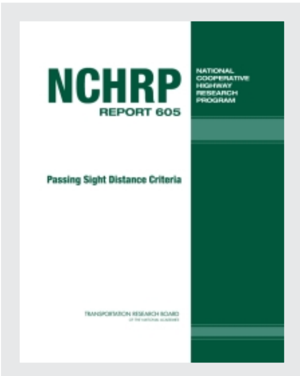

Passing Sight Distance Criteria

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 605

Passing Sight Distance Criteria

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Christopher J. Hedges
Staff Officer
Transportation Research Board

This report presents recommendations on the adequacy of current procedures and guidelines used to estimate minimum passing site distance (PSD) requirements for highway design and pavement marking. The research involved a review of current practice, an extensive analysis of various alternative PSD models, and field studies of passing maneuvers on two-lane highways. Video data collection was used to study distance travelled by the passing vehicle in the opposing lane, the speed differential between the passed and passing vehicles, and the deceleration rate used by the passing vehicle when the passing maneuver was aborted. The report includes specific text recommended for inclusion in the next edition of the AASHTO *A Policy on Geometric Design of Highways and Streets* (the "Green Book"). The report will be of interest and value to all users of the current design and pavement marking guides to apply the best available knowledge on passing sight distance requirements.

The procedures used to determine passing sight distance (PSD) in the 2001 AASHTO *A Policy on Geometric Design of Highways and Streets* (the "Green Book") have remained virtually unchanged since they were incorporated into the 1954 edition of the policy. The 1954 policy used a procedure based on a summary report of extensive field observations of passing maneuvers made during 1938 to 1941 by Prisk and published in *Proceedings HRB Volume 21*. Surveys conducted in 1971 and 1978 found that AASHTO values for PSD were conservative, except at passing vehicle speeds above 65 mph, but these values continued to be used in the 1984, 1990, 1994, and 2001 editions. Other papers have been developed and presented in various forums discussing PSD in subsequent years, but the procedures remain unchanged. The vehicle fleet, operating conditions, and characteristics of the driver have changed considerably over the past 50 years, but the current PSD procedures do not take these variables into account. Furthermore, the FHWA *Manual on Uniform Traffic Control Devices for Streets and Highways* (*MUTCD)* and the Green Book show different PSD values for similar conditions. The current edition of the FHWA's *Older Driver Highway Design Handbook* briefly addresses PSD with recommendations for minimum distances at specified speed ranges.

Under NCHRP Project 15-26, a research team led by Douglas Harwood of the Midwest Research Institute evaluated current methods for determining minimum passing site distance requirements. The research included a review of existing research, extensive analysis of various alternative PSD models, and subsequent field trials. Based on the results, the research team assessed the guidance on PSD provided in the AASHTO Green Book and MUTCD. The assessment considered safety concerns on two-lane highways, driver behavior, and the possible influence of longer trucks and older drivers. The report presents recommendations to bring consistency between PSD design standards and pavement marking practices.

CONTENTS

S U M M A R Y

Passing Sight Distance Criteria

The operational efficiency of many two-lane highways depends on the opportunity for faster drivers to pass slower drivers. Where faster drivers encounter a slower driver and are unable to pass, platoons form and the level of service of the two-lane highway deteriorates. Passing Sight Distance (PSD) is provided in the design of two-lane highways to provide opportunities for faster drivers to pass where gaps in opposing traffic permit. Passing and no-passing zones are marked in the centerline of two-lane highways to indicate where it is legal for drivers to make such passing maneuvers.

PSD design for two-lane highways is based on criteria in the AASHTO *Green Book* that were derived from older data and have been unchanged for many years. Marking of passing and no-passing zones are based on PSD criteria presented in the *Manual on Uniform Traffic Control Devices* (MUTCD). The MUTCD criteria are based on the values in a 1940 AASHO guide and represent a subjective compromise between sight distances computed for flying passes and sight distances computed for delayed passes. The marking PSD criteria are substantially less than the PSD criteria used in design.

The MUTCD also provides guidance on minimum passing zone length of 120 m (400 ft) by stating that, where successive no-passing zones come within 120 m (400 ft) of one another, the no-passing-zone marking should be continued between them.

A number of alternative PSD models were reviewed in the research. The alternative models that appear to most appropriately represent the PSD needs of passing drivers are those developed by Glennon and Hassan et al. Both of these models recognize that, in the early stages of a passing maneuver, the passing driver can easily and safely abort the passing maneuver.

Field studies conducted in Missouri and Pennsylvania as part of the current research, together with field data from a recent Texas study, can be used to characterize driver behavior and quantify traffic performance measures for passing maneuvers.

Application of the field study results in the Glennon model produces PSD values equal to or slightly less than the MUTCD PSD values. Application of the field study results in the Hassan et al. model produces PSD values that are less than the MUTCD values at speeds of 72 km/h (45 mph) or less and greater than the MUTCD values by only 6 to 40 m (19 to 132 ft) at speeds of 80 km/h (50 mph) or more. These small differences in PSD, together with the good safety record for passing maneuvers on existing two-lane highways, do not indicate any need to modify the current MUTCD PSD criteria.

Short passing zones with lengths of 120 to 240 m (400 to 800 ft) contribute little to the operational efficiency of two-lane roads. Passing maneuvers were observed by only 0.4 percent of all vehicles and 1.6 percent of vehicles with headways of 3 sec or less in short passing zones; comparable values for longer passing zones are 1.9 and 7.8 percent, respectively. Traffic simulation analyses of two-lane highway operations also show very few passes occurring in short

passing zones. Furthermore, of the passing maneuvers that do occur in short passing zones, 92 percent extended beyond the end of the marked passing zone and, in 17 percent of passing maneuvers, the position at which the passing and passed vehicles are abreast occurred beyond the end of the marked passing zone; comparable values for longer passing zones are 21 and 0 percent, respectively. However, short passing zones do serve a role in providing an opportunity for flying passes and for passing slower moving vehicles such as farm tractors. In the absence of any indication that such short zones result in poor safety performance on two-lane highways, no change in the MUTCD 120-m (400-ft) minimum passing zone length guideline is recommended.

The MUTCD PSD criteria used for marking of passing and no-passing zones also are recommended for use in PSD design. This will provide desirable consistency between PSD design and marking practices. The research found that two-lane highways can be designed safely with any set of PSD criteria equal to or greater than the PSD criteria currently used in marking passing and no-passing zones. The longer PSD criteria currently presented in the AASHTO *Green Book* might provide improved traffic operational efficiency, but are often considered so long as to be impractical.

Modifications to the text of the AASHTO *Green Book* are recommended to implement the recommended change in PSD design criteria.

CHAPTER 1

Introduction

Background

Passing sight distance (PSD) is a key consideration in the design of two-lane highways and the marking of passing and no-passing zones on two-lane highways. The design criteria for minimum PSD for two-lane highways are presented in the 2004 AASHTO *Policy on Geometric Design of Highways and Streets (1)*, commonly known as the *Green Book*. These *Green Book* criteria have remained virtually unchanged since they were incorporated in the 1954 version of the policy. The 1954 policy used criteria based on a summary report of extensive field observations of passing maneuvers made between 1938 and 1941. Surveys conducted in 1971 and 1978 found that AASHTO values for PSD were conservative, except at passing vehicle speeds above 105 km/h (65 mph). While the vehicle fleet has changed dramatically over the past 50 years, the PSD values in the *Green Book* remain unchanged.

The *Green Book* PSD criteria are used in the design process to ensure that sight distance is available over a sufficient percentage of the roadway length to allow drivers to pass slower vehicles where oncoming traffic permits. However, the *Green Book* does not specify over what percentage of the roadway length the minimum PSD should be available. This is a decision left to the designers of individual projects considering a range of factors such as passing demand, desired level of service, terrain, environmental factors, and construction cost.

While the *Green Book* PSD criteria are used in the design of two-lane highways, they are not used directly in the marking of passing and no-passing zones once the highway is open to traffic. PSD criteria for marking are set in the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) *(2)*. The PSD levels that warrant the placement of no-passing zone barrier markings on a two-lane highway are roughly half of the minimum PSD criteria used in design. The *Green Book* design criteria and MUTCD marking criteria for PSD are based on different assumptions about critical passing maneuvers. Research is needed to evaluate whether these two sets of criteria need replacement or modification and whether there is a need to rationalize or reconcile these two separate sets of criteria.

Research Objectives and Scope

The research objectives were to evaluate the design and operational criteria for determining minimum PSD and to modify or develop new PSD criteria. The project scope included consideration of potential modifications to both the PSD design criteria presented in the *Green Book* and the PSD marking criteria presented in the MUTCD.

The research included an extensive review of current and proposed models of the PSD needs in passing maneuvers and field studies of passing maneuvers of two-lane highways in Missouri and Pennsylvania. The field studies consider passing maneuvers in long passing zones with lengths of 300 to 1,650 m (1,000 to 5,400 ft) and in short passing zones with lengths of 120 to 240 m (400 to 800 ft).

Organization of This Report

This report presents the results of the research on PSD criteria. Chapter 2 reviews current PSD criteria for geometric design and marking of passing and no-passing zones. Chapter 3 presents a review and critique of various alternative PSD models that have been presented in the literature. Chapter 4 describes the data collection conducted for the study and the research results. Chapter 5 reviews key PSD-related issues and assesses the need for changes in PSD criteria. Chapter 6 presents the conclusions and recommendations of the research. References presents a list of references cited in this report.

Summary of Nomenclature

The following list defines all of the nomenclature used in PSD models in the remainder of the report. Where these symbols are used in multiple models, the variable has the same meaning in each model. However, individual authors may differ on the appropriate values estimated for these variables. In some cases, the value of a given variable may vary as a function of speed or vehicle type, while in other cases a constant value may apply. These variables are more fully explained, as needed, where they are first introduced in the text of the report.

a = acceleration rate of the passing vehicle to increase its speed from V_i to $V_i + m$ (ft/sec²)
a_{max} = maximum vehicle acceleration achievable at zero speed (ft/sec²)
d_1 = distance traveled by the passing vehicle during perception and reaction time and during initial acceleration to the point of encroachment on the left lane (ft)
d_2 = distance traveled by the passing vehicle while it occupies the left lane (ft)
d_3 = distance between passing vehicle and opposing vehicle at the end of the passing maneuver (i.e., clearance distance) (ft)
d_4 = distance traveled by an opposing vehicle for two-thirds of the time the passing vehicle occupies the left lane, or ⅔ of d_2 (ft)
d_5 = distance traveled by the passing vehicle from the start of the passing maneuver to the critical position (ft)
d_6 = distance traveled by the passing vehicle from the critical position until it returns to its own lane (ft)
d_7 = distance traveled by the opposing vehicle from the time the passing vehicle reaches the critical position until it returns to its own lane (ft)
d_a = deceleration rate used in aborting a passing maneuver (ft/sec²)
G_1 = space headway between passing and passed vehicles at the instant the passing vehicle returns to the normal lane (ft)
G_1^N = space headway between passed and passing vehicles at the start of the passing maneuver (ft)
G_2 = space headway between the front of the passing (i.e., aborting) vehicle and the rear of the passed vehicle (ft)
G_3 = space headway between passing and passed vehicles (ft)
h = minimum headway between the passing and passed vehicles at the end of a completed or aborted passing maneuver and minimum headway between passing and oncoming vehicles at the end of a completed or aborted passing maneuver (sec)
L_i = length of passed vehicle (ft)
L_p = length of passing vehicle (ft)
m = speed differential between passed and passing vehicles (mph)
p_a = perception-reaction time required by the passing driver to abort the passing maneuver (sec)
p_c = perception-reaction time required by the passing driver to complete the passing maneuver (sec)
PSD = passing sight distance (ft)
PSD_c = passing sight distance required to complete or abort the passing maneuver when the passing vehicle is at the critical position (ft)
t_1 = time required for initial maneuver (sec)
t_2 = time the passing vehicle occupies the opposing lane (sec)
t_5 = travel time of the passing vehicle from the start of the passing maneuver to the critical position (sec)
t_6 = time required for the passing vehicle to return to its own lane from the critical position for a completed passing maneuver (sec)
t_6^* = time required to complete a passing maneuver from the position where the front bumpers of the passing and passed vehicles are abreast (sec)
t_8 = deceleration time needed for the passing vehicle to slow down to the minimum speed, V_{min} (sec)
t_9 = additional time at which the passing vehicle travels at V_{min} (sec)
t_a = time required to abort a passing maneuver from the critical position (after perception-reaction time) (sec)
t_d = deceleration time (sec)
V_{85} = 85th percentile speed (mph)
V_{close} = closing rate between the passing and opposing vehicles (mph)
V_{crit} = speed of passing vehicle at the critical position (mph)
V_d = design speed (mph)
V_i = speed of passed vehicle (mph)
V_{max} = maximum vehicle speed achieved when vehicle acceleration capability drops to zero (mph)
V_{min} = minimum speed of the passing vehicle which is equal to V_d-2m (mph)
V_o = speed of opposing vehicle (mph)
V_p = average speed of passing vehicle (mph)
Δ_c = relative position of the front bumpers of the passing and passed vehicles at the critical position (negative Δ_c means that the passing vehicle is behind the passed vehicle; positive Δ_c means that the passing vehicle is in front of the passed vehicle) (ft)

CHAPTER 2

Current Passing Sight Distance Design and Marking Criteria

This chapter presents a review and critique of current PSD design criteria in the AASHTO *Green Book* (*1*) and current PSD criteria for marking passing and no-passing zones in the MUTCD (*2*). The review addresses the conceptual model for the *Green Book* and MUTCD criteria, the assumptions on which the models are based, and the comparison of the models.

Definition of Passing Sight Distance

PSD is the distance that drivers must be able to see along the road ahead to safely and efficiently initiate and complete passing maneuvers of slower vehicles on two-lane highways using the lane normally reserved for opposing traffic. PSD is provided along roads to enable drivers to assess whether to initiate, continue, and complete or abort passing maneuvers. PSD sufficient for passing maneuvers is generally provided at intervals along a two-lane highway where it is cost-effective to do so. Separate PSD criteria are used in design of two-lane highways and in marking passing and no-passing zones on those highways.

AASHTO *Green Book* Criteria for PSD Design

The current PSD design criteria for two-lane highways in the 2001 *Green Book* (*1*) are essentially unchanged from the criteria in the 1954 AASHO policy and are based on the results of field studies conducted between 1938 and 1941 and validated by another study conducted in 1958 *(3, 4, 5)*. Based on these studies, the *Green Book* policy defines the minimum PSD as the sum of the following four distances:

$$PSD = d_1 + d_2 + d_3 + d_4 \qquad (1)$$

where

d_1 = distance traveled during perception and reaction time and during initial acceleration to the point of encroachment on the left lane;

d_2 = distance traveled while the passing vehicle occupies the left lane;

d_3 = distance between passing vehicle and opposing vehicle at the end of the passing maneuver (such as, clearance distance); and

d_4 = distance traveled by an opposing vehicle for two-thirds of the time the passing vehicle occupies the left lane, or $\frac{2}{3}$ of d_2.

Design values for the four distances described above were developed using the field data and the following assumptions stated in the *Green Book:*

- The passed vehicle travels at uniform speed.
- The passing vehicle reduces speed and trails the passed vehicle as it enters the passing section. (This is called a delayed pass.)
- When the passing section is reached, the passing driver requires a short period of time to perceive the clear passing section and to begin to accelerate.
- Passing is accomplished under what may be termed a delayed start and a hurried return in the face of opposing traffic. The passing vehicle accelerates during the maneuver, and its average speed during the occupancy of the left lane is 16 km/h (10 mph) higher than that of the passed vehicle.
- When the passing vehicle returns to its lane, there is a suitable clearance length between it and any oncoming vehicle in the other lane.

