longer stopping distances on curves are indicated by this equation. These greater stopping distances are particularly significant at higher speeds, as indicated by the data in Table 3.

Figure 2. Friction requirements for stopping on horizontal curves.

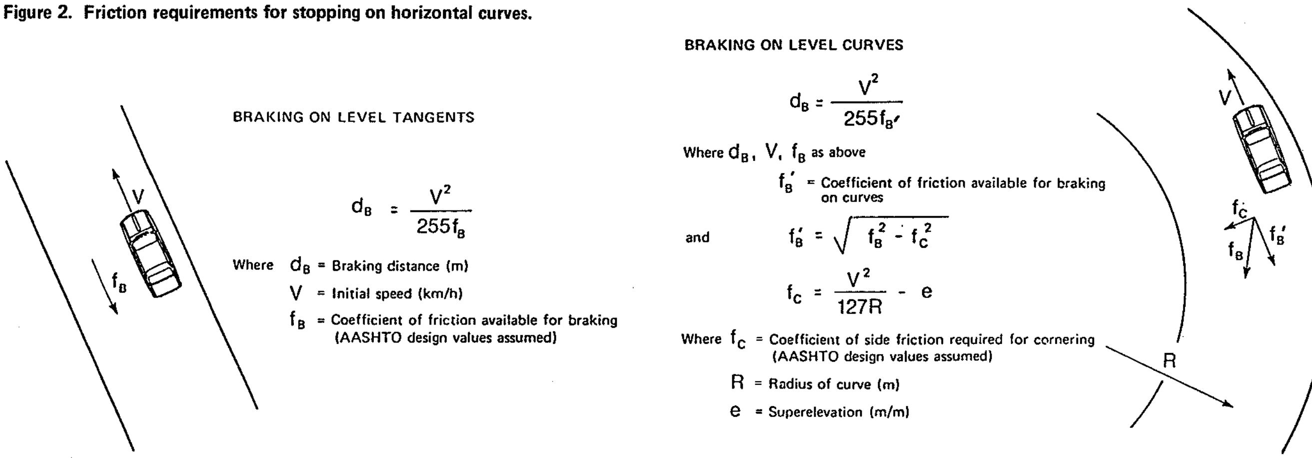


Table 3. SSD requirements for passenger cars on curves (e_{max} = 0.10).

Design Speed (km/h)	Perception-Reaction Distance (m)	Braking on Tangents (wet conditions)			Braking on Curves (wet conditions)			
			Distance (m)				Distance (m)	
		f^a	Braking	Total	f^b	f_c	Braking	Total
50	35	0.347	28	63	0.308	0.159	32	67
60	42	0.328	43	85	0.290	0.153	48	90
70	49	0.313	61	110	0.276	0.147	70	119
80	56	0.301	83	139	0.266	0.140	94	150
90	63	0.294	108	171	0.261	0.134	122	185
100	69	0.288	136	205	0.256	0.128	152	221
110	76	0.282	168	244	0.254	0.122	187	263
120	83	0.275	205	288	0.250	0.115	226	309

[a] $f = f_B$ (AASHTO design values).

[b] $f = \sqrt{f_B^2 - f_c^2}$; f_c = cornering friction required at design speed on controlling curve (AASHTO design values).

Even greater braking distances are required on horizontal curves if the design event is further defined in terms of driver behavior. Studies by Glennon and Weaver (6) and ongoing research under the FHWA contract ("Effectiveness of Design Criteria for Geometric Elements") have indicated that a large proportion of vehicles corner on horizontal curves at path radii significantly shorter than the roadway radius. This sharper cornering requires even greater side friction, thereby further reducing the available friction for braking on the pavement. Therefore, the effect of horizontal curvature on SSD requirements can be considerable.

Combined Effect of Downgrade and Horizontal Curvature on SSD

When drivers encounter combinations of severe grades and controlling horizontal curvature, SSD requirements are much greater than the basic AASHTO values. The combined effect of grades and curvature on SSD are given in Table 4.

