INTEROFFICE MEMORANDUM

DATE: January 19, 1999

TO: Bridge Division Personnel

FROM: Edward T. Fain, Bridge Engineer

SUBJECT: Stopping Sight Distance

The following procedure shall be used for determining compliance with stopping sight distance requirements for bridges:

1. Meet AASHTO's *A Policy on Geometric Design for Highways and Streets* (Green Book) requirements using the minimum value within the range for stopping sight distances. Should these requirements not be initially satisfied, the roadway designers should be contacted to determine what changes can be made to the vertical or horizontal alignment that will result in compliance with the Green Book.

2. If, after coordination with roadway designers, the AASHTO Green Book requirements cannot be provided, the requirements of NCHRP Report 400 *Determination of Stopping Sight Distances* must be met, and a design exception from the Assistant Chief Engineer-Design will be required. Bridge widths should be increased in 6" (100 mm if a metric job) increments, as necessary, to comply with Report 400. The initial speed shall be taken as equal to the design speed when using the tables in this report.

Relevant pages of NCHRP Report 400 *Determination of Stopping Sight Distances* are attached for your information.

CPB
Attachment

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Report 400

Determination of Stopping Sight Distances

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Subject Areas

Highway and Facility Design
Highway Operations and Safety
Safety and Human Performance
Transportation Law

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CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations of this research address a revised model for determining required stopping sight distances for roadway design. The revised model is similar to AASHTO's current stopping sight distance model and suitable for inclusion in AASHTO's *A Policy on Geometric Design for Highways and Streets*.

This chapter provides a brief summary of each conclusion and recommendation from the research.

CONCLUSIONS

A revised stopping sight distance model based on driver behavior and vehicle and roadway characteristics was developed as a product of this research. Parameters for the revised model have been validated with field data and represent safe driving behavior. The parameters also reflect driver, vehicle, and roadway limitations related to the stopping sight distance situation.

The revised model is intended as the design control for locations or geometric features where stopping sight distance is the appropriate criterion, specifically vertical curves on tangents and horizontal curves near lateral obstructions. In general, the model is intended for use where speed and path changes are not required. At these locations, intersection or decision sight distance may be the appropriate control.

The following sections describe the revised model and the recommended parameter values for use in highway geometric design.

Revised Stopping Sight Distance Model

The revised stopping sight distance model developed as a product of this research is similar to the existing AASHTO model, but with initial speed equal to the design speed and design deceleration substituted for friction coefficient. Stopping sight distance is still the sum of two components—brake-reaction distance (distance traveled from the moment an unexpected object could be sighted to the moment the brakes are applied) and the braking distance (distance traveled from the moment the brakes are applied to the moment the vehicle is decelerated to a stop).

Conceptually, stopping sight distance can still be expressed by the following equation:

$$SSD = \text{Reaction Distance} + \text{Braking Distance} \qquad (14)$$

For level roadways, these two components can be mathematically expressed as follows:

$$SSD = 0.278Vt + 0.039V^2/a \qquad (15)$$

where: SSD = stopping sight distance, m;
V = initial speed, km/h;
t = driver perception-brake reaction time, sec; and
a = driver deceleration, m/sec^2.

As with the current AASHTO model, the minimum stopping sight distance, driver eye height, and object height values are used to calculate the minimum length of vertical curve required and the minimum rate of curvature or lateral clearance required on horizontal curves. This required length of curve is such that, at a minimum, the stopping sight distance calculated by Equation 15 is available at all points on the curve.

Initial Speed

This research and other studies documented in the literature show that many drivers exceed the inferred design speed (design speed calculated using current criteria and existing geometry) of horizontal and vertical curves. The consistency of these results does not support the use of initial speeds less than the roadway's design speed for determining stopping sight distance requirements.

Initial speeds for determining stopping sight distance requirements should be a speed that encompasses the desired speed of most drivers: e.g., the roadway's operating or 85th percentile free flow speed. When a roadway's operating speed is expected to change over time, the highest anticipated operating speed should be used to determine stopping sight distance requirements.