The four components of PSD are illustrated in Figure 1, based on *Green Book* Exhibit 3-4. Figure 2 shows the *Green Book* design values for PSD. Table 1, based on *Green Book* Table 3-5, shows the numerical derivation of the PSD design values shown in Figure 2. This table shows that the speeds used to compute the design values for PSD differ from the design speed of the highway. The speed of the passed vehicle is assumed to represent the average running speed of traffic, which may be up to 22 mph less than the design speed of the

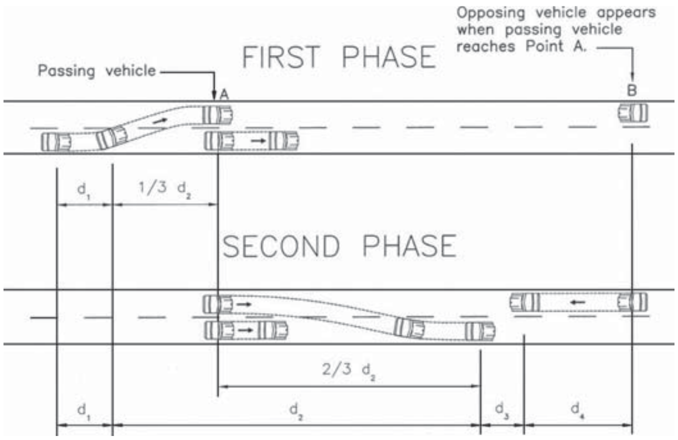

Figure 1. Elements of passing sight distance for two-lane highways (1).

highway. The speed of the passing vehicle is assumed to be 10 mph higher than the speed of the passed vehicle.

The distance traveled during the initial maneuver period (d_l) is computed in the *Green Book* as:

Metric

$$d_1 = 0.278 t_1 \left(v - m + \frac{a t_1}{2} \right)$$

where

t_1 = time of initial maneuver, s;
a = average acceleration, km/h/s;
v = average speed of passing vehicle, km/h; and
m = difference in speed of passed vehicle and passing vehicle, km/h.

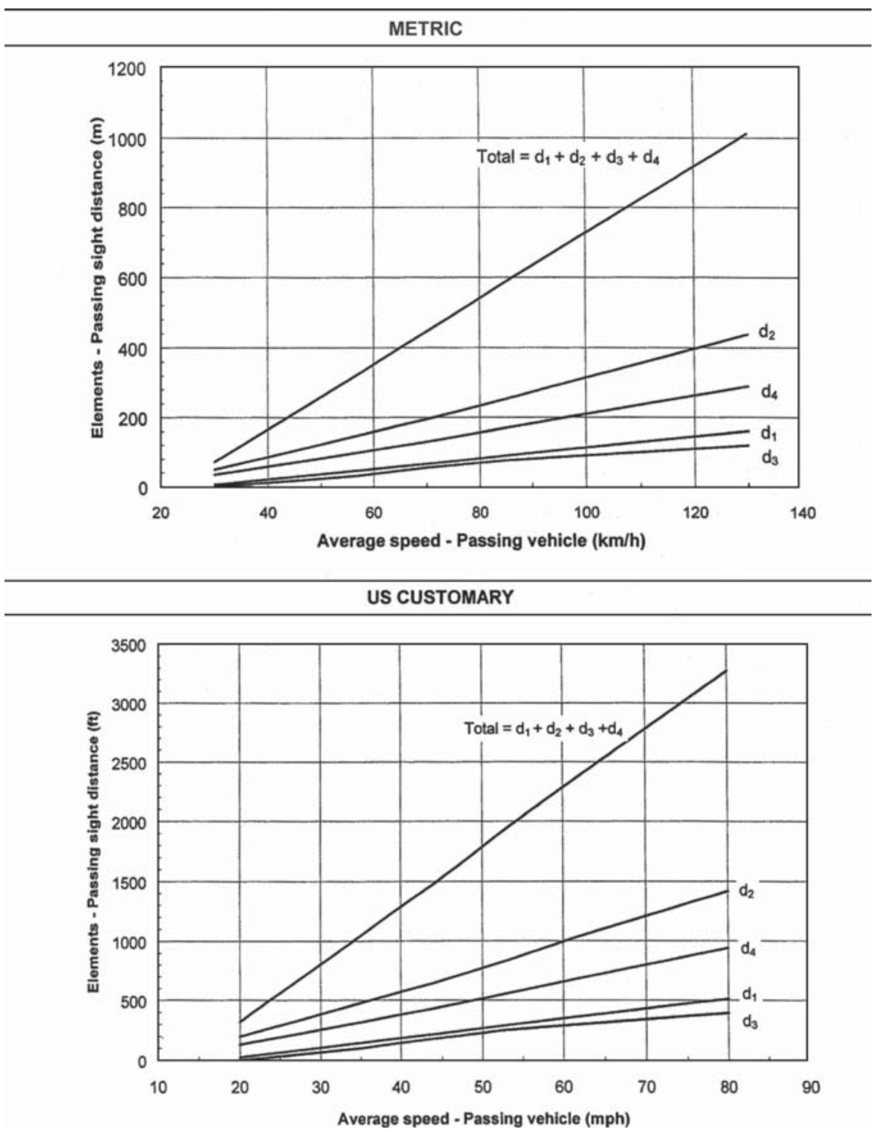

Figure 2. Total passing sight distance and its components—two-lane highways (1).

Table 1. Elements of safe passing sight distance for design of two-lane highways (*1*).

Component of passing maneuver	Metric				US Customary			
	Speed range (km/h)				Speed range (mph)			
	50-65	66-80	81-95	96-110	30-40	40-50	50-60	60-70
	Average passing speed (km/h)				Average passing speed (mph)			
	56.2	70.0	84.5	99.8	34.9	43.8	52.6	62.0
Initial maneuver:								
a = average acceleration[a]	2.25	2.30	2.37	2.41	1.40	1.43	1.47	1.50
t_1 = time (sec)[a]	3.6	4.0	4.3	4.5	3.6	4.0	4.3	4.5
d_1 = distance traveled	45	66	89	113	145	216	289	366
Occupation of left lane:								
t_2 = time (sec)[a]	9.3	10.0	10.7	11.3	9.3	10.0	10.7	11.3
d_2 = distance traveled	145	195	251	314	477	643	827	1030
Clearance length:								
d_3 = distance traveled[a]	30	55	75	90	100	180	250	300
Opposing vehicle:								
d_4 = distance traveled	97	130	168	209	318	429	552	687
Total distance, $d_1 + d_2 + d_3 + d_4$	317	446	583	726	1040	1468	1918	2383

[a] For consistent speed relation, observed values adjusted slightly.
Note: In the metric portion of the table, speed values are in km/h, acceleration rates in km/h/s, and distances are in meters. In the U.S. customary portion of the table, speed values are in mph, acceleration rates in mph/sec, and distances are in feet.

U.S. Customary

$$d_1 = 1.47 t_1 \left(v - m + \frac{a t_1}{2} \right) \tag{2}$$

where

t_1 = time of initial maneuver, s;
a = average acceleration, mph/s;
v = average speed of passing vehicle, mph; and
m = difference in speed of passed vehicle and passing vehicle, mph.

The *Green Book* policy estimates the time for the initial maneuver (t_1) as within the 3.6 to 4.5 s range, based on older field data. Similarly, based on older data, the average acceleration rate during the initial maneuver is assumed to range from 2.22 to 2.43 km/h/s (1.38 to 1.51 mph/s).

The distance traveled by the passing vehicle while occupying the left lane (d_2) is estimated in the *Green Book* from the following equation:

Metric

$$d_2 = 0.278 v t_2$$

where

t_2 = time passing vehicle occupies the left lane, s; and
v = average speed of passing vehicle, km/h

U.S. Customary

$$d_2 = 1.478 v t_2 \tag{3}$$

where

t_2 = time passing vehicle occupies the left lane, s; and
v = average speed of passing vehicle, mph

Based on older field data, the *Green Book* assumes that the time the passing vehicle occupies the left lane ranges from 9.3 to 11.3 s for speed ranges from 48 to 113 km/h (30 to 70 mph).

The clearance distance (d_3) is estimated in the *Green Book* to range from 30 to 90 m (100 to 300 ft), depending upon speed.

The distance traveled by an opposing vehicle (d_4) is estimated as two-thirds of the distance traveled by the passing vehicle in the left lane. Conservatively, the distances d_2 and d_4 should be equal, but the *Green Book* assumes that the full clearance distance is not needed because the passing vehicle could abort its pass and return to the right lane if an opposing vehicle should appear early in the passing maneuver.

The *Green Book* design values for PSD, shown in Table 2, range from 220 to 820 m (710 to 2,680 ft) for design speeds from 20 to 80 mph. The *Green Book* PSD criteria are measured with both a driver eye height and object height of 1,080 mm (3.50 ft). The *Green Book* criteria are used in highway design to determine if a particular highway project has sufficient length with PSD to ensure an adequate level of service on the completed highway. The acceptable level of service for a particular project is considered to be a design decision and, therefore, is not specified in the *Green Book*. The *Green Book* criteria for PSD are not used in the marking of passing and no-passing zones.

MUTCD Marking Criteria

The criteria for marking passing and no-passing zones on two-lane highways are set by the MUTCD (*2*). Passing zones are not marked directly. Rather, the warrants for no-passing zones are established by the MUTCD, and passing zones merely happen where no-passing zones are not warranted. Table 3 presents the MUTCD PSD warrants for no-passing zones. These criteria are based on prevailing off-peak 85th-percentile speeds rather than design speeds.

Table 2. Passing sight distances for design of two-lane highways.

Metric					US Customary				
Design speed (km/h)	Assumed speeds (km/h)		Passing sight distance (m)		Design speed (mph)	Assumed speeds (mph)		Passing sight distance (ft)	
	Passed vehicle	Passing vehicle	Calculated	Rounded for design		Passed vehicle	Passing vehicle	Calculated	Rounded for design
30	29	44	200	200	20	18	28	706	710
40	36	51	266	270	25	22	32	897	900
50	44	59	341	345	30	26	36	1088	1090
60	51	66	407	410	35	30	40	1279	1280
70	59	74	482	485	40	34	44	1470	1470
80	65	80	538	540	45	37	47	1625	1625
90	73	88	613	615	50	41	51	1832	1835
100	79	94	670	670	55	44	54	1984	1985
110	85	100	727	730	60	47	57	2133	2135
120	90	105	774	775	65	50	60	2281	2285
130	94	109	812	815	70	54	64	2479	2480
					75	56	66	2578	2580
					80	58	68	2677	2680

Source: AASHTO *Green Book (1).*

The MUTCD PSD criteria are substantially less than the *Green Book* PSD design criteria. For example, at a speed of 97 km/h (60 mph), the AASHTO and MUTCD PSD criteria are 651 and 305 m (2,135 ft and 1,000 ft), respectively. The MUTCD criteria are measured based on driver eye height and object height equal to 1,070 mm (3.50 ft); the metric value is slightly less than the *Green Book* value, but is less by so little that the corresponding U.S. customary values are identical.

The rationale for the MUTCD PSD criteria is not stated in the MUTCD. However, the MUTCD warrants are identical to those presented in the 1940 AASHO policy on marking no-passing zones *(6)* and were first incorporated in the MUTCD in 1948. These earlier AASHO warrants represent a subjective compromise between distances computed for flying passes and distances computed for delayed passes. As such, they do not represent any particular passing situation. Table 4 presents the basic assumptions and data used to derive the MUTCD PSD warrants.

Another consideration in the marking of passing and no-passing zones on two-lane highways is the minimum length of a passing zone. The *Green Book* does not address passing zone lengths at all. The MUTCD indirectly sets a minimum passing zone length of 120 m (400 ft) by providing guidance that, where the distance between successive no-passing zones is less than 120 m (400 ft), no-passing zone markings should connect the zones. This minimum passing zone length was first incorporated in the MUTCD in 1961.

Comparison of Current Design and Marking Criteria

As discussed above, there is a substantial difference between the current PSD criteria used for design and marking. Figure 3 compares the PSD values resulting from the *Green Book* and MUTCD models. A key issue to be addressed in the research is whether the PSD models presented above are the appro-

Table 3. Minimum passing sight distance for marking passing and no-passing zones on two-lane highways.

Metric		U.S. Customary	
85th percentile speed or posted or statutory speed limit (km/h)	Minimum passing sight distance (m)	85th percentile speed or posted or statutory speed limit (mph)	Minimum passing sight distance (ft)
40	140	25	450
50	160	30	500
60	180	35	550
70	210	40	600
80	245	45	700
90	280	50	800
100	320	55	900
110	355	60	1,000
120	395	65	1,100
		70	1,200

Source: Manual on Uniform Traffic Control Devices (*2*).

Table 4. Derivation of MUTCD passing sight distance warrants (based on 1940 AASHO policy) (*6*).

	Speed of passing vehicle (mph)				
	30	40	50	60	70
Assumed speed differential between passing and passed vehicles (mph)	10	12	15	20	25
Assumed speed of opposing vehicle (mph)	25	32	40	46	55
Required sight distance for flying pass (ft)	440	550	660	660	660
Required sight distance for delayed pass (ft)	510	760	1,090	1,380	1,780
Recommended minimum sight distance (ft)	500	600	800	1,000	1,200

priate models and whether the use of separate PSD criteria for design and marking is justified based on different needs in design and operational applications.

Key considerations in the evaluation of the current criteria include:

- Both the *Green Book* and MUTCD PSD criteria are based largely on field data that are more than 50 years old. These field studies considered only passenger cars and did not consider trucks.
- Both the *Green Book* and MUTCD PSD criteria are based on PSD models that have questionable premises (for example, assumptions concerning the maneuver types and speeds involved in passing) which are discussed in Chapter 4.
- Neither the *Green Book* nor the MUTCD models contain a vehicle length term that would allow consideration of different vehicles types (for example, passenger cars and trucks) as the passing and passed vehicles.
- At high speeds, the *Green Book* PSD criteria are based on assumed vehicle speeds for the passing vehicle that are less than the design speed. In fact, it seems that many passing drivers would be likely to exceed the roadway design speed.
- The *Green Book* PSD model assumes that, very early in the passing maneuver, the driver is committed to pass. Observation of two-lane highways shows that passing drivers frequently abort passing maneuvers.
- The MUTCD PSD criteria are based on a compromise between delayed and flying passes and, therefore, do not represent any particular passing situation. A delayed pass is a maneuver in which the passing vehicle slows to the speed of the passed vehicle before initiating the passing maneuver. A flying pass is a maneuver in which the passing vehicle comes up behind the passed vehicle at a higher speed than the passed vehicle and initiates the passing maneuver without slowing down to the speed of the passed vehicle.

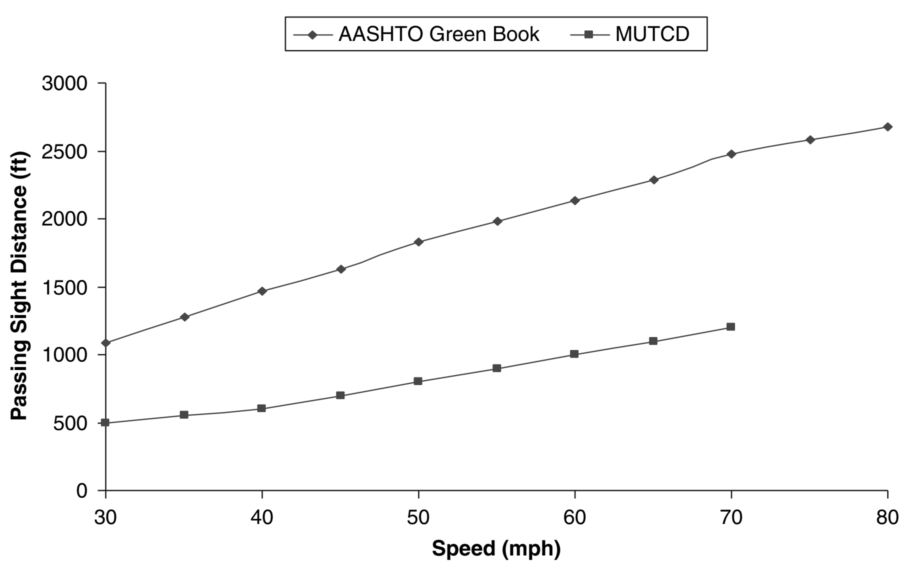

Figure 3. Comparison of PSD values for Green Book and MUTCD models.