Other Geometric Features

The total geometric character of the highway has an effect on safe SSD outside of that quantifiable in terms of braking requirements. Although current AASHTO policy does not explicitly handle this issue, it is clear that certain geometric elements produce especially greater hazards in combination with minimum SSD. Such elements include intersections or driveways, bifurcations, hidden horizontal curves, narrow structures, and railroad crossings. These features partly relate to the highway events previously discussed. They also relate to basic assumptions about driver behavior. Adequate perception-reaction time for collision avoidance is undoubtedly more critical for situations that involve these geometric features.

Table 4. SSD requirements on combined grades and curves for passenger cars (wet conditions).

Design Speed (km/h)	SSD on Tangent (m)	SSD (m) on Controlling Curve with Grade of		
		0 Percent	3 Percent	6 Percent
50	63	67	70	74
60	85	90	96	103
70	110	119	127	138
80	139	150	162	177
90	171	185	200	221
100	205	221	241	268
110	244	263	288	321
120	288	309	340	381

Environmental Conditions

A third aspect of the operational model for SSD is the set of environmental conditions that affect driver and vehicle behavior, the most important of which is pavement condition. AASHTO policy currently accounts for the lower friction provided by wet pavements by assuming wet conditions in the development of design requirements. Other important environmental questions relate to visibility and its effect on the perception-reaction process by the driver. Decreased visibility during rain, snow, and night conditions create sight-distance restrictions because of the limitations of vehicle headlight systems.

Modifying Factors

SSD operational requirements are also influenced by a variety of modifiers, which relate to the performance of both driver and vehicle. The perception-reaction ability of drivers is a direct input to SSD. Current AASHTO policy assumes a worse-than-average driver in establishing a design value for perception-reaction time. However, no variability is indicated in perception-reaction time for the range of events and conditions confronted by drivers.

Vehicle characteristics also play a major role in the design for SSD. Braking distances are a function of vehicle type, tire condition, and brake conditions. Vehicle type is the most important characteristic; trucks require much greater stopping distances than do passenger cars. The eye height of the driver is also a function of the vehicle. This dimension is critical in establishing the sight line from the driver to an object in the road over a crest vertical curve.

AASHTO policy treats the multitude of vehicle characteristics in a cursory manner. Basic SSD design values are a function solely of passenger car braking ability and eye heights of passenger car drivers. Only passing reference to SSD requirements for trucks is made. This is justified by noting that the greater eye heights (and hence longer sight lines) afforded truck drivers tend to balance out the greater truck braking distances.

Nevertheless, a variety of geometric conditions can negate the advantages of greater eye heights for truck drivers. Horizontal sight obstructions (e.g., retaining walls, rock cut, tree lines) restrict the view ahead from trucks and passenger cars equally. Furthermore, a complete functional analysis of such situations reveals a significant inconsistency in AASHTO SSD design policy. As discussed earlier, braking distance requirements on curves are greater than the requirements provided by AASHTO policy. Thus SSD restrictions along horizontal curves present particularly severe problems to trucks. Their greater braking distances, loss of eye-height advantage, and friction demands for cornering contribute to much greater SSD requirements than that indicated by AASHTO design policy.

GEOMETRICS OF SSD

The importance of SSD relative to other highway features can be estimated only after understanding how SSD restrictions are created. A study of the frequency and types of sight-distance restrictions on the highway provides further meaning to the operational model presented previously.

AASHTO recognizes two basic types of SSD restrictions: horizontal and vertical. The following discussion considers the character of these restrictions with horizontal curvature, vertical curvature, grades, and the presence of obstructions adjacent to the traveled way.

Vertical Alignment and SSD

Crest vertical curves restrict available SSD whenever the approach grades are steep, the vertical curve is short, or both. Current AASHTO minimum standards for lengths of vertical curves are based on a combination of design speed and the algebraic difference in the grades (A). The minimum length of vertical curve produces minimum SSD at the assumed design speed.

The salient characteristic of vertical curves to consider in a study of SSD is its distribution throughout the vertical curve. A common misconception is that the minimum SSD provided by a vertical curve is manifest over the entire length of curve. Nevertheless, a plot of SSD along the vertical curve (referred to as a sight-distance profile) reveals SSD decreasing to a minimum value and then rapidly increasing as the vehicle reaches the crest of the curve.

SSD profiles are useful because they reveal the relations among vertical curve length, grades, and SSD. SSD profiles for the range of typical values of A (difference in grade) are shown in Figure 3. Inspection of these profiles reveals three basic characteristics of SSD on crest vertical curves.