Perception-Brake Reaction Time

This research and other studies documented in the literature show that AASHTO's 2.5 sec perception-brake reac-

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tion time for stopping sight distance situations encompasses the capabilities of most drivers (including those of older drivers). In fact, the data shows that 2.0 sec exceeds the 85th percentile SSD perception-brake reaction time for all drivers, and 2.5 sec exceeds the 90th percentile SSD perception-brake reaction time for all drivers.

Thus, the 2.5 sec value should be used for determining required stopping sight distances; however, it should be noted that at locations where stopping sight distance is not the appropriate control, different perception-reaction times may be appropriate. For example, shorter perception-brake reaction times may be appropriate for traffic signal design where change intervals are expected, and longer perception-brake reaction times may be appropriate for intersection or interchange design where driver speed and path corrections are unexpected.

Design Deceleration

This research and other studies documented in the literature show that most drivers choose decelerations greater than 5.6 m/sec^2 when confronted with the need to stop for an unexpected object in the roadway. Approximately 90 percent of all drivers choose decelerations that are greater than 3.4 m/sec^2. These decelerations are within drivers' capability to stay within their lanes and maintain steering control during braking maneuvers on wet surfaces.

Thus, 3.4 m/sec^2 (a comfortable deceleration for most drivers) is recommended as the deceleration threshold for determining required stopping sight distance. Implicit in this deceleration threshold is the requirement that the vehicle braking system and pavement friction values are at least equivalent to 3.4 m/sec^2 (0.34 g). Skid data show that most wet pavement surfaces on state maintained roadways exceed this threshold. Braking data show that most vehicle braking systems can exceed the skidding friction values for the pavement.

Recommended Stopping Sight Distances

The recommended stopping sight distances for design are based on below average drivers detecting an unexpected object in the roadway and stopping a vehicle before striking the object. The recommended values are shown in Table 57. The values in the bottom five rows of the table represent those stopping sight distances beyond the driver's visual capabilities for detecting small objects (150 to 200 mm objects) during the day and large, low contrast objects at night.

For comparison purposes, AASHTO's 1994 design stopping sight distances are shown in Table 58 and Figure 19. Note that the recommended values are approximately midway between the 1994 minimum and desirable values for all initial speeds.

Eye Heights and Object Heights

This research and other studies documented in the literature show that more than 90 percent of all passenger-car driver eye heights exceed 1,080 mm. This eye height encompasses an even larger proportion of the vehicle fleet when trucks and multipurpose vehicles are included in the population. Thus, 1,080 mm is recommended as the driver eye height for determining required stopping sight distances.

TABLE 57 Recommended stopping sight distances for design

Initial Speed (km/h)	Perception-Brake Reaction		Deceleration (m/s^2)	Braking Distance (m)	Stopping Sight Distance for Design (m)
	Time (s)	Distance (m)			
30	2.5	20.8	3.4	10.2	31.0
40	2.5	27.8	3.4	18.2	45.9
50	2.5	34.7	3.4	28.4	63.1
60	2.5	41.7	3.4	40.8	82.5
70	2.5	48.6	3.4	55.6	104.2
80	2.5	55.6	3.4	72.6	128.2
90	2.5	62.5	3.4	91.9	154.4
100	2.5	69.4	3.4	113.5	182.9
110	2.5	76.4	3.4	137.3	213.7
120	2.5	83.3	3.4	163.4	246.7

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TABLE 58 Current stopping sight distances for design (AASHTO 1994)

Design Speed (km/h)	Assumed Speed for Condition (km/hr)	Brake Reaction Time (s)	Brake Reaction Distance (m)	Coefficient of Friction f	Braking Distance on Level (m)	Stopping Sight Distance for Design (m)
30	30-30	2.5	20.8-20.8	0.40	8.8-8.8	29.6-29.6
40	40-40	2.5	27.8-27.8	0.38	16.6-16.6	44.4-44.4
50	47-50	2.5	32.6-34.7	0.35	24.8-28.1	57.4-62.8
60	55-60	2.5	38.2-41.7	0.33	36.1-42.9	74.3-84.6
70	63-70	2.5	43.7-48.6	0.31	50.4-62.2	94.1-110.8
80	70-80	2.5	48.6-55.5	0.30	64.2-83.9	112.8-139.4
90	77-90	2.5	53.5-62.5	0.30	77.7-106.2	131.2-168.7
100	85-100	2.5	59.0-69.4	0.29	98.0-135.6	157.0-205.0
110	91-110	2.5	63.2-76.4	0.28	116.3-170.0	179.5-246.4
120	98-120	2.5	68.0-83.3	0.28	134.9-202.3	202.9-285.6