The design values for the individual component distances in the *Green Book* criteria are subject to question because, at high-speeds, they are based on vehicle speeds less than the design speed of the highway. On the other hand, the definition of passing sight distance as the sum of the four distance elements (d_1 through d_4) is extremely conservative, since it assumes that very early in the passing maneuver, the passing driver is committed to complete the pass. In fact, field data from St. John and Kobett (*29*) and from the current study shows that passing drivers do abort passing maneuvers when the traffic situation dictates.

While the MUTCD PSD criteria are not based on an explicit assumption about the passing situation represented, Chapter 3 shows that the MUTCD PSD values are approximately equal to computed PSD values for a delayed pass by a driver that is not committed to pass until pulling about even with the passed vehicle (such as, a driver that has the option to abort the pass). It is not much of an oversimplification to say that the *Green Book* PSD criteria are appropriate for a passing driver who will never abort a passing maneuver in progress (except very early in the maneuver), while the MUTCD criteria are appropriate for a passing driver who will abort the pass, if necessary, until the point is reached at which the driver requires less PSD to complete the pass than to abort it. Clearly, the *Green Book* design criteria are more conservative and provide passing zones with longer sight distances on the completed highway. What is not known is whether these more conservative PSD design criteria provide a substantive improvement in safety on the highway.

The MUTCD minimum passing zone length of 120 m (400 ft) is clearly inadequate for high-speed passes. A 1970 study evaluated several very short passing zones (*7*). In two passing zones with lengths of 120 and 200 m (400 and 640 ft), it was found that very few passing opportunities were accepted in such short zones and, of those that were accepted, more than 70 percent resulted in a slightly forced or very forced return to the right lane in the face of opposing traffic.

Driver awareness of and acceptance of existing PSD criteria is not well understood. Drivers may have a sense of the MUTCD marking criteria from their driving experience, but it is unlikely that they are aware that different PSD criteria are used in the design process.

Given the inconsistencies of the *Green Book* and MUTCD models described above, it seems likely that either a new model, or a variation of an existing model incorporating more consistent assumptions, is needed. A total of 12 studies published since 1970 have questioned the premises of the *Green Book* and MUTCD models and/or suggested revisions to those models (*8–19*). In the early 1970s, two studies independently recognized that a key stage of a passing maneuver occurs at the point where the passing driver can no longer safely abort the pass and is, therefore, committed to complete it. One study called this the *point of no return* and another called it the *critical position* (*8, 9*). A 1976 paper added the insight that the critical position is the point at which the sight distances required to abort the pass and to complete the pass are equal (*10*). Until the critical position is reached, the passing vehicle can abort the pass and return to the right lane behind the passed vehicle. Beyond the critical position, the driver is committed to complete the pass, because the sight distance required to abort the pass is greater than the sight distance required to complete the pass. The critical position concept also has been incorporated in research on passing sight distance requirements published in 1982, 1984, 1998, 1990, and 1996 (*11, 12, 14, 16, 18*). A key goal of the research is to evaluate all of the alternative models that have been proposed and to recommend whether any are appropriate as a replacement for the *Green Book* or MUTCD models. These models are reviewed in Chapter 3.

International PSD Criteria

This review of international PSD criteria is based on a paper by Harwood et al. (*20*) prepared in 1995. This paper in turn draws upon an earlier review by Proudlove (*21*). The international PSD criteria from the 1995 paper are presented here for comparison to U.S. practice, but have not been updated for potential changes since 1995.

PSD values in this review of international practices are based on the distances shown in Figure 4. The figure shows the position of the passing, passed, and oncoming vehicles at various points in time. At Point A, the passing vehicle (Vehicle 1) starts from a position trailing the passed vehicle (Vehicle 2), as it would in making a delayed pass. The passing vehicle accelerates and, at Point B, begins to enter the opposing lane of traffic. At Point C, the passing vehicle reaches the *critical position* or *point of no return* at which the sight distance required to abort the pass is equal to the sight distance required to complete the pass. Beyond Point C, the driver of the passing vehicle is committed to complete the pass, because more sight distance would be required to abort the pass than to complete it. At Point D, the passing vehicle completes the passing maneuver and returns to its normal traffic lane.

It is assumed that the most critical opposing vehicle (Vehicle 3) that would still result in acceptable operations would move from Point H to Point G in time that the passing vehicle moves from Point A to Point B; then, the opposing vehicle would move from Point G to Point F in the time the passing vehicle moves from Point B to Point C, and the opposing vehicle moves from Point F to Point E in the time the passing vehicle moves from Point C to Point D.

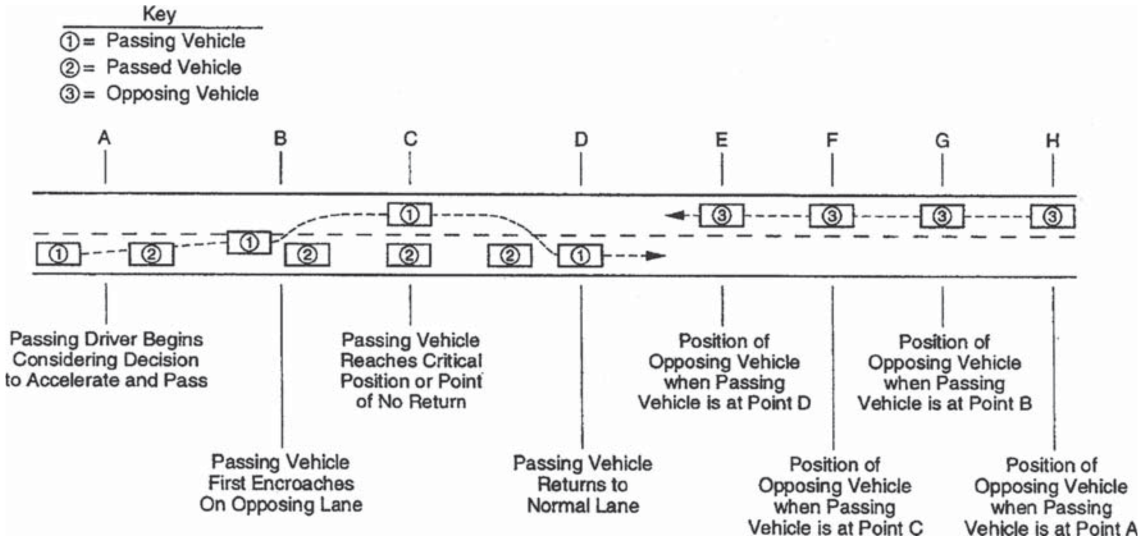

Figure 4. Components of the passing maneuver used in passing sight distance criteria in various countries (20).

This results in a clearance margin equal to the distance from Point D to Point E at the end of the passing maneuver.

The PSD criteria used in geometric design in different countries are based on varying assumptions about which of the distances shown in Figure 4 should be included in PSD and on varying assumptions about the speeds, accelerations, decelerations, and clearance margins that will be used by the passing, passed, and oncoming vehicles. The rationale for why particular countries selected particular PSD models is explained below to the extent that the rational is known.

Table 5 presents the PSD criteria used in geometric design in comparison to the criteria used in Canada, Britain, Australia, Austria, Germany, Greece, and South Africa as explained below. The models are compared in Figure 5.

Canada

The criteria for passing sight distance used in Canada are essentially the same as the AASHTO criteria used in the U.S. (*1*). However, they differ slightly, as shown in Table 5, because they were converted into metric units at different times and in slightly different ways.

Britain

In Britain two PSD values are used in geometric design. The Full Overtaking Sight Distance (FOSD) is used to determine the point where adequate PSD begins, and the Abort Sight Distance (ASD) is used to determine where adequate PSD ends. The FOSD used in Britain is based on an estimate of distance BG in Figure 4, which represents the full distance traveled by the passing vehicle in the opposing lane, a clearance margin, and the full distance traveled by the opposing vehicle while the passing vehicle occupies the opposing lane. Thus, the British criteria assume in geometric design that a region of adequate PSD begins only at a location where the passing driver can see, when entering the opposing lane, any oncoming vehicle that could potentially conflict with the passing vehicle. In contrast, the British criteria assume that a region of adequate PSD extends past the point where FOSD is lost, and continues throughout any downstream region in which ASD is available. ASD is assumed to be half of FOSD. No justification for this assumption is stated, but it is in good agreement with the corresponding assumption that the Australian equivalent of ASD is equal to an estimate of distance CF in Figure 4.

In Britain, the design speed is defined as the 85th percentile speed of traffic on the completed facility. The British criteria make explicit assumptions about the driver and vehicle population involved in passing maneuvers. PSD criteria are presented that are considered adequate for passing maneuvers by 50, 85, and 99 percent of the vehicle and driver population. Most PSD design is based on the 85th percentile vehicle and driver population, which was used to derive the PSD design values shown in Table 5.

Australia

The Australian PSD criteria used in geometric design are conceptually similar to those used in Britain, except that distance AB is included as part of the PSD needed to begin a region of adequate sight distance for passing and an explicit distance is specified for the PSD required to continue a passing zone.

Table 5. Passing sight distance criteria used in geometric design in several countries (20).

Country	Design situation	Based on distance shown in Figure 5	Design or operating speed (km/h)											
			30	40	50	60	70	80	85	90	100	110	120	130
			Passing sight distance (m)											
Australia	ESD—beginning of PSD	AH	–	–	330	420	520	640	–	770	920	1100	1300	1500
	CSD—end of PSD	CF	–	–	165	205	245	300	–	360	430	500	600	700
Austria	beginning and end of PSD	BG	–	–	–	400	–	525	–	–	650	–	–	–
Britain	FOSD—beginning of PSD	BG	–	–	290	345	410	–	490	–	580	–	–	–
	ASD—end of PSD	1/2 BG	–	–	145	170	205	–	245	–	290	–	–	–
Canada	beginning and end of PSD	AF	–	–	340	420	480	560	–	620	680	740	800	–
Germany	beginning and end of PSD	BG	–	–	–	475	500	525	–	575	625	–	–	–
Greece	beginning and end of PSD	BG	–	–	–	475	500	525	–	575	625	–	–	–
South Africa	beginning and end of PSD	AF	–	–	340	420	490	560	–	620	680	740	800	–
United States	beginning and end of PSD	AF	217	285	345	407	482	541	–	605	670	728	792	–

Note: Australian CSD and British FOSD and ASD values (see text for explanation) represent the 85th percentile of the driver and vehicle population. Among the countries reviewed, only Britain uses 85 km/h as a standard design speed.

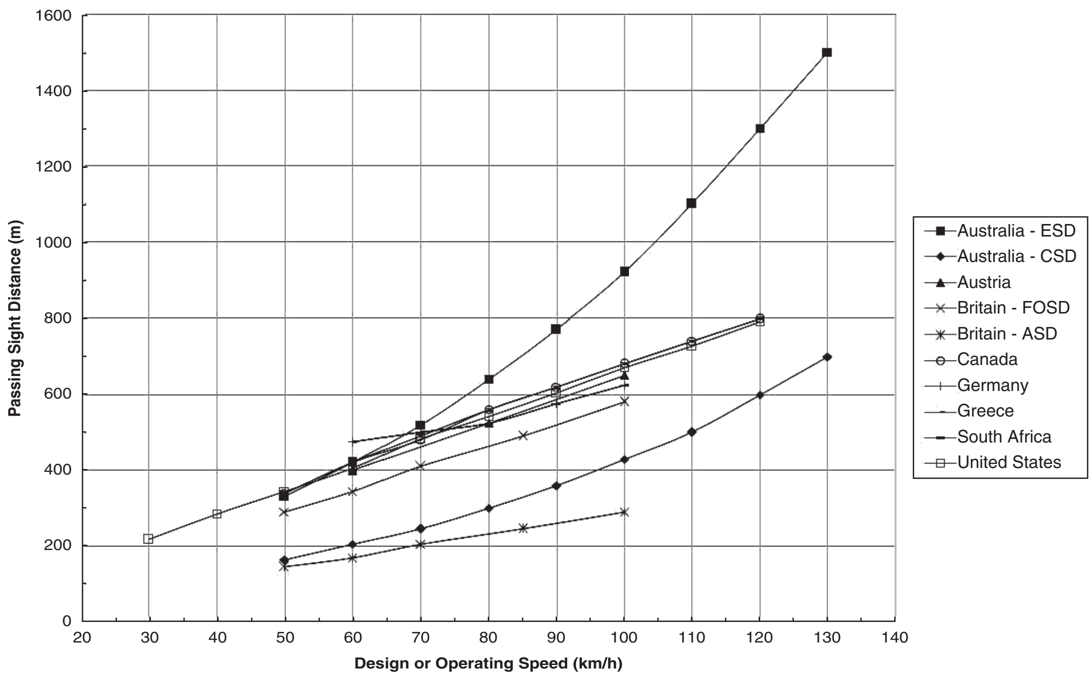

Figure 5. Passing sight distance criteria used in geometric design in several countries (20).

The Australian equivalent of the British FOSD is called the Establishment Sight Distance (ESD). This distance is an estimate of distance AH in Figure 4. Adequate sight distance to continue a passing maneuver is based on the Continuation Sight Distance (CSD), which is an estimate of Distance CF in Figure 4. The Australian terminology makes this concept of using two different PSD values very clear: the ESD represents the sight distance required for the passing driver's decision to *start* a passing maneuver; the CSD represents the sight distance necessary for the passing driver's decision to *continue* or *abort* the passing maneuver. Thus, the ESD values are used to define the beginning of a region of acceptable passing sight distance, and the CSD values are used to define the end of a region of acceptable passing sight distance.

Table 5 presents the ESD and CSD values used in geometric design in Australia.

Austria, Germany, and Greece

Austria, Germany, and Greece use a PSD concept similar to that used in the other countries discussed above. The PSD criteria used in Germany and Greece are based on the prevailing 85th percentile speed of traffic, while those used in Austria are based on the project speed. During the passing maneuver, the passing vehicle is assumed to travel at 110 percent of the 85th percentile speed, the passed vehicle is assumed to travel at 85 percent of the 85th percentile speed, and the oncoming vehicle is assumed to travel at the 85th percentile speed of traffic. The design values for passing sight distance used in Austria, Germany, and Greece are presented in Table 5.

South Africa

Geometric design values for minimum PSD used in South Africa are presented in Table 5 and Figure 5. These minimum PSD values are essentially the same as those currently used in the U.S. and Canada.

Marking Criteria for Passing and No-Passing Zones

Each country reviewed uses criteria that differ from their geometric design criteria for actually marking passing and no-passing zones on the centerlines of two-lane highways. Table 6 and Figure 6 compare the criteria for marking passing and no-passing zones in each country, as a function of 85th percentile speed. A comparison between Tables 5 and 6 shows that the marking criteria are slightly less than the geometric criteria used in Britain and Australia, and substantially less in the United States, Canada, and South Africa.

Proudlove (*21*) also points out that countries differ in the location of the beginning of a no-passing zone barrier line marking relative to the point where the minimum PSD for marking of a passing zone is lost. Two concepts generally have been employed in marking and enforcement of passing and no-passing zones. Under the short zone concept, all passing maneuvers must be completed before the point where the no-passing zone barrier line begins. The long zone concept allows drivers who

Table 6. Passing sight distance criteria used as warrants for marking no-passing zone barrier lines in selected countries.

Country	Prevailing 85th Percentile Speed (km/h)							
	50	60	70	80	85	90	100	120
	Passing sight distance (m)							
Australia	150	180	210	240	–	270	300	–
Britain	90	105	125	–	155	–	185	–
Canada	160	200	240	275	–	330	400	–
South Africa	150	180	–	250	–	–	–	400
United States	155	175	210	240	–	280	315	–

Note: Australian and British values represent the 85th percentile of the driver and vehicle population. Among the countries reviewed, only Britain uses 85 km/h as a standard design speed.

begin a passing maneuver in a marked passing zone to complete that passing maneuver beyond the beginning of the barrier line marking. Australia, Britain, Canada, and the United States all generally use the short zone concept in laws concerning passing maneuvers on two-lane highways. However, Proudlove (*21*) notes that Britain, Canada, and the United States all mark passing and no-passing zones on their highways as if the long zone concept were in effect; that is, the marked no-passing zone barrier line begins at the point where the required PSD shown in Table 6 is lost. In contrast, Australia extends the marked passing zone a distance equal to half the CSD beyond the point where the no-passing zone warrant is first met. This practice recognizes that substantial sight distance is still available at the point where the no-passing zone warrant is first met. Moreover, since the Australian CSD is a geometric design concept rather than a marking concept, its use in determining the end of a passing zone makes the resulting passing zones marked on the highway more like those that would result if the geometric design criteria were applied directly.