1. Vertical curves that create limited SSD do so over relatively short lengths of highway. Similarly, less severe SSD limitations affect longer sections of highway.
2. The length of highway over which SSD is at a minimum is relatively short compared with the length of a vertical curve.
3. Different combinations of grades with the same A have similar lengths of highway at which SSD is at a minimum.

Horizontal Alignment and SSD

SSD restrictions are also created by a combination of horizontal curvature and roadside obstacles or features that obstruct the driver's vision to the pavement ahead. AASHTO policy calls for minimum offsets from such obstacles to the edge of pavement. These requirements are a function of the design speed of the roadway and the curve radius. For example, the AASHTO minimum offset for a 440-m radius curve at 115 km/h is 7.6 m from the edge of a 3.65-m lane.

However, as was discussed earlier, braking requirements on curves are greater than the requirements provided for by AASHTO. These greater braking distances necessitate much greater offsets to roadside obstacles. For example, the same 440-m radius at 115 km/h would require 24 m of offset rather than 7.6 m. Consideration of such great offset requirements is important given that a wide range of conditions and features (buildings, cut slopes, rock cuts, retaining walls, trees, and so on) exist, which create horizontal SSD restrictions. As with vertical SSD restrictions, the character of SSD varies in each case.

SSD profiles are also useful in evaluating the character of SSD on horizontal curves. Consider the SSD profiles for a 440-m-radius curve with different obstructions on the inside (Figure 4). In both cases a sight restriction occurs 7.6 m from the edge of pavement along the curve. The resulting minimum SSD is 183 m. In case A the obstruction is a point (e.g., corner of a building); in case B the obstruction is continuous throughout the curve (e.g., retaining wall, row of trees, or vertical cut slope). The difference in SSD profiles for the two cases is apparent. Minimum SSD in case A is limited to a relatively short length of highway compared with the entire length of curve for case B. (For comparison, also note the required SSD based on the braking on curve operational criterion developed earlier.)

Horizontal SSD restrictions have certain significant characteristics that differ from vertical SSD restrictions.

1. The sight-distance restriction is usually unidirectional; except for extreme restrictions it differs in the direction of travel between the inner lane and the second or outer lane. Generally, only

Figure 3. SSD profiles for vertical curves.