This research showed that accidents involving small objects are extremely rare events and almost never result in injuries to vehicle occupants. This research also showed that small objects are beyond most drivers' visual capabilities at the stopping sight distances required for most rural highways, especially at night. Specifically, small objects are beyond most drivers' visual capabilities at distances greater than 130 m, and except for reflective or illuminated objects. Large, low contrast objects are beyond most drivers' nighttime visual capabilities at distances greater than 100 m.

More realistic and frequent hazards to drivers are large animals (cattle, deer, etc.) and other vehicles. From a potential hazard standpoint, the critical object for stopping sight distance should be the smallest visible object during the day and at night that represents a hazard to the driver, that is, the taillight or headlight height of another vehicle.

Approximately 95 percent of the taillight heights and 90 percent of the headlight heights exceed 600 mm. Additionally, this research showed that accidents with smaller objects are extremely rare and of low severity in nature. Thus, 600 mm is

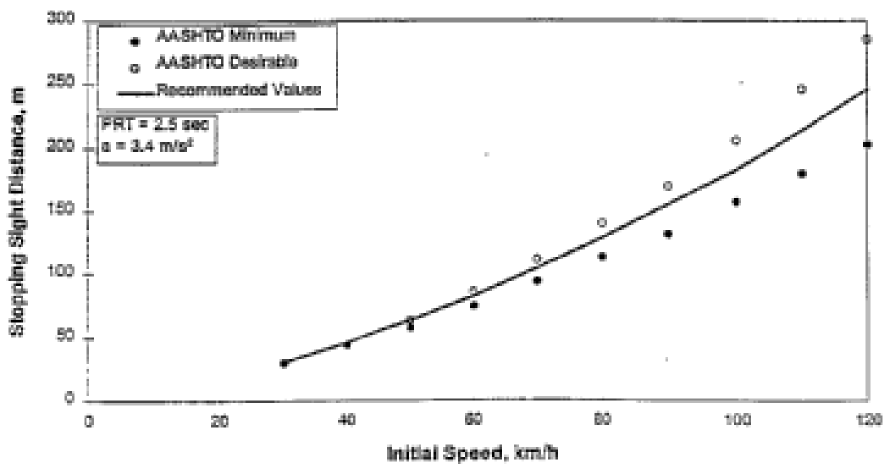

Figure 19. Comparison of 1994 AASHTO and recommended values for stopping sight distance.

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recommended as the appropriate object height for determining required stopping sight distances except in those locations where the probability of rocks or other debris in the roadway is high. In those locations, a shorter object height is appropriate.

Design Controls for Vertical Curves

Minimum lengths of vertical curves are determined by the provision of ample sight distance for the initial speed before braking and the controlling situation. Required stopping sight distances should be the control where stopping sight distance is the appropriate control, and intersection, decision, or passing sight distance should be the control where speed reduction or path correction is the appropriate control. The largest control value determines the minimum length of vertical curve.

Crest Vertical Curves. When eye height and object height are 1,080 mm and 600 mm, respectively, as used for stopping sight distance, the required length of curve (L) in terms of algebraic difference in grade (A) and sight distance (S) can be computed as follows:

For S less than L,

$$L = AS^2/658 \qquad (16)$$

For convenience in describing different combinations of approach and departure grades, the quantity L/A, termed "K" is the horizontal distance to effect a 1 percent change in gradient, that is, a measure of curvature. Table 59 shows the computed K values for lengths of crest vertical curves as required for the stopping sight distances shown in Table 57.

For comparison purposes, the 1994 AASHTO design controls for crest vertical curves are shown in Table 60 and Figure 20. Note that the recommended K values for crest vertical curves are slightly below the 1994 minimum values for all initial speeds.