Austria, Germany, Greece, and Switzerland use a concept known as opposing sight distance as the basis of marking criteria for passing zones. The opposing sight distance is equal to the sum of the stopping sight distances of two opposing vehicles, or twice the SSD design values. Where opposing sight distance cannot be provided, for economic or environmental reasons, a no-passing zone barrier line is marked.

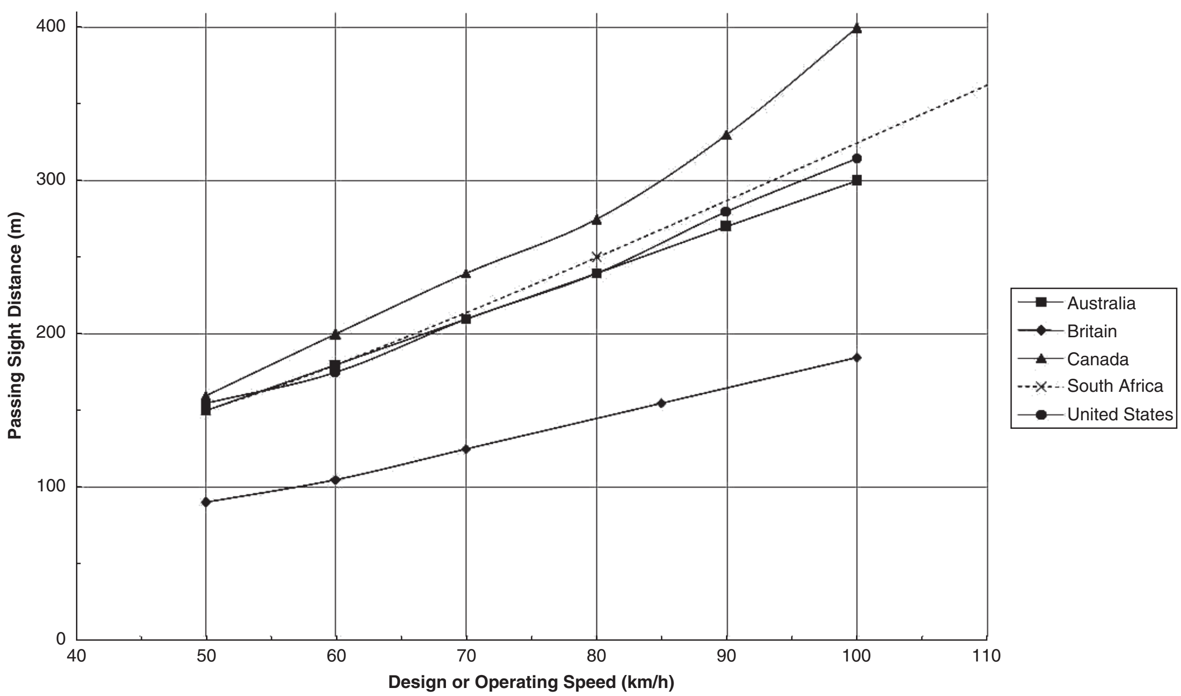

Figure 6. Passing sight distance criteria used as warrants for marking no-passing zone barrier lines in selected countries (20).

Table 7. Australian criteria for minimum lengths and spacings between no-passing zone barrier lines (*20*).

	Prevailing 85th Percentile Speed (km/h)					
	50	60	70	80	90	100
Maximum length (m) (see Note 1)	75	90	105	120	135	150
Minimum spacing (m) (see Note 2)	125	150	175	200	225	250

Note 1: Minimum length of barrier line. If this length is *not* reached, no barrier line is marked.

Note 2: Minimum distance between adjacent barrier lines. If this distance is not achieved, then the barrier line is made continuous. The comparable U.S. value is 120 m [400 ft], independent of speed.

Table 8. Comparison of criteria for driver eye height and object height used in measuring passing sight distance (*20*).

Country	Driver eye height		Object height	
	(ft)	(m)	(ft)	(m)
Australia	3.8	1.15	3.8	1.15
Austria	3.3	1.00	3.3	1.00
Britain	3.4	1.05	–	–
Canada	3.4	1.05	–	–
Germany	3.3	1.00	3.3	1.00
Greece	3.3	1.00	3.3	1.00
South Africa	3.4	1.05	4.25	1.30
United States	3.5	1.08	3.5	1.08

Note: All values in the table are based on passenger cars; none of the countries reviewed are known to consider trucks in their PSD criteria.

As in other countries, the South African PSD values used for marking no-passing barrier lines, as shown in Table 6, are generally less than half of the PSD values used in geometric design, as shown in Table 5. The barrier line PSD values also are used in South Africa.

Table 7 illustrates the criteria used in Australia for the minimum length of no-passing zone barrier line and the minimum spacing between adjacent barrier lines, as a function of prevailing 85th percentile speed. The United States has no policy comparable to the Australian policy for minimum length of barrier line. The United States requires a minimum spacing of 120 m (400 ft) between adjacent barrier line segments, independent of speed. Where this distance is not achieved, the barrier line is made continuous.

Passing Sight Distance Measurement Criteria

Table 8 summarizes the values of driver eye height and object height that are assumed in the geometric design and marking of two-lane highways.

CHAPTER 3

Review Of Alternative Passing Sight Distance Models

This chapter reviews a variety of alternative PSD models formulated and published in the literature from 1971 to 1998. The review follows a debate that has been ongoing for nearly 30 years to identify and refine the most appropriate PSD models. Various authors have proposed new ideas and critiqued one another's work, leading to refinements of PSD modeling concepts. The review of each PSD model includes a summary of the conceptual approach on which the model is based, and presentation of the specific analytical models used to determine PSD, the assumed values of model parameters, the PSD values obtained from the model, and a critique of the model by the research team. The critique of the model focuses on the reasonableness of the model assumptions and its similarities to and differences from other models, including the *Green Book* and MUTCD models reviewed in Chapter 2.

A graph illustrating the PSD values obtained from each model is presented with the models and graphs comparing the PSD values obtained from all of the models presented in the latter part of the chapter.

Each model is presented with symbols and notation uniquely defined in this report and may differ from the symbols and notation used by the original author or developer of the model. If the same symbol is used in presenting two different models, then that symbol represents the identical variable in both models. If different symbols are used to represent similar variables, this is an indication that there are, in fact, differences between those variables. For example, d_1 through d_4 always refer to distances defined identically to those in the *Green Book* PSD criteria. Distances that are defined differently than in the *Green Book* criteria are represented by different symbols (for example, d_5, d_6, or d_7). Time variables with the same numerical subscript as a distance variable refer to the time required for a vehicle to travel the corresponding distance (such as, t_1 represents the time required to travel distance d_1). All variables and models have been converted to use U.S. customary units, even for models presented in metric units by their original authors. The final section of this chapter summarizes all of the nomenclature used in PSD models in this report.

The review of each PSD model is presented, followed by a comparison of all of the PSD models.

Van Valkenburg and Michael (1971)

Conceptual Approach

Van Valkenburg and Michael (*8*) computed PSD as the sum of three distances. They did not develop explicit mathematical models for these distances but rather quantified them based on field data. The formulation of the PSD model as the sum of three distances was based on the concept of a *point of no return* in the passing maneuver; this point also has been referred to by others as the *critical point* or *critical position.* The authors did not include in their model the distance required for the passing vehicle to accelerate and reach the point of no return because during this phase of the passing maneuver, the passing vehicle can abort and return to its own lane with no consequences.

The Van Valkenburg and Michael model was intended for use in marking passing and no-passing zones. It was anticipated that the PSD values determined with the model are intended to be available throughout each passing zone. The authors recognized that their model implicitly implements the long-zone concept for passing zones in which passing maneuvers begun in a passing zone can be safely completed in a no-passing zone, and they recommended that the long-zone concept be used in enforcement of no-passing zone barrier stripes.

Analytical Models

The model developed for minimum required PSD was based on the sum of three distances.

$$PSD = d_6 + d_7 + d_3 \quad (4)$$

where

PSD = passing sight distance (ft);

d_6 = distance traveled by the passing vehicle from the critical position until it returns to its own lane (ft);

d_7 = distance traveled by the opposing vehicle from the time the passing vehicle reaches the critical position until it returns to its own lane (ft); and

d_3 = minimum clearance distance between the passing and opposing vehicle at the end of the passing maneuver to avoid a collision (ft).

Assumed Values of Model Parameters

The authors defined the point of no return as the location where the rear bumper of the passed vehicle is abreast of the middle of the passing vehicle. It was assumed that if the passing vehicle were at or beyond this point, the driver will generally determine that it is safer to complete rather than abort the passing movement. Speed assumptions are taken since the opposing vehicle will be traveling at the design speed and the impeding vehicle will be traveling at a constant speed, so the speed differential between the impeding and passing vehicles is a constant 16 km/h (10 mph) and the minimum clearance between the passing and opposing vehicles is 6 m (20 ft). For this model, the passing vehicle will be making a delayed pass where the passing vehicle will be required to accelerate to a constant speed in order to pass after beginning at a speed equivalent to that of the impeding vehicle.

The distances d_6 and d_7 were set based on field data and were never developed as a function of parameters into model form. Passing distances and speeds were determined in the field for four types of passing maneuvers:

- Accelerative voluntary return;
- Flying voluntary return;
- Accelerative forced return; and
- Flying forced return.

Table 9. PSD values determined with the Van Valkenburg and Michael model (*8*).

Average off-peak speed (mph)	Minimum passing sight distance (ft)
30	750
35	900
40	1,050
45	1,200
50	1,300
55	1,450
60	1,600
65	1,750
70	1,900

The passing distances and speeds measured in the field for these four types of passing maneuvers are presented in Chapter 4.

Passing Sight Distance Values

The PSD values recommended by Van Valkenburg and Michael are presented in Table 9 and the PSD values plotted as a function of average speed are shown in Figure 7.

Critique

The Van Valkenburg and Michael work is the first published recognition of the critical position in the passing maneuver, which the authors referred to as the point of no return. The authors defined the point of no return as occurring when the rear bumper of the passed vehicle is abreast of the middle of the passing vehicle, although the authors offered no proof that

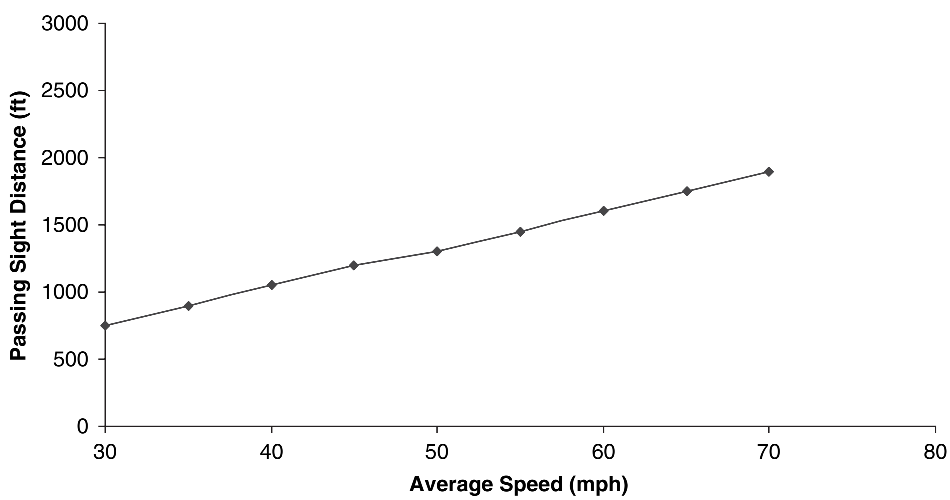

Figure 7. PSD values as a function of average speed from the Van Valkenburg and Michael model (8).

this, in fact, is the point of no return. Van Valkenburg and Michael provided very useful field data on passing distances and speeds for maneuvers of varying criticality, but did not formulate a model that can be used to derive specific PSD values. The author's recommendation of the long-zone concept for enforcement is a concern to the research team, because this would remove a key margin of safety in passing maneuvers. The importance of this margin of safety is addressed in Chapter 4. The Van Valkenburg and Michael field data appear to be useful for comparison to PSD values proposed by others. However, the author's recommended PSD values are not based on an explicit model of the critical position, but rather are based on field observations of where the authors estimated the critical position to be. For this reason, direct implementation of the authors' PSD values is not recommended.

Weaver and Glennon (1972)

Conceptual Approach

Weaver and Glennon (*9*) developed a PSD model for two-lane rural highways as an alternative to the AASHTO model which was the basis of current practice. The authors recognized a need to improve upon what they perceived as a weak relationship between design policies and operational policies (such as, striping policies). The model proposed by Weaver and Glennon differed from the AASHTO model in that it was based on the assumption that minimum PSD needed to be maintained throughout the passing zone and that PSD must be sufficient for a driver to be in the critical position at the end of the passing zone.

Analytical Models

Estimate of available PSD at the beginning of a passing zone:

$$PSD = d_1 + 2.33 d_2 + d_3 \tag{5}$$

Required PSD at the end of a passing zone

$$PSD = 4/3\ d_2 + d_3 \tag{6}$$

$$d_1 = 1.47 t_1 \left(V_p - m + \frac{a t_1}{2} \right) \tag{7}$$

$$d_2 = 1.47 V_p t_2 \tag{8}$$

where

d_1 = distance traveled by the passing vehicle during perception and reaction time and during initial acceleration to the point of encroachment on the left lane (ft);
d_2 = distance traveled by the passing vehicle while it occupies the left lane (ft);
d_3 = distance between passing vehicle and opposing vehicle at the end of the passing maneuver (i.e., clearance distance) (ft);
t_1 = time required for initial maneuver (sec);
V_p = average speed of passing vehicle (mph);
m = speed difference between passed and passing vehicle (mph);
a = acceleration rate of the passing vehicle to increase its speed from V_i to $V_i + m$ (ft/sec^2); and
t_2 = time passing vehicle occupies the opposing lane (sec).

Assumed Values of Model Parameters

As in the AASHTO model, Weaver and Glennon assumed that the passing is accomplished under a delayed start and a hurried return in the face of opposing traffic. The critical position was taken as the point at which the passing vehicle is abreast of the impeding vehicle and the required times to complete or abort the passing maneuver are equal.

Design speed, passing vehicle speed, and opposing vehicle speed are assumed to be equal. The authors recommended the speed differential between the passing and passed vehicles should vary from 13 to 19 km/h (8 to 12 mph) as a function of passed vehicle speed rather than being a constant value of 16 km/h (10 mph). The speed differential was assumed to decrease as the speed of the passed vehicle increased.

Passing Sight Distance Values

The PSD values determined with the model shown in Equation (5) are presented in Table 10 and the PSD values plotted as a function of design speed are shown in Figure 8.

Critique

Weaver and Glennon independently recognized the importance of the critical position in the passing maneuver in work published the next year after Van Valkenburg and Michael. Weaver and Glennon state that the critical position in a passing maneuver occurs at the point where the time required to complete the maneuver is equal to the time required to abort

Table 10. PSD values determined with the Weaver and Glennon model (*9*).