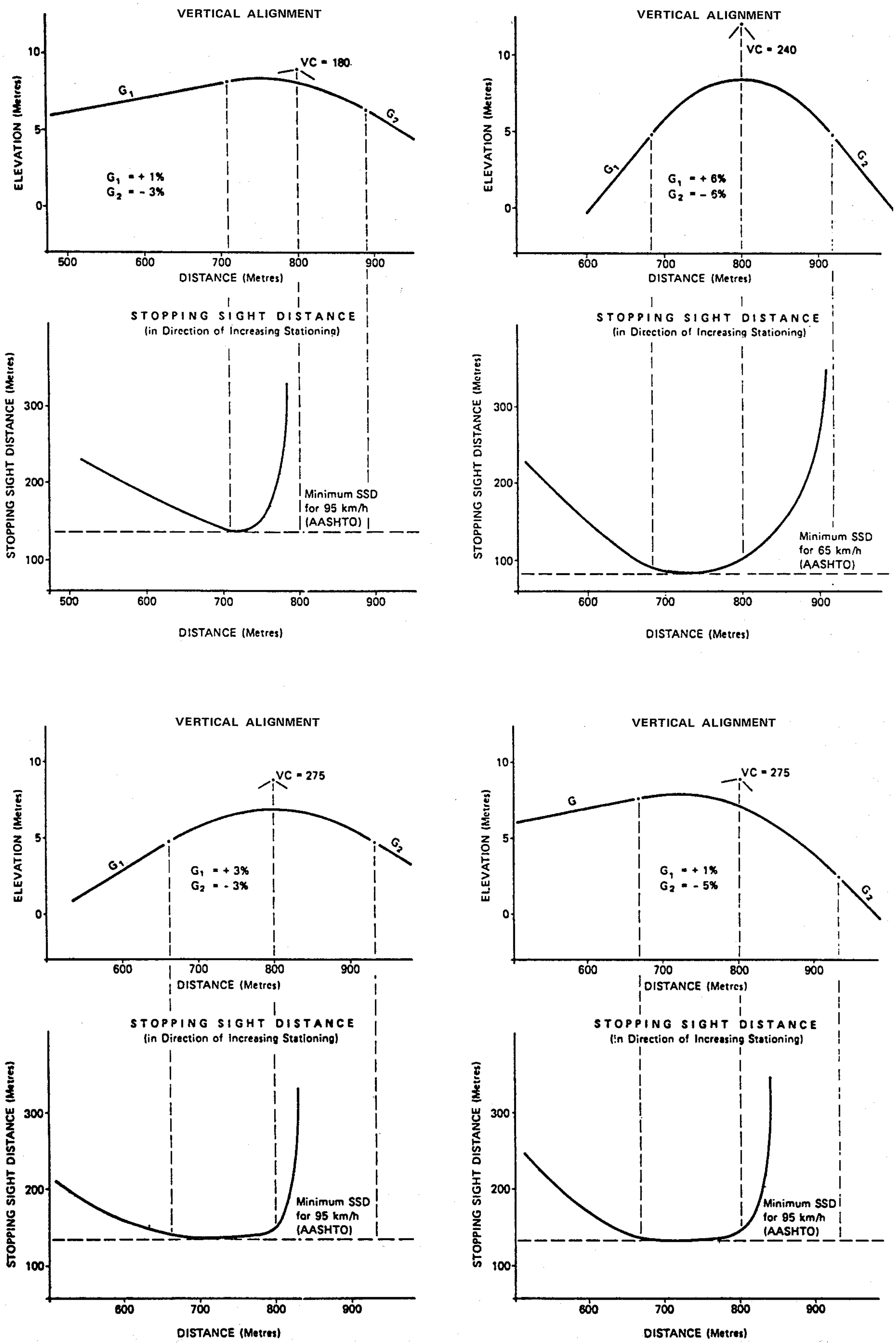
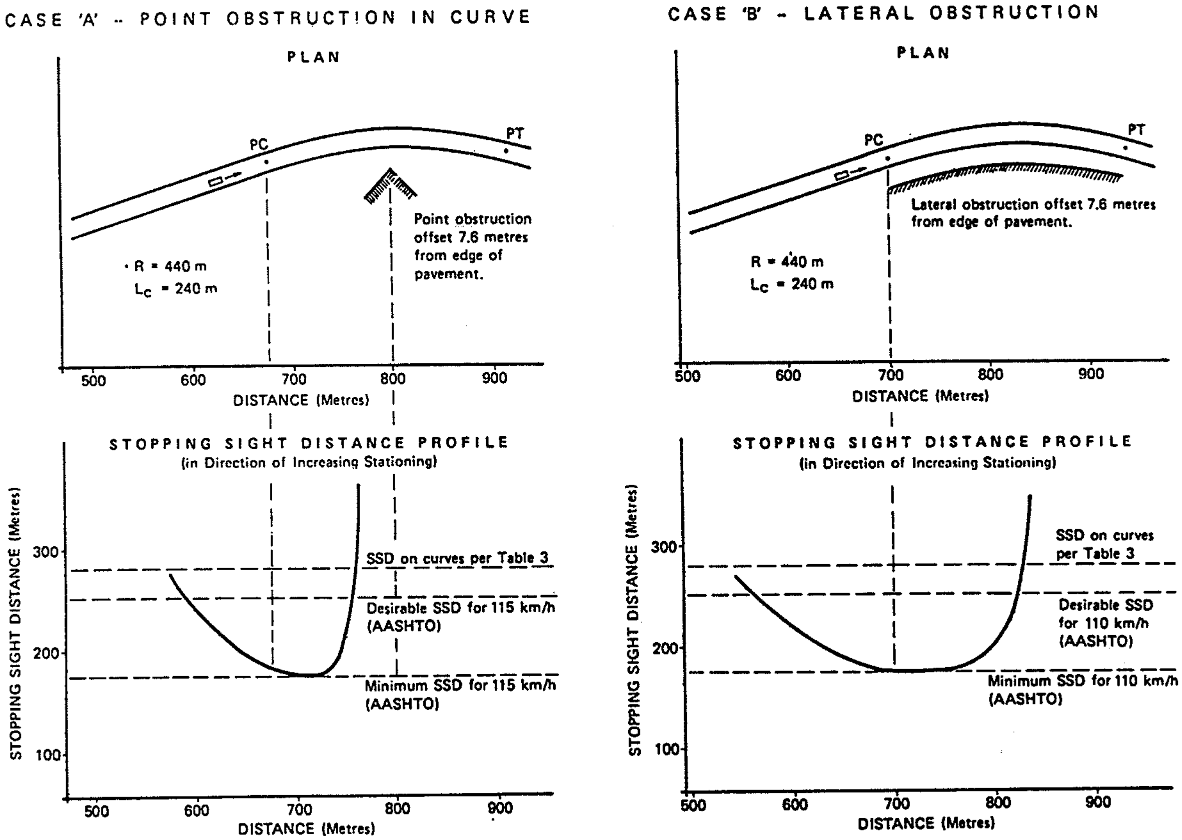