Sag Vertical Curves. Headlight sight distance generally controls the minimum length of sag vertical curves. In this case, a headlight height of 600 mm and a 1 degree upward divergence of the light beam from the longitudinal axis of the vehicle is used to define the driver's line of sight. The following equation shows the relationship between S, L, and A, using S as the distance between the vehicle and the point where the 1 degree upward angle of light intersects the surface of the road:

For S less than L,

$$L = AS^2/(120 + 3.5S) \qquad (17)$$

Table 59 shows the computed K values for lengths of sag vertical curves as required for the stopping sight distances shown in Table 57.

For comparison purposes, the 1994 AASHTO design controls for sag vertical curves are shown in Table 61 and Figure 21. Note that the recommended values are between the 1994 minimum and desirable values for all initial speeds.

Design Controls for Horizontal Curves

Minimum rate of curvature or lateral clearance for horizontal curves is determined by providing ample sight distance

TABLE 59 Recommended design controls for vertical curves

Initial Speed (km/h)	Stopping Sight Distance for Design (m)	Rate of Vertical Curvature, K [length (m) per % of A]	
		Crest Curves	Sag Curves
30	31.0	2	5
40	45.9	4	8
50	63.1	7	12
60	82.5	11	17
70	104.2	17	23
80	128.2	25	29
90	154.4	37	37
100	182.9	51	45
110	213.7	70	53
120	246.7	93	62

TABLE 60 Design controls for crest vertical curves (AASHTO 1994)

Design Speed (km/h)	Assumed Speed for Condition (km/h)	Coefficient of Friction f	Stopping Sight Distance for Design (m)	Rate of Vertical Curvature, K (length (m) per % of A)	
				Computed	Rounded for Design
30	30-30	0.40	29.6-29.6	2.17-2.17	3-3
40	40-40	0.38	44.4-44.4	4.88-4.88	5-5
50	47-50	0.35	57.4-62.8	8.16-9.76	9-10
60	55-60	0.33	74.3-84.6	13.66-17.72	14-18
70	63-70	0.31	94.1-110.8	21.92-30.39	22-31
80	70-80	0.30	112.8-139.4	31.49-48.10	32-49
90	77-90	0.30	131.2-168.7	42.61-70.44	43-71
100	85-100	0.29	157.0-205.0	61.01-104.02	62-105
110	91-110	0.28	179.5-246.4	79.75-150.28	80-151
120	98-120	0.28	202.9-285.6	101.90-201.90	102-202

for the initial speed before braking and the controlling situation. Required stopping sight distances should be the control where stopping sight distance is the appropriate control, and intersection, decision, or passing sight distance should be the control where speed reduction or path correction is the appropriate control. The largest control value determines the minimum rate of curvature or lateral clearance.

In design of horizontal curves, the sight line is a chord of the curve, and the applicable sight distance is measured along the centerline of the inside lane around the curve. The middle ordinates (M) for clear sight areas to satisfy required stopping sight distances (S) for curves of different radii (R) can be expressed as follows:

$$M = R\left[\left(1 - \cos\frac{28.65S}{R}\right)\right] \tag{18}$$

This formula applies only to circular curves longer than the sight distance for the initial speed. For any initial speed, the relationship between radius and middle ordinate is a straight line. The required middle ordinates to provide the stopping sight distance shown in Table 59 are shown in Table 62 and Figure 22.

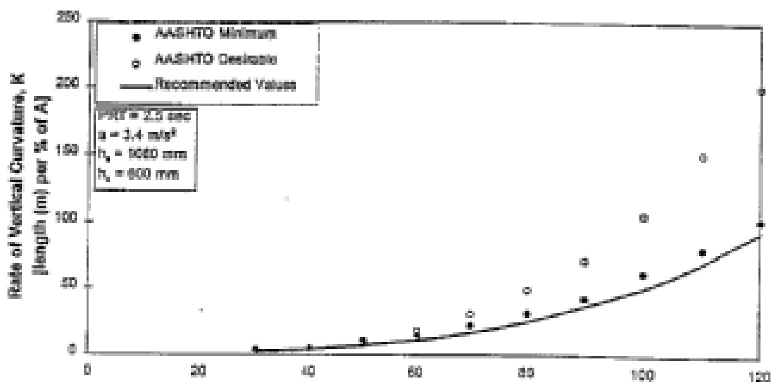

Figure 20. Comparison of 1994 AASHTO and recommended K values for crest vertical curves.