Design speed (mph)	Minimum sight distance throughout zone (ft)
50	1,135
60	1,480
65	1,655
70	1,825
75	2,000
80	2,170

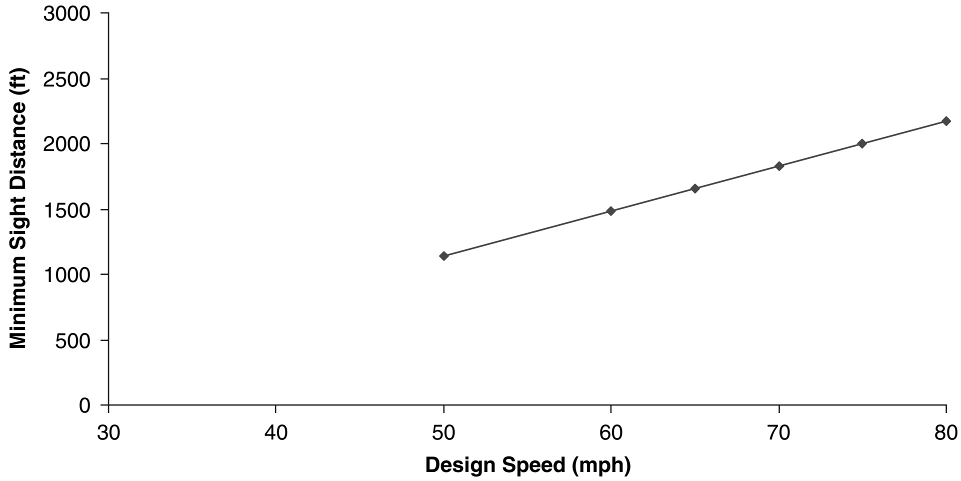

Figure 8. PSD values as a function of design speed from the Weaver and Glennon model (9).

the maneuver. Later authors recognized that the critical position is more logically based on equal sight distances than on equal times. Weaver and Glennon did not state explicitly where the critical position occurs in the passing maneuver except to state that it occurs when the passing and passed vehicles are approximately abreast. The authors recognized that their model could be used to implement the long-zone concept, but they recommended retaining the short-zone concept for enforcement purposes to provide a margin of safety at the end of the passing maneuver.

In addition to providing a model for required PSD at the end of (and throughout) a passing zone, Weaver and Glennon recognized that rolling terrain is such that the greater-than-minimum PSD is often available at the beginning of a passing zone. This PSD at the beginning of a passing zone is approximated by Equation (5). This insight that more sight distance is generally available at the beginning of a passing zone than at the end is an early recognition of the concept used in geometric design in Britain and Australia that requires more PSD to begin a region of adequate sight distance for passing than to end one (see Figure 5).

The Weaver and Glennon model was a definite step forward in the development of PSD concepts, but the model lacks the recognition that the critical position should be defined in terms of sight distance (rather than time) and the model does not explicitly implement the balance between pass completion and pass abort maneuvers. Therefore, the Weaver and Glennon model is not recommended for implementation.

Harwood and Glennon (1976)

Conceptual Approach

Harwood and Glennon (*10*) recommended a model for PSD that was essentially the same as the Weaver and Glennon model (*9*) in Equation (6), since d_4 is defined as equal to $\frac{2}{3}\,d_2$. The Harwood and Glennon model is, therefore, also based on the assumption that the driver of the passing vehicle can abort the passing maneuver at any time until the critical position is reached.

Analytical Models

$$PSD = 2/3\, d_2 + d_3 + d_4 \tag{9}$$

where d_4 is the distance traveled by an opposing vehicle for two-thirds of the time the passing vehicle occupies the left lane (or $\frac{2}{3}$ of d_2) (ft).

Assumed Values of Model Parameters

With the exception of assuming the distance traveled by the passing vehicle to reach the critical position as $\frac{1}{3}\,d_2$, the authors adopted most all the same assumptions put forth in the 1965 AASHO policy, namely:

- The passed vehicle travels at a uniform speed.
- The passing vehicle reduces speed and trails the impeding vehicle as it enters a passing section.
- When the passing section is reached, the passing driver requires a short period of time to perceive the clear passing section and react to start their maneuver.
- Passing is accomplished under what may be termed a delayed start and a hurried return in the face of opposing traffic. The passing vehicle accelerates during the occupancy of the left lane to a constant speed that is 10 mph higher than that of the impeding vehicle.
- When the passing vehicle returns to its lane, there is a suitable clearance length between it and an opposing vehicle in the other lane.

The distance values that comprise the required passing sight distance also are taken from 1965 AASHO policy.

Passing Sight Distance Values

The PSD values determined with the model shown in Equation (9) are presented in Table 11 and the PSD values plotted as a function of design speed are shown in Figure 9.

Critique

Harwood and Glennon provided a new insight that the critical position in the passing maneuver occurs at the point where the sight distance needed to abort or complete the pass is equal, in contrast to Weaver and Glennon, who indicated that the critical position occurs where the time needed to abort or complete the pass is equal. The insight that the critical position should be based on a balance between the sight distances to complete and abort the passing maneuver has been accepted in subsequent work by Lieberman (*11*), Saito (*12*), Glennon (*14*), Harwood and Glennon (*15*), Rilett et al. (*16*), Forbes (*17*), Hassan et al. (*18*), and Good et al. (*25*). However, while Harwood and Glennon recognized that the critical position should be based on a balance of sight distances, they did not formally incorporate that balance in the PSD model shown in Equation (9). Thus, the Harwood and Glennon work performed in 1976 represents a step forward conceptually, but their model is not suitable for implementation.

Lieberman (1982)

Conceptual Approach

Lieberman (*11*) developed a model that incorporated parameters related to vehicle size and performance capabilities that played a part in determining the required PSD. This results in more complex models than the previous studies.

Table 11. PSD values determined with the Harwood and Glennon model (*10*).

Design speed (mph)	Passing sight distance (ft)
30	628
35	769
40	918
45	1,074
50	1,238
55	1,408
60	1,586
65	1,772
70	1,964
75	2,164
80	2,371

As in the Van Valkenburg and Michael (*8*), Weaver and Glennon (*9*), and Harwood and Glennon (*10*) models, Lieberman assumes that sight distance should be based on a critical position. Lieberman states that the critical position occurs at the point where the clearance to an opposing vehicle in aborting or completing the pass is equal. This is essentially equivalent to Harwood and Glennon's assertion that the critical position occurs where the sight distance needed to abort or complete the passing maneuver is equal. However, Lieberman also asserts that the PSD should include the distance required for the passing vehicle to reach the critical position as well as the sight distance required to complete the pass from the critical position.

Analytical Models

$$PSD = d_5 + PSD_c \tag{10}$$

$$d_5 = G_1^N + 1.47V_i t_5 + \Delta_c \tag{11}$$

$$PSD_c = 1.47(2V_i + m)t_6 + d_3 \tag{12}$$

$$t_6 = 0.68[(G_1 + \Delta_c)/m] + (1.47\,m/2a) \tag{13}$$

$$\Delta_c = G_1 - 1.47\,m\,t_6 \tag{14}$$

$$a = a_{max}\left[1 - \frac{\left(V_i + \frac{m}{2}\right)}{V_{max}}\right] \tag{15}$$

where

d_5 = distance traveled by passing vehicle from the start of the passing maneuver to the critical position (ft);
PSD_c = sight distance required to complete or abort the passing maneuver when the passing vehicle is at the critical position (ft);
G_1^N = space headway between passed and passing vehicles at the start of the passing maneuver (ft);
G_1 = space headway between passing and passed vehicles at the instant the passing vehicle returns to the normal lane (ft);
V_i = speed of passed vehicle (mph);
t_5 = travel time from the start of the passing maneuver to the attainment of the critical position (sec);
t_6 = time required for the passing vehicle to return to its own lane from the critical position for a completed passing maneuver (sec);
Δ_c = relative position of the front bumpers of the passing and passed vehicles at the critical position (negative

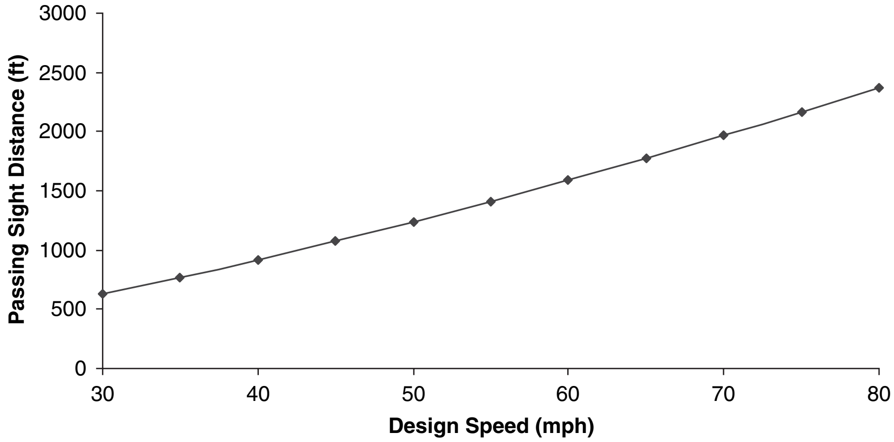

Figure 9. PSD values as a function of design speed from the Harwood and Glennon model (10).

Δ_c means that passing vehicle is behind passed vehicle; positive Δ_c means that passing vehicle is in front of passed vehicle) (ft);

a_{max} = maximum vehicle acceleration achievable at zero speed (ft/sec^2); and

V_{max} = maximum vehicle speed achieved when vehicle acceleration capability drops to zero (mph).

Assumed Values of Model Parameters

This model assumes that the passed vehicle and opposing vehicle travel at constant speeds and that the passed vehicle speed is the speed chosen as the basis for determining passing sight distance. The speed difference between the passing and the passed vehicles is assumed to be 16 km/h (10 mph) for all speeds. Aside from these values, the author does not explicitly state many of the assumptions that should be used as input into the model. This was due, in part, to the authors' intention of developing several representative PSD curves based on the specific types of passing and passed vehicles. In order to make this model comparable to other models, the research team has used passenger cars as the passing and passed vehicles. In the process of estimating PSD using Lieberman's model, the research team was required to make some assumptions based upon what was thought to be the author's intention because of a lack of information provided in the paper. For instance, Δ_c was assumed to have a linear relationship with vehicle speed, V_i, in order to determine its value for a range of speeds.

Passing Sight Distance Values

The PSD values determined with the models shown in Equations (10) through (15) are presented in Table 12 and the PSD values plotted as a function of speed are shown in Figure 10.

Critique

Because the author did not provide complete information, several values had to be assumed and/or extrapolated from tables and figures found in the report. Several of these issues are outlined in the preceding section, "Assumed Values of Model Parameters."

Lieberman (*11*) uses the critical position concept, but models the PSD requirement as the sum of the distance needed for the passing vehicle to reach the critical position and the sight distance needed to complete or abort the passing maneuver from the critical position. This sets PSD requirements well above the value needed to safely complete a passing maneuver if the passing driver exercises good judgment as to whether to abort the passing maneuver in its early stages.

A strength of the Lieberman model is that, for the first time, relative position of the passing and passed vehicles at the critical position is mathematically determined [see Equation (14)], rather than merely estimated; however, Lieberman's formulation of Δ_c does not appear to be complete.

Lieberman's long sight distances are clearly not needed at the end of a passing zone, but sight distances similar to

Table 12. PSD values determined with the Lieberman model (*11*).

Speed (mph)	Passing sight distance (ft)
30	860
35	1,084
40	1,320
45	1,568
50	1,828
55	2,099
60	2,383

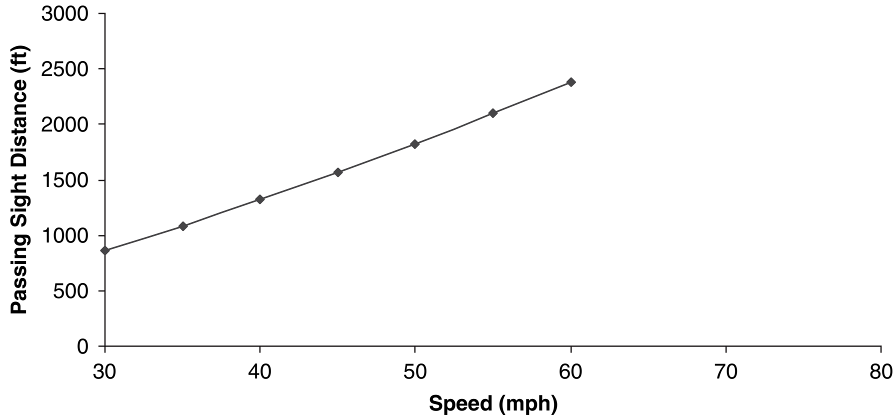

Figure 10. PSD values as a function of speed from the Lieberman model (11).

those recommended by Lieberman often are available at the beginning of passing zones and are required at the beginning of a region of adequate PSD in the geometric design criteria used in Britain and Australia.

The Lieberman model has some inconsistencies and does not appear appropriate for use in determining the PSD needed at the end of a passing zone (or throughout a passing zone), but it is an alternative that could be considered for determining the desirable PSD at the beginning of a passing zone or in the early stages of a passing maneuver.

Saito (1984)

Conceptual Approach

The stated purpose of the research by Saito (*12*) was to evaluate the adequacy of the minimum sight distance provided by the MUTCD for drivers to abort a passing maneuver. It was acknowledged by the author that numerous studies had investigated the minimum distance required to complete a passing maneuver, but that the objective of this model was to quantify what the author thought to be the often neglected issue of the minimum sight distance required to abort an attempted passing maneuver. The result of this research was two separate models that differ based on the location of the critical position because the author stated that two of these separate locations were potentially critical. Those two potentially critical positions are where the head of the passing vehicle is positioned laterally at the tail of the passed vehicle (head to tail position) or when the passing vehicle is at a position alongside the passed vehicle (abreast position).

Analytical Models

$$PSD = 2.93V_{85}t_d + d_3 - 0.73d_a t_d^2 \qquad (16)$$

Passing maneuver aborted from head and tail position:

$$t_d = \frac{2.93m + \sqrt{8.60m^2 + 11.73d_a G_2}}{2d_a} \qquad (17)$$

Passing maneuver aborted from abreast position:

$$t_d = \frac{2.93m + \sqrt{8.60m^2 + 11.73d_a G_3}}{2d_a} \qquad (18)$$

where

V_{85} = 85th percentile speed (mph);
t_d = deceleration time (sec);
d_a = deceleration rate used in aborting a passing maneuver (ft/sec²);
G_2 = space headway between the front of the passing (such as, aborting) vehicle and the rear of the passed vehicle (ft); and
G_3 = space headway between the passing and passed vehicles (ft).

Assumed Values of Model Parameters

- The passing vehicle reaches the constant passing speed by the time it approaches the critical position.
- The passing vehicle decelerates at a constant deceleration rate from the critical position until it attains the desired space headway from the impeding vehicle to return to the right lane.
- The impeding vehicle travels at a constant speed.
- The opposing vehicle maintains a constant speed throughout the maneuver that is equal to that of the passing vehicle.
- Deceleration rate was assumed to be 3.0 m/sec² (9.7 ft/sec²).
- Length of impeding vehicle is accounted for in the value of G_3.

Table 13. PSD values determined with the Saito model (*12*).

85th percentile speed (mph)	$PSD_{(head-tail)}$	$PSD_{(abreast)}$
30	410	284
35	524	372
40	646	463
45	773	559
50	905	659
55	1,043	763
60	1,186	870
65	1,334	980
70	1,486	1,093

In his paper, Saito refers to a table in which values for G_3 can be formed, but that table is not actually included in the paper. To compute PSD values with the Saito model, the research team assumed a space headway value based on an assumed time headway of 1.5 sec, thereby giving the space headway a linear relationship to the speed of the passing vehicle. This value of space headway was selected to be similar to other models. The research team also chose to use a value of 16 km/h (10 mph) for the speed difference between the passing and passed vehicles since the author referred to multiple values for this variable.

Passing Sight Distance Values

The PSD values for aborted passes determined with the models shown in Equations (16) through (18) are presented in Table 13, and the PSD values plotted as a function of speed are shown in Figure 11.

Critique

Saito documents the following aspects of PSD:

- Sight distance required to abort a passing maneuver from the head-to-tail position, and
- Sight distance required to abort a passing maneuver from the abreast position.

The Saito model appears to suggest that more sight distance is needed to abort a passing maneuver from the head-to-tail position than from the abreast position, which seems counter-intuitive. The research team cannot be certain that this is truly what Saito intended because, as noted above, the values of two parameters in Saito's model had to be assumed.

The Saito model is an interesting variation of the critical position concept, but is conceptually incomplete and does not appear to be sufficiently developed for implementation.