Figure 4. SSD profiles for horizontal curves.



vehicles traveling in the inside lane are subjected to the greatest restriction. Vehicles in the outside lane have an additional lane of lateral offset, which increases available SSD for these vehicles.

2. In some cases (e.g., near vertical obstructions caused by retaining walls, rock cuts, buildings, or rows of trees) driver eye and object heights are not factors in determining SSD.

Point 1 reveals a significant aspect of horizontal SSD restrictions. Because for most conditions the traffic exposure to the sight-distance deficiencies is unidirectional, any accident experience related to the restriction may be a function of only one-half the average daily traffic (ADT) of a two-way roadway. Point 2 provides insight on specific accident problems that involve trucks. The cumulative effect of greater braking distances for trucks, additional requirement for braking on curves (possibly combined with a downgrade that has an additional braking requirement), and loss of benefit from greater eye height indicates a particular vulnerability of trucks to this type of SSD restriction.

SUMMARY OF FUNCTIONAL ASPECTS OF SSD

Analysis of the functional requirements for SSD focuses on the types of accidents and hazardous situations that result from limited SSD. The following points are useful in understanding the link between SSD and safety.

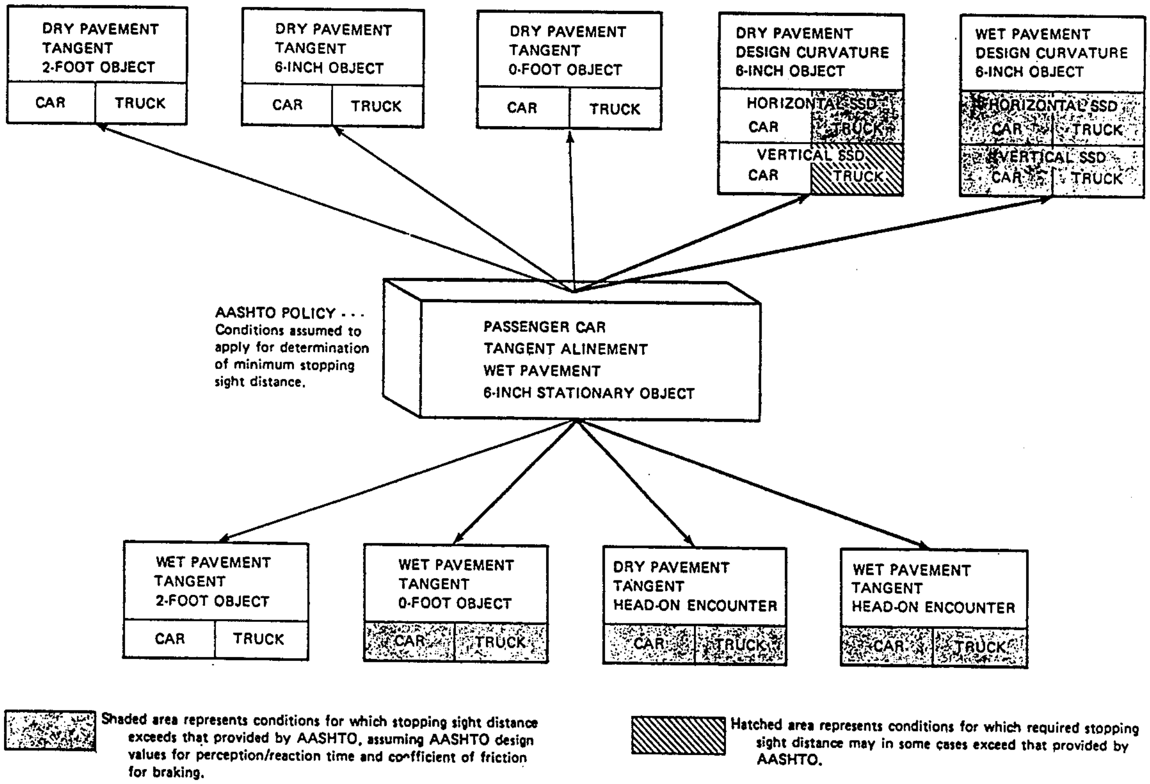
1. SSD accidents are event oriented: The mere presence of a segment of highway with inadequate SSD does not guarantee that accidents will occur. SSD-related accidents occur only after an event(s) creates a critical situation. These events can take the form of arrivals of conflicting vehicles, the presence of objects on the road, inadequate visibility, or unsatisfactory road surface conditions. Some of these events are a function of the highway type (e.g., crossing conflicts at intersections do not occur on freeways), some are related to other geometric or environmental elements (e.g., requirement for severe cornering maneuver on wet pavement), whereas others may be totally random (e.g., presence of an object in the road).