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TABLE 61 Design controls for sag vertical curves (AASHTO 1994)

Design Speed (km/h)	Assumed Speed for Condition (km/h)	Coefficient of Friction f	Stopping Sight Distance for Design (m)	Rate of Vertical Curvature, K (length (m) per % of A)	
				Computed	Rounded for Design
30	30-30	0.40	29.6-29.6	3.88-3.88	4-4
40	40-40	0.38	44.4-44.4	7.11-7.11	8-8
50	47-50	0.35	57.4-62.8	10.20-11.54	11-12
60	55-60	0.33	74.3-84.6	14.45-17.12	15-18
70	63-70	0.31	94.1-110.8	19.62-24.08	20-25
80	70-80	0.30	112.8-139.4	24.62-31.86	25-32
90	77-90	0.30	131.2-168.7	29.62-39.95	30-40
100	85-100	0.29	157.0-205.0	36.71-50.06	37-51
110	91-110	0.28	179.5-246.4	42.95-61.68	43-62
120	98-120	0.28	202.9-285.6	49.47-72.72	50-73

For comparison purposes, the middle ordinates to provide the 1994 AASHTO minimum stopping sight distances are shown in Table 63. Note that the middle ordinates based on the recommended stopping sight distances are larger than those based on AASHTO minimum stopping sight distances; however, they are smaller than those based on AASHTO desirable stopping sight distances.

Safety Considerations

Safety is of the utmost importance when designing roadways; therefore, any recommended guidelines should result in designs that do not create hazards or unsafe conditions. This research and other studies show that for moderate reductions in available stopping sight distance, there are no noticeable safety problems associated with crest curves on rural high-speed highways. This research also showed that there are no tort problems associated with current stopping sight distances.

Specifically, this research shows that accident rates on rural two-lane highways with limited stopping sight distance crest vertical curves (curves with stopping sight distances slightly below current criteria) are similar to accident rates on all two-lane highways. Additionally, crest vertical curves with moderate reductions in stopping sight distance do not appear to cause a safety problem for large trucks or older

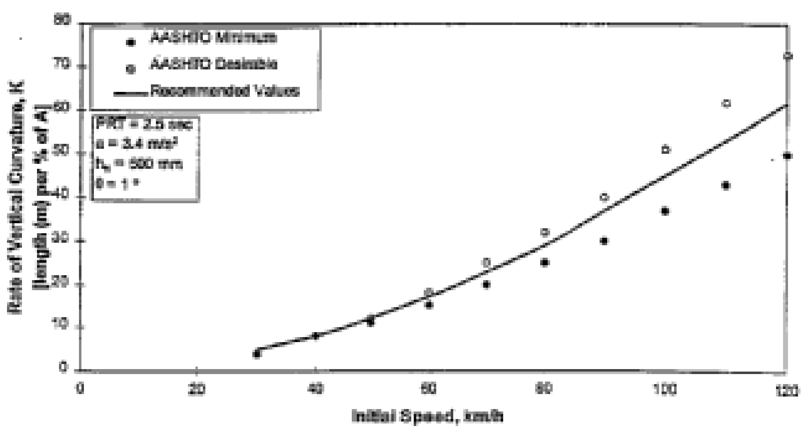

Figure 21. Comparison of 1994 AASHTO and recommended K values for sag vertical curves.

TABLE 62 Required middle ordinates for various initial speeds and horizontal curve radii

Initial Speed (km/h)	Stopping Sight Dist. (m)	Minimum* Radius (R)	Radius, R, Centerline of Inside Lane (m)						
			80	100	150	300	500	1000	1500
30	31.0	25	–	–	–	–	–	–	–
40	45.9	45	3.3	2.6	–	–	–	–	–
50	63.1	75	6.1	4.9	3.3	–	–	–	–
60	82.5	115	–	–	5.6	2.8	–	–	–
70'	104.2	160	–	–	–	4.5	2.7	–	–
80	128.2	210	–	–	–	6.8	4.1	2.1	–
90	154.4	275	–	–	–	9.9	6.0	3.0	2.0
100	182.9	360	–	–	–	–	8.3	4.2	2.8
110	212.7	455	–	–	–	–	11.4	5.7	3.8
120	246.7	595	–	–	–	–	–	7.6	5.1