Ohene and Ardekani (1988)

Conceptual Approach

Ohene and Ardekani (*13*) used models and theories from several previous studies in order to develop their model. Their basic model was drawn from previous work by Herman and

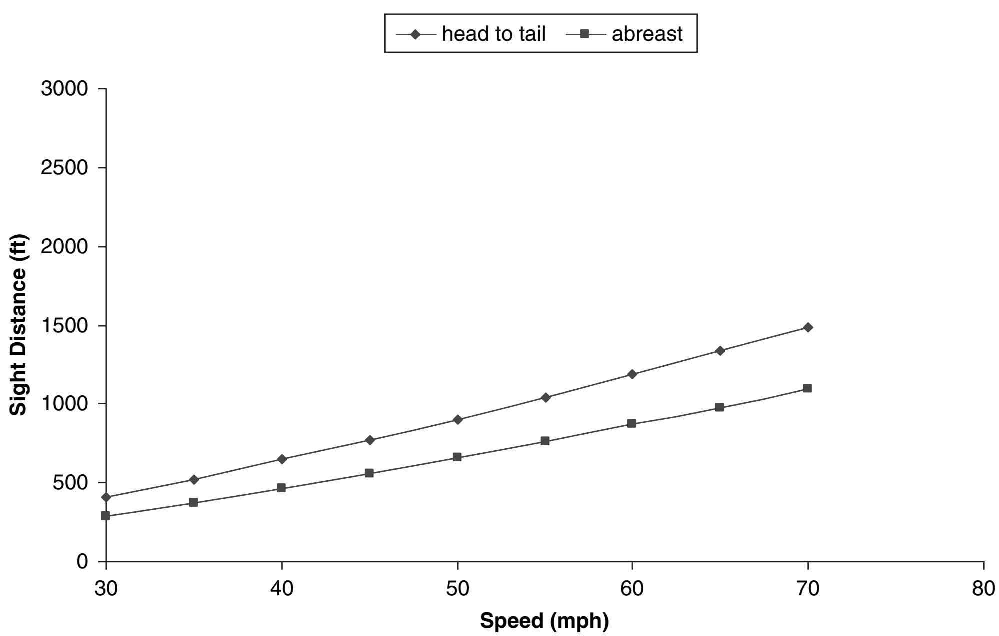

Figure 11. PSD values as a function of 85th percentile speed from the Saito model (12).

Tenny (*22*). The authors took the view that the MUTCD does not provide adequate PSD unless the passing vehicle possesses exceptional acceleration and deceleration capabilities. The authors cited field work done by others (*11, 12, 22, 23, 24*) and use parameter values they considered well accepted to make a comparison between their model and that of the MUTCD. However, there were not many details provided by the authors in describing their analysis.

Analytical Models

$$PSD = 1.47 V_{close}\left\lfloor -B + \sqrt{(B^2 - 4\alpha\gamma)}\right\rfloor / 2a \quad (19)$$

$$B = -ap_c - d_a p_a - ad_3 / 1.47 V_{close} \quad (20)$$

where

V_{close} = closing rate between the passing and opposing vehicles (mph);

α = parameter not defined by author;

γ = parameter not defined by author;

p_c = perception-reaction time to complete the passing maneuver (sec); and

p_a = perception-reaction time to abort the passing maneuver (sec).

Assumed Values of Model Parameters

- The speed of the passing and opposing vehicles is assumed to be the same.
- A speed differential between the passing vehicle and the impeding vehicle of 16 km/h (10 mph) is assumed; however, speed differentials ranging from 8 to 40 km/h (5 to 25 mph) also were considered, so that MUTCD assumptions would be covered.
- Not many details are given on other assumptions, but it appears that when the authors were in need of an assumed value they generally used an equivalent value from the AASHTO model.

Table 14. PSD values determined by Ohene and Ardekani (*13*).

Speed (mph)	Passing sight distance (ft)
30	570
40	900
50	1,300
60	1,700
70	2,050

Passing Sight Distance Values

The PSD values reported by the authors are presented in Table 14 and the PSD values plotted as a function of speed are shown in Figure 12.

Critique

There were no units given in the report for the variables in the models and two variables were not defined. Therefore, the authors of this report have not been able to reproduce Ohene and Ardekani's computations, but only have been able to present their recommended PSD values. The

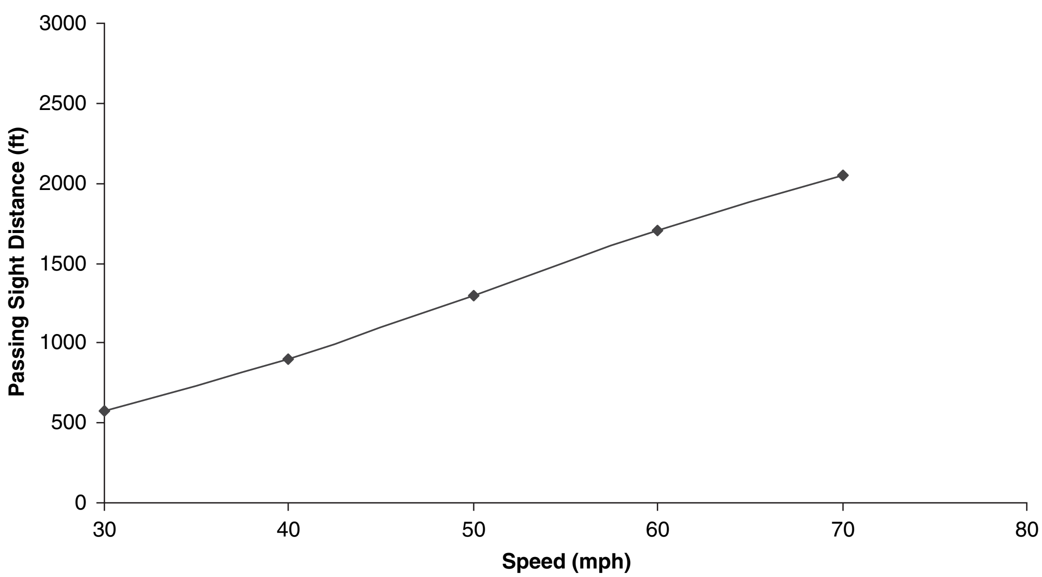

Figure 12. PSD values as a function of speed reported by Ohene and Ardekani (13).

Ohene and Ardekani model does not appear to be sufficiently developed for implementation.

Glennon (1988)

Conceptual Approach

A new PSD model by Glennon (*14*) evolved out of research to address what the author considered to be inconsistencies in previous models. Like previous models, the Glennon model is based on the concept of a critical position in the passing maneuver. Unlike previous models, the Glennon model used the correct kinematic relationships to implement the assumption that the critical position occurs at the point where the sight distances needed to complete or abort the passing maneuver are equal.

Analytical Models

$$PSD = 2V_d\left(2.93 + \frac{L_p - \Delta_c}{m}\right) \qquad (21)$$

$$\Delta_c = L_p + 1.47m\left\{\frac{(2.93m + L_i + L_p)}{1.47(2V_d - m)} - \left[\frac{5.87V_d(2.93m + L_i + L_p)}{1.47d_a(2V_d - m)}\right]^{1/2}\right\} \qquad (22)$$

where

V_d = design speed (mph);
L_p = length of passing vehicle (ft);
L_i = length of passed vehicle (ft); and
Δ_c = relative position of the front bumpers of the passing and passed vehicles at the critical position (negative Δ_c means that passing vehicle is behind passed vehicle; positive Δ_c means that passing vehicle is in front of passed vehicle) (ft).

Assumed Values of Model Parameters

Glennon made the following assumptions in implementing his model:

- The average length of a passenger car is 4.9 m (16 ft).
- A reasonable deceleration rate in the aborting maneuver is 2.4 m/sec^2 (8 ft/sec^2).
- The speed differential between the passing and passed vehicles will vary from 13 to 19 km/h (8 to 12 mph) based on the design speed, with lower speed differentials at higher speeds.
- The maximum sight distance during a passing maneuver is required at the critical position when the sight distances required to complete or abort the pass are equal.
- The speeds of the passing vehicle and opposing vehicle are equal and represent the design speed of the highway.
- The passing vehicle has sufficient acceleration capability to reach the specified speed difference relative to the passed vehicle by the time it reaches the critical position.
- The driver's perception-reaction time prior to beginning a pass is 1 sec.
- For a completed pass, the space headway between the passing and passed vehicles at the completion of the maneuver is 1 sec.
- For an aborted pass, the space headway between the passing and passed vehicles at the completion of the maneuver is 1 sec.
- The minimum clearance between the passing and opposing vehicles at the point when the passing vehicle returns to its own lane is 1 sec.

Passing Sight Distance Values

The PSD values determined with Equations (21) and (22) are presented in Table 15, and the PSD values plotted as a function of design speed are shown in Figure 13. PSD criteria for a truck as the passed vehicle are based on truck lengths of 17, 20, and 34 m (55, 65, and 110 ft).

Critique

The Glennon model appears to be the first model in published literature based analytically on the concept that the critical position is the point in the passing maneuver when the sight distances to complete or abort the passing maneuver are equal. Previous references that stated this concept used analytical models that were incorrect or approximate.

Table 15. PSD values determined with the Glennon model (*14*).

Design speed (mph)	PSD based on vehicle being passed (ft)			
	Passenger vehicle	55-ft truck	65-ft truck	110-ft truck
40	670	760	780	850
50	830	960	980	1,080
60	990	1,150	1,180	1,320
70	1,140	1,320	1,380	1,550

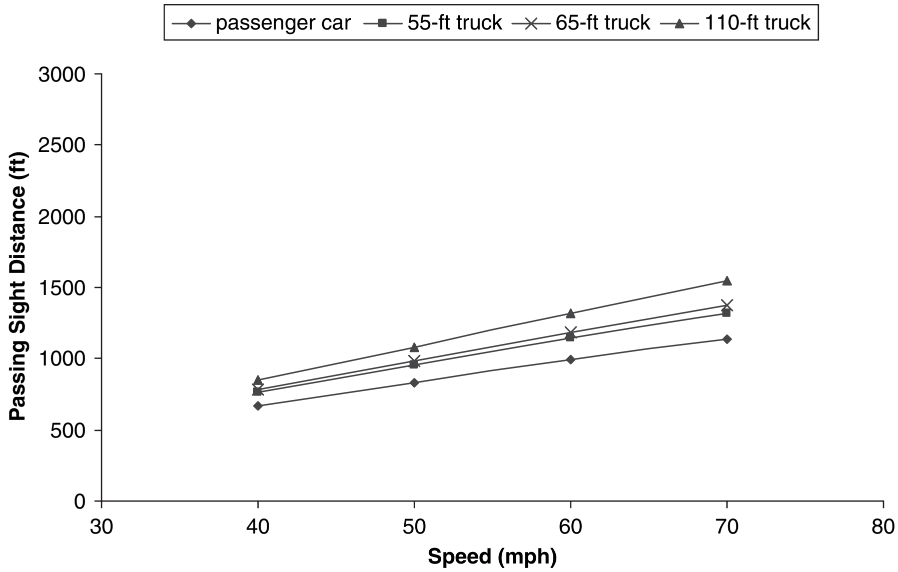

Figure 13. PSD values as a function of design speed from the Glennon model (14).

An advantage of the Glennon model is that, like the Lieberman model, it incorporates an explicit mathematical relationship to determine the relative positions of the passing and passed vehicles at the critical position [see Equation (22)].

Another advantage of the Glennon model is that the lengths of the passing and passed vehicles appear explicitly in the model so that the sensitivity of the required PSD to vehicle length can be examined. This issue is examined further in Chapter 4 of this report.

Potential concerns raised by reviewers of the Glennon model are:

- Rilett et al. (*16*) raised a concern that the Glennon model allows the passing vehicle to slow down to relatively low speeds in aborting a pass. Rilett et al. suggested a minimum speed for the passing vehicle of $V_d - 2m$. However, Good et al. (*25*) concluded that the constraint suggested by Rilett et al. is too conservative and would result in unrealistically long sight distances. This issue is further addressed in the discussion of the Rilett et al. model later in this chapter.
- Hassan et al. (*18*) were concerned that, at higher speeds, the critical position determined with the Glennon model could occur with the passing vehicle in front of the passed vehicle. Hassan et al. expressed the view that the passing driver would be unlikely to abort the passing maneuver when the front of the passing vehicle was actually ahead of the front of the passed vehicle. This issue is further addressed in the discussion of the Hassan et al. model later in this chapter.
- Hassan et al. (*18*) were concerned that the Glennon model should include a term representing the perception-reaction time required for the passing driver to decide whether to abort the passing maneuver. This issue is further addressed later in this chapter.

The Glennon model appears to be conceptually sound and should be considered as a candidate for implementation. The authors accept the analysis by Good et al. (*25*) that the introduction of a minimum speed for the passing vehicle in a pass abort maneuver is not needed. The two concerns about the Glennon model raised by Hassan et al. are addressed below.

Harwood and Glennon (1989)

Conceptual Approach

Harwood and Glennon (*15*) used the Glennon model (*14*) described above to examine the sensitivity of PSD to several factors including the presence of passenger cars and trucks (which differ in length and performance characteristics) as both the passing and passed vehicles. The Harwood and Glennon analysis results were reported first by Harwood et al. (*26*) in an FHWA report on the role of truck characteristics in highway design and operation.

Analytical Models

No new analytical models were developed for passing maneuvers involving a passenger car as the passing vehicle. The models used by Harwood and Glennon for this situation were the same as those shown in Equations (21) and (22). Where a truck serves as the passing vehicle, Harwood and

Glennon thought it unlikely that the truck would attain the same differential used by a passenger car in passing. This assumption was implemented in the model by keeping the speeds of the passed and opposing vehicles the same and decreasing the speed of the passing vehicle. In the revised model, the V term in Equations (21) and (22) is replaced by 0.5 ($V_p + V_o$), where V_p is the speed of the passing vehicle (mph) and V_o is the speed of the opposing vehicle (mph).

Assumed Values of Model Parameters

The assumed values of the model parameters were the same as those described above for the Glennon model, except that Harwood and Glennon used a passenger car length of 19 ft for consistency with the *Green Book* passenger car design vehicle, while Glennon had used an assumed passenger car length of 4.9 m (16 ft). In addition, Harwood and Glennon used a truck length of 23 m (75 ft) in examining PSD requirements with a truck as the passing vehicle, while Glennon conducted a sensitivity analysis with truck lengths of 17, 20, and 34 m (55, 65, and 110 ft). Harwood and Glennon also recommended a deceleration rate for use by a truck in aborting a pass (1.5 m/sec^2 or 5 ft/sec^2), which is lower than the deceleration rate used by Glennon (*14*) for a passenger car in aborting a pass (2.4 m/sec^2 or 8 ft/sec^2).

Passing Sight Distance Values

The PSD values determined by Harwood and Glennon are presented in Table 16, and the PSD values plotted as a function of design speed are shown in Figure 14.

Critique

Harwood and Glennon used the Glennon model (*14*) discussed earlier in this chapter. The vehicle length input parameters to the model were changed slightly. The results presented in Figure 14 show that for a passenger car passing another passenger car, the resulting PSD values are essentially the same as the MUTCD PSD criteria currently used in marking passing and no-passing zones. The PSD values for various passing scenarios involving trucks are all between the MUTCD marking criteria and the AASHTO *Green Book* design criteria. The review of the Harwood and Glennon study reinforces the recommendation made above that of the Glennon model should receive further consideration.

Rilett et al. (1989)

Conceptual Approach

In order to address the issue of whether long combination vehicles (LCVs) should be permitted on two-lane highways, Rilett et al. (*16*) developed a PSD model based on previous research, but modified it to allow for parameters such as acceleration, deceleration, and vehicle clearances along with previously included variables to provide what the authors considered a more accurate representation of an actual passing maneuver. Unlike Glennon (*14*) and several others cited above, Rilett et al. included in their PSD model the distance required for the passing vehicle to reach the critical position. Previous work by Lieberman (*11*) also took this approach. The author argued that for Glennon's approach to be sufficient, the passing vehicle would have to reach the critical position at the beginning of the passing zone and that this is not always the case. The authors also stipulated that if a minimum speed for the passing vehicle during an aborted passing maneuver is not set, then long passed vehicles can create unrealistically low speeds for the passing vehicle at the end of an aborted maneuver. Additionally, Rilett et al. stated that for higher speeds in Glennon's model the clearance between the passed and passing vehicles reaches an unacceptable length of less than that of a passenger car.