2. The probabilities of critical events occurring within the influence of SSD restrictions define the relative hazard of these restrictions: The relative hazard of various SSD-deficient locations can be estimated by examining the probabilities of critical events. Traffic volume, frequency of conflicts (rear-end, head-on, crossing, object in road), and time exposure of each vehicle to the restricted SSD are all useful in estimating these probabilities.

3. Severity as well as frequency is significant: SSD situations that create severe although infrequent conflicts (e.g., head-on, angle collisions) may be as important as situations with frequent but less-severe conflicts. Cost-effectiveness analysis rightfully values injuries and fatalities forestalled much higher than property-damage-only accidents.

4. Many uncontrollable or unquantifiable factors also contribute to accident causation: Driver performance characteristics such as perception-reaction time, vehicle characteristics such as braking ability, and certain imponderables such as the driver's state of mind contribute to increased accident potential. Although these factors are exclusive of the presence of a SSD-deficient location, their importance is undoubtedly heightened when the deficiency in SSD means that the driver has less

Figure 5. Analysis of functional requirements for SSD on two-lane highways.



time to react to an event. This reduced time may make the difference between collision avoidance and an accident.

The complexity of SSD requirements when viewed as a function of all the elements discussed earlier is shown in Figure 5. Current AASHTO policy, which defines SSD requirements based on only one event and a set of conditions, produces sufficient SSD for certain events or conditions but not for others.

CONCLUSIONS

There is currently great interest in the effects of smaller passenger cars on eye heights and SSD. To date such interest within the traffic engineering and design profession has focused on the traditional parameters associated with SSD: eye height, object height, and perception-reaction time.

It is believed that a broader perspective is necessary when considering SSD requirements. A framework for evaluating such requirements is presented that is based on the functional aspects of SSD. SSD is described in terms of (a) the types and frequencies of conflicts or events that occur on the highway, (b) the geometry of the highway, (c) the environmental conditions, and (d) the variable performance capabilities of drivers and vehicles.

When viewed in terms of these four elements, SSD is revealed as being much more complex than the AASHTO object-in-road model. The inadequacy of the AASHTO model is illustrated by considering the particular problems for trucks with horizontal sight obstructions on curves. Indeed, current AASHTO policy was revealed as being inconsistent for all vehicles encountering limited SSD on horizontal curves. Cornering friction requirements are not included in SSD design policy, even though they are an integral feature in design policy for horizontal curves.

Application of the functional model for SSD revealed a range of situations for which current design standards are inadequate. What implications does this finding have for SSD design policy? It is clearly impossible to design for all situations, and it is not suggested that such a design policy is even desirable. Nevertheless, given the functional model presented here, it appears evident that a fresh look at SSD design policy may be fruitful. It may be appropriate to consider variable facility types in SSD design. A more explicit consideration of other geometric elements such as curvature also appears appropriate. Although comprehensive analyses of all situations were not possible given the research scope, it is believed that sufficient direction is provided for further research.

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