* Minimum radius when $e_{max} = 0.10$

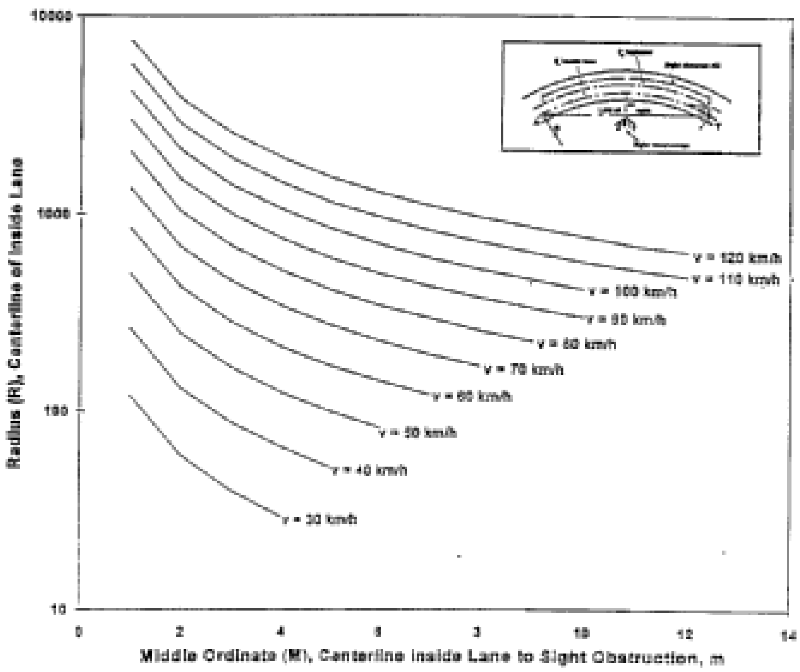

Figure 22. Relationship between radius and value of middle ordinate necessary to provide stopping sight distance on horizontal curves.

TABLE 63 **Required middle ordinates for various design speeds and horizontal curve radii (AASHTO 1994, desirable values)**

Design Speed (km/h)	Stopping Sight Dist. (m)	Minimum* Radius (R)	Radius, R, Centerline of Inside Lane (m)						
			80	100	150	300	500	1000	1500
30	29.6	25	–	–	–	–	–	–	–
40	44.4	45	3.1	2.5	–	–	–	–	–
50	62.8	75	6.1	4.9	3.3	–	–	–	–
60	84.6	115	–	–	5.9	3.0	–	–	–
70	110.8	160	–	–	–	5.1	3.1	–	–
80	139.4	210	–	–	–	8.1	4.9	2.4	–
90	168.7	275	–	–	–	–	7.1	3.6	2.4
100	205.0	360	–	–	–	–	–	5.2	3.5
110	246.4	455	–	–	–	–	–	7.6	5.1
120	285.6	595	–	–	–	–	–	–	6.8

* Minimum radius when $e_{max} = 0.10$

drivers. Finally, most accidents with limited stopping sight distance as a possible contributing factor occurred on vertical curves with stopping sight distances of 120 m or less and involved another vehicle entering or exiting an intersection or driveway.

It should be noted that the revised model is intended for use in designing those curves where stopping sight distance controls. If speed or path corrections are needed in addition to stopping sight distance, intersection or decision sight distance may control the design of curves in combination with other roadway features.

RECOMMENDATIONS

The revised stopping sight distance model and parameter values represent driver capabilities and performance that can be validated with field data and defended as representative of safe driving behavior. It is similar to the existing AASHTO model so department of transportation personnel will not need to learn a new methodology. The revised model does recommend stopping sight distances and crest curve lengths that are longer than the current minimum design values; however, it should be noted that these recommendations are based on driver capabilities and performance rather than on a need for additional safety.

Thus, it is recommended that the revised model, associated documentation, and suggested changes to the *Green Book* be presented to the AASHTO Task Force on Geometric Design for possible inclusion in the next update of the *Green Book*. It also is recommended that a research project be initiated to address the differences in AASHTO definitions of design and operating speed because of their importance in geometric design.

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