The models presented below for both completing and aborting a passing maneuver that are derived from the Rilett et al. research were based upon the idea of a variable critical position and include the distance traveled by the passing vehicle, the distance traveled by the opposing vehicle, and the head-on clearance distance.

Table 16. PSD values determined by Harwood and Glennon for specific passing scenarios (*15*).

Design or prevailing speed (mph)	Required passing sight distance (ft): Passenger car passing passenger car	Passenger car passing truck	Truck passing passenger car	Truck passing truck
20	325	350	350	350
30	525	575	600	675
40	700	800	875	975
50	875	1,025	1,125	1,275
60	1,025	1,250	1,375	1,575
70	1,200	1,450	1,625	1,875

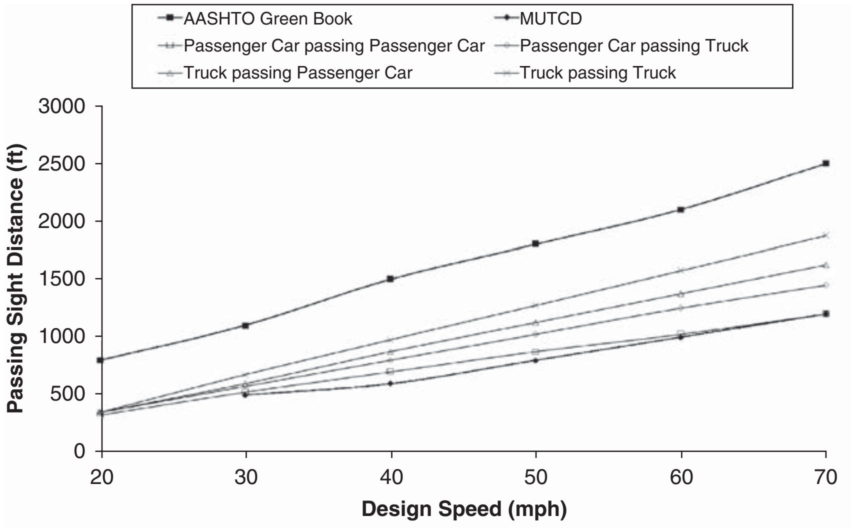

Figure 14. PSD values determined by Harwood and Glennon for specific passing scenarios (15).

Analytical Models

PSD to complete a passing maneuver:

$$PSD_{complete} = 1.47V_{crit}t_5 + \frac{1.47at_3^2}{2} + 1.47V_d t_6 d_3 + 1.47V_o(t_5 + t_6) \quad (23)$$

where

V_{crit} = speed of passing vehicle at critical position (mph), and

V_o = speed of the opposing vehicle (mph).

PSD to abort a passing maneuver:

$$PSD_{abort} = 1.47V_{crit}p_a + 1.47V_{crit}t_8 - \frac{1.47dt_5^2}{2} + 1.47V_{min}t_9 + d_3 + 1.47V_o(p_a + t_8 + t_9) \quad (24)$$

where

V_{min} = minimum speed of the passing vehicle which is equal to $V_d - 2m$ (mph);

t_8 = deceleration time needed for the passing vehicle to slow down to the minimum speed, V_{min} (sec); and

t_9 = an additional time during which the passing vehicle travels at V_{min} (sec).

Assumed Values of Model Parameters

In order to apply the model, the authors included several commonly accepted assumed values for passing maneuvers:

- Passed vehicle travels at a constant speed ($V_d - m$);
- Passing vehicle accelerates to the design speed at or before the critical position and continues at this speed unless the maneuver is aborted;
- Perception-reaction time before a pass is aborted is 1 sec; and
- Opposing vehicle travels at the design speed of the roadway.

In addition, the authors introduce the following additional assumptions:

- Space headway between passing and impeding vehicles in both completed and aborted passing maneuvers is related to the speed rather than speed differential;
- For an aborted pass, the aborting vehicle will not decelerate below the minimum speed, V_{min}, which is set equal to $V_d - 2_m$.
- For a completed pass, the passing vehicle is assumed to be traveling at a speed of V_{crit} at the critical position; if this value is less than V_d, then the passer is assumed to be accelerating at a magnitude of the acceleration, a; and
- Speed differential is set at 10 mph so that the minimum speed constraint for an aborted pass is 32 km/h (20 mph) less than the design speed.

In producing an illustration of the Rilett et al. model, the authors of this report assumed a 1-sec headway between

Table 17. PSD values for Rilett et al. model (*16*).

Design speed (mph)	Passing sight distance for passing specified vehicle type (ft)	
	16-ft passenger car	66-ft truck
37	722	1,027
44	984	1,312
50	1,296	1,640
56	1,624	1,952
62	1,952	2,257
68	2,297	2,575

the passing and passed vehicles and also that the passed vehicle lengths for passenger cars and trucks were 5 and 20 m (16 and 66 ft), respectively.

Passing Sight Distance Values

The PSD values determined with the Rilett et al. model are presented in Table 17, and the PSD values plotted as a function of design speed are shown in Figure 15.

Critique

Rilett et al. raised a concern that the Glennon model may result in an unrealistically low speed for a vehicle aborting a passing maneuver in which the passed vehicle is a long truck. A minimum passed vehicle speed (for example, Rilett et al. suggest $V_d - 2m$) could be added to the PSD models. However, a later review of the Rilett et al. work by Good et al. (*25*) concluded that the assumption of Rilett et al. that a driver aborting a passing maneuver would cease to decelerate upon reaching speed $V_d - 2m$ is too conservative to be realistic. Specifically, Good et al. argue that a driver aborting a passing maneuver, facing the potential of a collision with an opposing vehicle, would be unlikely to stop decelerating and resume a constant speed once a speed of $V_d - 2m$ was reached. The authors of this report accept this critique by Good et al. concerning the Rilett et al. model.

The statement by Rilett et al. that for the Glennon model to be correct, the passing vehicle would need to reach the critical position at the beginning of the passing zone is a misinterpretation. In fact, the Glennon model and the other models that include the potential for aborting a passing maneuver are intended to provide sufficient sight distance to complete a passing maneuver even if the passing vehicle is in the critical position at the end of the passing zone. This comment by Rilett et al. is more an argument for an increased minimum length of passing zone than an argument against the concept used in the Glennon model for PSD.

The concern raised by Rilett et al. that the Glennon model would result in unrealistically low clearance times between passed and passing vehicles does not appear appropriate at least for passenger cars. The Glennon model always results

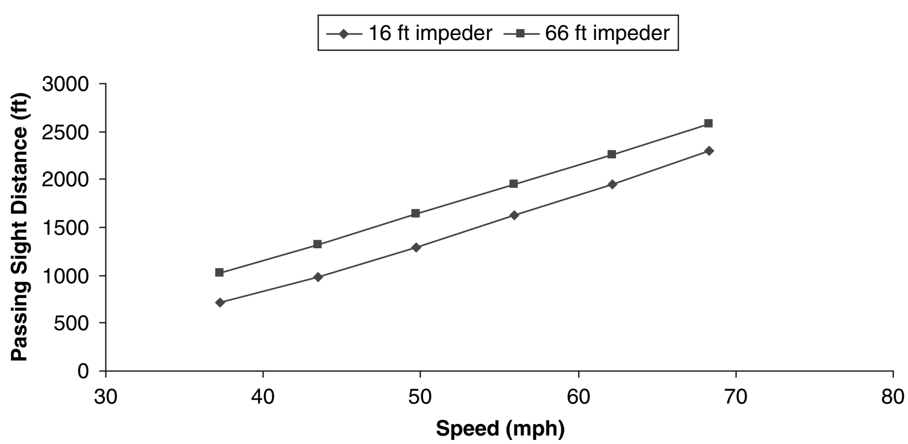

Figure 15. PSD values from Rilett et al. model (16).

in a headway of 1 sec between the passed and passing vehicle, which appears adequate, at least for a passenger car as the passed vehicle. Some adjustment may be needed for consideration of a truck as the passed vehicle.

The Rilett et al. model does not appear to be appropriate for further evaluation.

Forbes (1990)

Conceptual Approach

The goal of the paper by Forbes (*17*) was to analyze the current PSD model for marking passing and no-passing zones presented in the MUTCD and compare it to the models developed by Van Valkenburg and Michael (*8*), Weaver and Glennon (*9*), and Glennon (*14*). Each phase of the passing maneuver is investigated by the author along with its inclusion and the level of significance it is given within each model. This allowed the author to provide his assessment as to the accuracy of each model based on what is felt to be the necessary factors and phases of a passing maneuver. Forbes concluded that the ". . . outdated and unsubstantiated reasoning that the current minimum PSDs for operations are based on and the novel approach of Glennon suggest that a reexamination of the logic behind PSDs for operation is warranted."

Passing Sight Distance Values

No new PSD values were suggested.

Critique

The Forbes paper generally supports the application of PSD models based on the critical position concept and, most particularly, the Glennon model.

There appears to be one possible misinterpretation in the Forbes paper. The author appears to believe that the speed differential between the passing and passed vehicles is the speed difference when a passing vehicle will determine that a pass is necessary. In other words, if a model suggests a speed differential of 16 km/h (10 mph), then Forbes appears to assume that passing drivers will opt only to pass if cars are traveling more than 16 km/h (10 mph) less than the design speed. This misunderstanding becomes critical when the author is critiquing models that assume a variable speed differential based on the design speed. In these models the speed differential tends to decrease as design speed increases, and this is counterintuitive to what Forbes believes should be happening. The research team believes that the speed differential that would lead a driver to decide to pass and the speed differential that a passing driver would choose to adopt during a passing maneuver are two distinct quantities.

Hassan et al. (1996)

Conceptual Approach

The revised model developed by Hassan et al. (*18*) sought to improve on what was perceived to be inadequate models currently used to illustrate the kinematic relationship between passing, passed, and opposing vehicles due to either too liberal or too conservative assumptions. The authors sought to find a balance between proven passing principles and known driver behaviors in accurately locating the critical position of the passing maneuver. Ultimately, the authors decided that two models were needed to estimate appropriate PSDs based on the location of the front bumper of the passing vehicle with respect to the front bumper of the passed vehicle.

The revised model provides a margin of safety for the passing maneuver that increases as design speed increases. After their model was completed, the authors validated it using two sets of field data from the Van Valkenburg and Michael (*8*) research.

Analytical Models

The basic PSD model recommended by Hassan et al. is a variation of the Glennon model and is represented in the following equations:

$$PSD_c = 2.93V_d\left(t_6 + h\right) \tag{25}$$

$$t_6 = p_a + t_a - \frac{d_a t_a}{5.88\ V_d}\left(t_a + 2h\right) \tag{26}$$

$$t_a = -h + \sqrt{\frac{h^2 + 5.88\ V_d\left[L_p + L_i + 1.4h\left(2V_d - m\right)\right]}{1.47d_a\left(2V_d - m\right)}} \tag{27}$$

where

- t_6 = time required for the passing vehicle to return to its own lane from the critical position for a completed passing maneuver (sec);
- h = minimum headway between the passing and passed vehicles at the end of a completed or aborted passing maneuver and minimum headway between passing and oncoming vehicle at the end of a completed or aborted passing maneuver (sec);
- p_a = perception-reaction time required for passing driver to decide to abort a passing maneuver (sec);
- d_a = deceleration rate used by the passing vehicle in aborting the passing maneuver (ft/sec^2);and
- t_a = time required to abort a passing maneuver from the critical position (after perception-reaction time) (sec).

Equation (25) is potentially applicable to any passing situation and represents the sight distance required to either complete or abort the passing maneuver for a passing vehicle in the critical position.

Hassan et al. developed a model for the location of the critical position that is conceptually similar to Glennon's model presented in Equation (22). The Hassan et al. model for the location of the critical position is:

$$\Delta_c = L_p + 1.47(V_d - m)h - 1.47mt_6 \qquad (28)$$

where

Δ_c = relative position of the front bumpers of the passing and passed vehicles at the critical position (negative Δ_c means that passing vehicle is behind passed vehicle; positive Δ_c means that passing vehicle is in front of passed vehicle) (ft).

With Equation (28), Hassan et al. found that the location of the critical position varies, and that in some cases the critical position may occur when the front bumper of the passing vehicle is ahead of the front bumper of the passed vehicle ($\Delta_c > 0$). Hassan et al. concluded that a passing driver would be unlikely to abort a passing maneuver when the front bumper of the passing vehicle was ahead of the front bumper of the passed vehicle, even if aborting the maneuver actually requires less sight distance than completing the maneuver. Therefore, Hassan et al. proposed that additional sight distance be provided so that any passing maneuver can be completed from the position where the front bumpers of the passing and passed vehicles are even. The sight distance to provide for this maneuver is:

$$PSD_c = 2.93V_d\left(t_6^* + h\right) \qquad (29)$$

$$t_6^* = \frac{1.47(V_d - m)h + L_p}{1.47m} \qquad (30)$$

where

t_6^* = time required to complete the passing maneuver from the position where the front bumpers of the passing and passed vehicles are abreast (sec).

The Hassan et al. model would be applied as follows:

- Use Equation (25) when $\Delta_c \le 0$; and
- Use Equation (29) when $\Delta_c \ge 0$.

Assumed Values of Model Parameters

Hassan et al. assume many of the same values that are found in previous models:

- The passed vehicle is traveling at a constant speed of $V_d - m$ during the entire maneuver.
- The opposing vehicle is traveling at a constant speed of V_d during the entire maneuver.
- At the beginning of the pass, the passing vehicle is trailing the passed vehicle and traveling at a speed of $V_d - m$.
- Then, the passing vehicle accelerates with a constant rate, a, to speed, V_d, while shifting to the left lane. The sight distance required at this stage is minimal and falls within the sight distance needed to abort the pass safely.
- As the pass proceeds, the sight distance required for the passing vehicle to abort the pass increases and that required to complete the pass decreases.

If the driver perceives a need to abort the passing maneuver, the maneuver should be aborted as follows:

- A minimum headway, h_1, should be maintained between the front bumper of the passing vehicle and the rear bumper of the passed vehicle.
- Similarly, a minimum headway, h_0, should be maintained between the front bumper of the passing vehicle and the front bumper of the opposing vehicle until the passing vehicle is completely clear of the opposing lane.
- In aborting the pass, the driver of the passing vehicle takes a perception-reaction time, p_a, before applying the brakes. During this perception-reaction time, the speed profile of the passing vehicle is assumed not to be influenced by the need to abort the pass.
- Then the passing vehicle keeps decelerating with a constant rate, d_a, until it is back in its normal lane.

Once the passing driver reaches the critical position, the sight distance needed to abort the pass equals that required to complete the pass. The following characteristics pertain at the critical position:

- By reaching the critical position, the passing vehicle has already accelerated to the design speed, V_d. (The authors demonstrated in their paper that this assumption is correct.)
- By traveling past the critical position, the passing vehicle can complete the pass safely with less sight distance than would be required to abort the passing maneuver.
- At the end of the completed pass, the minimum headways h_0 and h_1 should be maintained between the front bumpers of the passing and opposing vehicles and between the rear bumper of the passing vehicle and the front bumper of the passed vehicle, respectively.

Hassan et al. made the assumption that the values of h_0 and h_1, for both completing and aborting the passing maneuvers, are equal with a value of 1 sec. In other words, Hassan et al. assume $h = h_0 = h_1 = 1$ sec.

It also was assumed that the speed differential would vary according to speed by the following relationship:

$$m = 14.91 - V_d/10\left(\text{mph}\right) \text{ or } m = 24 - V_d/10\left(\text{km/h}\right) \qquad (31)$$

Hassan et al. assumed values of 4.9 m (16 ft) for the passing and passed vehicles; the research team has used a 5.8-m (19-ft) passenger vehicle length for consistency with the AASHTO *Green Book* design vehicles.

The Hassan et al. model includes a term for the perception-reaction time needed for the passing driver to decide whether to abort a passing maneuver. Hassan et al. do not provide a value for this term, but the research team has used a tentative value of 1 sec. The critique presented below discusses the applicability of this term.

The research team has assumed a deceleration rate of 2.4 m/sec^2 (8 ft/sec^2), independent of speed, in contrast to Hassan et al. who assumed a deceleration rate that varies with speed based on older stopping sight distance research (*24*). The assumption of a deceleration rate independent of speed is consistent with the most recent stopping sight distance research by Fambro et al. (*27*). The deceleration rate of 2.4 m/sec^2 (8 ft/sec^2) used by the research team in the Hassan et al. model is less than the 3.4 m/sec^2 (11 ft/sec^2) deceleration rate recommended by Fambro et al. and used in the current AASHTO *Green Book* criteria for stopping sight distance.

Passing Sight Distance Values

The PSD values determined with the Hassan et al. model are presented in Table 18, and the PSD values plotted as a function of design speed are shown in Figure 16. For comparative purposes, Figure 16 also shows PSD values from the MUTCD criteria and the Glennon model.

Table 18. PSD values for Hassan et al. model (*18*).

Speed (mph)	Passing sight distance (ft)
30	470
35	590
40	710
45	840
50	980
55	1,160
60	1,440
65	1,770
70	2,150
75	2,610
80	3,160

Critique

The Hassan et al. model is equivalent to the Glennon model with two exceptions:

- Hassan et al. model uses a more conservative approach than the Glennon model by assuming that a passing driver whose front bumper draws even with the front bumper of the passed vehicle will complete the pass even if the critical position has not yet been reached; and
- Hassan et al. model uses a more conservative assumption that an additional perception-reaction time is required for the passing driver to decide whether to abort the passing maneuver.

The assumption by Hassan et al. that the passing driver is likely to complete the pass once the front bumpers of the passing and passed vehicles are abreast appears to be a reasonable interpretation of likely driver behavior. This provides larger PSD values than the MUTCD or the Glennon model at higher speeds. However, given the large margin of safety provided by marking and enforcement of the no-passing zone barrier stripe where PSD falls below PSD_c (see discussion in Chapter 5), it is not clear whether the additional PSD at high speeds provided by the Hassan et al. model is critical to safety.

The assumption by Hassan et al. that the passing driver requires additional PSD to decide whether to abort the passing maneuver appears reasonable in the situation where an oncoming vehicle comes suddenly into view (such as, at a vertical crest), but does not appear necessary when the oncoming vehicle is already in view. In the latter situation, perception-reaction by the passing driver occurs continuously while the passing maneuver is in progress. However, here also the legal requirement to complete passing maneuvers before the end of the no-passing barrier stripe provides a substantial margin of safety. There is sufficient PSD for the passing driver to complete the pass when in the critical position at the end of the passing zone, but it is also illegal for the passing driver to be in the critical position at the end of the passing zone.

The criticality of the perception-reaction time (p_a) term is further assessed in Chapter 5. Key issues are, in a variety of realistic terrain, what percentage of passing zone length has PSD at or just above PSD_c, where perception-reaction time may be critical, and to what extent does the introduction of the no-passing barrier stripe before the end of the region where it is safe to complete a pass provide an offset to the need for perception-reaction time.

Hassan et al. do not suggest a value of the perception-reaction time (p_a) needed by the passing driver to abort a passing maneuver. Unlike other sight distance conditions, the abort decision in a passing maneuver is an alerted condition. Any rational passing driver would have the target object (an

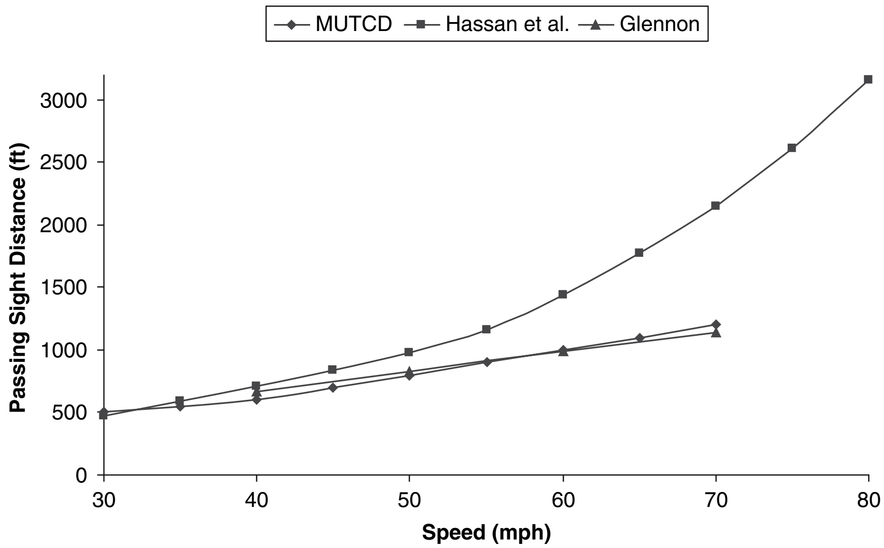

Figure 16. PSD values from Hassan et al. and Glennon model (18).

opposing vehicle) in mind and would be looking directly at the spot where an opposing vehicle might appear. The research team considers that, in this situation, a perception-reaction of 1 sec or less is reasonable.

For a perception-reaction time (p_a) of 1 sec or less and for speeds up to 80 km/h (50 mph), the PSD values indicated by the Hassan et al. model are nearly equivalent to the PSD values from the Glennon model and the MUTCD PSD criteria. At speeds higher than 80 km/h (50 mph), the Hassan et al. model begins to require substantially more PSD than either the Glennon or MUTCD models as a result of using Equation (29) to provide for completion of any passing maneuver from the abreast position.

Wang and Cartmell (1998)

Conceptual Approach

In this mathematical model the authors, Wang and Cartmell (*19*) go to great lengths to include all parameters that influence a passing maneuver, a task the authors felt that previous research had not accomplished. The authors suggest a need to reassess current PSD criteria because of improved vehicle capabilities and an increase in maximum permitted truck lengths. In this model, the path of the passing vehicle is described using a combination of quintic polynomials and straight lines, whereas most models assume the vehicle moves in a plane.

The Wang and Cartmell model includes what the authors consider to be the 11 most significant parameters that affect PSD, including factors related to vehicle trajectory in order to provide what the authors felt to be the most accurate model possible. It was concluded by the authors that the current AASHTO standards were too conservative for modern vehicles. The distance traveled by the passing vehicle during a driver's perception-reaction period before the start of a passing maneuver is not included in the model.

The Wang and Cartmell model addresses three stages of a passing maneuver as follows:

- Stage 1: From beginning of passing maneuver to the point where the passing vehicle is fully in the left lane and its front bumper is aligned with the rear bumper of the passed vehicle
- Stage 2: The period when the passing vehicle occupies the left lane from the end of Stage 1 to the point where the rear bumper of the passing vehicle is aligned with the front bumper of the passed vehicle.
- Stage 3: From the end of Stage 2 until the passing vehicle returns to its own lane.

Analytical Models

$$PSD = X_1 + X_2 + X_3 + C + 0.62V_o(T_1 + T_2 + T_3) \quad (32)$$

where

X_1 = distance traveled by the passed vehicle in Stage 1 in the x-axis direction (ft);
X_2 = distance traveled by the passed vehicle in Stage 2 in the x-axis direction (ft);
X_3 = distance traveled by the passed vehicle in Stage 3 in the x-axis direction (ft);
T_1 = time used during Stage 1 (sec);
T_2 = time used during Stage 2 (sec);
T_3 = time used during Stage 3 (sec); and
C = clearance between the front bumper of the passing and opposing vehicles at the end of the maneuver (ft).

Case 1: Maximum Speed Reached at Stage 1

Stage 1

$$S_1 = d_{pmax} + 0.62V_{pmax}\left(T_1 - T_{pmax}\right) \tag{33}$$

$$X_1 = 0.62V_iT_1 + G_s \tag{34}$$

Stage 2

$$S_2 = 0.62V_{pmax}T_2 \tag{35}$$

$$X_2 = 0.62V_iT_2 + L_p + L_i \tag{36}$$

Stage 3

$$S_3 = 0.62V_{pmax}T_3 \tag{37}$$

$$X_3 = 0.62V_iT_3 + G_e \tag{38}$$

where

d_{pmax} = distance traveled by the passing vehicle from its start point of the overtaking to the point where the maximum speed, V_{pmax}, is reached (ft/sec^2);
V_{pmax} = maximum speed of passing vehicle (mph);
T_{pmax} = time used to travel d_{pmax} (sec);
G_e = clearance between the head of the passing vehicle and the tail of the passing vehicle at the end of the pass (ft);
G_s = clearance between the head of the passing vehicle and the tail of the passed vehicle at the beginning of the pass (ft);
S_1 = total distance traveled by the passing vehicle during Stage 1 (ft);
S_2 = total distance traveled by the passing vehicle during Stage 2 (ft); and
S_3 = total distance traveled by the passing vehicle during Stage 3 (ft).

Case 2: Maximum Speed Reached at Stage 2

Stage 1

$$S_1 = 0.62V_iT_1 + 0.46a_{pmax}\left(T_1\right)^2 \tag{39}$$

$$X_1 = 0.62V_iT_1 + G_s \tag{40}$$

Stage 2

$$S_1 + S_2 = 0.91d_{pmax} + 0.62V_{pmax}\left(T_1 + T_2 - T_{pmax}\right) \tag{41}$$

$$X_2 = 0.62V_iT_2 + L_p + L_i \tag{42}$$

Stage 3

$$S_3 = 0.62V_{pmax}T_3 \tag{43}$$

$$X_3 = 0.62V_iT_3 + G_e \tag{44}$$

where

a_{pmax} = acceleration of the passing vehicle (ft/sec^2)

Case 3: Maximum Speed Reached at Stage 3

Stage 1

$$S_1 = 0.62V_iT_1 + 0.5a_{pmax}\left(T_1\right)^2 \tag{45}$$

$$X_1 = 0.62V_iT_1 + G_s \tag{46}$$

Stage 2

$$S_1 + S_2 = 0.62V_i\left(T_1 + T_2\right) + 0.46a_{pmax}\left(T_1 + T_2\right)^2 \tag{47}$$

$$X_2 = 0.62V_iT_2 + L_p + L_i \tag{48}$$

Stage 3

$$S_1 + S_2 + S_3 = 0.91d_{pmax} + 0.62V_{pmax}\left(T_1 + T_2 + T_3 - T_{pmax}\right) \tag{49}$$

$$X_3 = 0.62V_iT_3 + G_e \tag{50}$$

Case 4: Maximum Speed Not Reached by End of Stage 3

Stage 1

$$S_1 = 0.62V_iT_1 + 0.46a_{pmax}\left(T_1\right)^2 \tag{51}$$

$$X_1 = 0.62V_iT_1 + G_s \tag{52}$$

Stage 2

$$S_1 + S_2 = 0.62V_i\left(T_1 + T_2\right) + 0.46a_{pmax}\left(T_1 + T_2\right)^2 \tag{53}$$

$$X_2 = 0.62V_iT_2 + L_p + L_i \tag{54}$$

Stage 3

$$S_1 + S_2 + S_3 = 0.62V_i\left(T_1 + T_2 + T_3\right) + 0.46a_{pmax}\left(T_1 + T_2 + T_3\right)^2 \tag{55}$$

$$X_3 = 0.62V_iT_3 + G_e \tag{56}$$

Assumed Values of Model Parameters

- The passed vehicle and the opposing vehicle move forward at constant speeds V_i and V_o, respectively.
- The passing vehicle accelerates from its initial speed, V_i, at the start of the overtaking towards the maximum V_{pmax}, achievable by it. According to the AASHTO criteria, this value is normally 16 to 24 km/h (10 to 15 mph) higher than that of the overtaken vehicle. Once the V_{pmax} is reached, the passing vehicle will then keep moving at this constant speed.

Passing Sight Distance Values

The PSD values determined with the Wang and Cartmell model are presented in Table 19, and the PSD values plotted as a function of design speed are shown in Figure 17.

Table 19. PSD values from Wang and Cartmell model (*19*).

Design speed (mph)	Passing sight distance (ft)	
	a_{pmax1}	a_{pmax2}
19	869	673
25	1,043	801
31	1,240	948
37	1,417	1,083
44	1,617	1,230
50	1,765	1,352
56	1,972	1,516
62	2,142	1,650
68	2,320	1,795
75	2,497	1,942

Critique

The assumptions made in the Wang and Cartmell model are very similar to those made in the AASHTO *Green Book* and the model results in PSD values that are within 50 m (160 ft) of those provided by the AASHTO model. The model is more complex than the AASHTO model, but may do a better job at explicitly representing each element of the vehicle trajectories.

The Wang and Cartmell model does not address the possibility of aborting the passing maneuver and, therefore, does not incorporate the critical position concept. The Wang and Cartmell model is extremely conservative, and it appears to be out of step with the general direction of PSD modeling. This model is not recommended for further consideration.

Comparison of Passing Sight Distance Models

Table 20 presents a summary comparison of the PSD models presented in Chapter 2 and earlier in this chapter. The PSD values resulting from each of the PSD models in Table 20 are compared in Figure 18 and in Table 21.

Figure 18 shows that the PSD models proposed in the literature provide PSD values that cover the full range between the MUTCD and AASHTO values, with a few PSD values below the MUTCD values or above the AASHTO values.

The next chapter presents the results of field studies conducted to quantify driver behavior in passing and the parameters of PSD models. Chapter 5 of this report summarizes the key issues concerning PSD models, leading to an assessment of the appropriate models for future use.

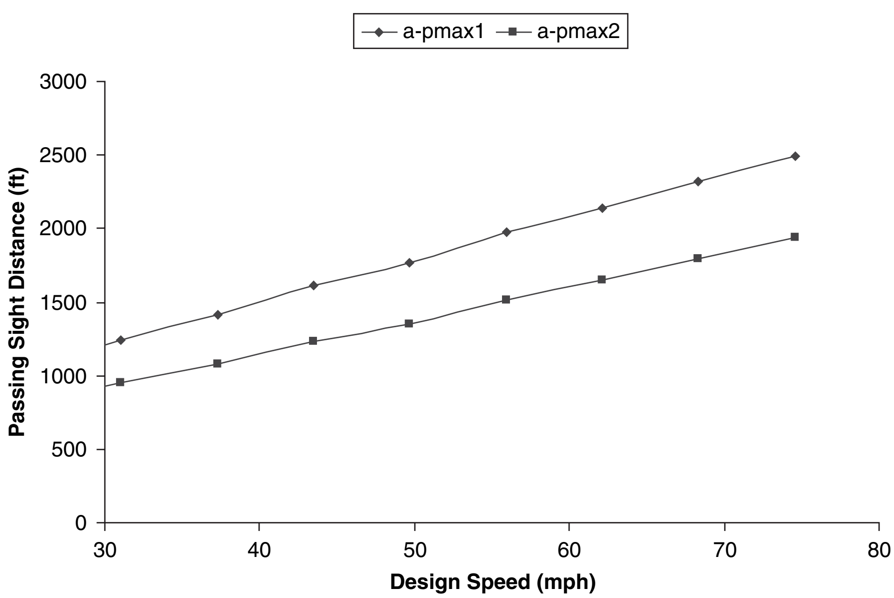

Figure 17. PSD values from Wang and Cartmell model (19).

Table 20. Summary of passing sight distance models.

Model	Application	Speed profile			Acceleration/deceleration Rates		Vehicle Type & Length		Perception-Reaction Time		Speed differential (between passing and passed vehicles)	Clearance time/distance		Comments
		Passing	Passed	Opposing	Pass initiation	Pass Abort	Passing	Passed	Pass Initiation	Pass Abort		After pass completion	After pass abort	
AASHTO *Green Book* (*1*)	Design	Variable speed with assumed average value [a]	Constant speed 10 mph less than average speed of passing vehicle	Same as passing vehicle [a]	Implicit in d_1 term	N/A	Passenger car—length implicit in d_2 term	Passenger car—length implicit in d_2 term	Implicit in d_1 term	N/A	10 mph	Implicit in d_2 term	N/A	Based on delayed pass with hurried return in the face of opposing traffic; assumes passing maneuver will only be aborted very early in the maneuver
MUTCD (*2*)	Marking	Constant speed equal to 85th percentile speed or speed limit	Constant speed 10 to 25 mph less than passing vehicle	Constant speed 5 to 15 mph less than passing vehicle	Implicit in sight distance estimates	N/A	Passenger car—length implicit in sight distance estimates	Passenger car—length implicit in sight distance estimates	Implicit in sight distance estimates	N/A	10 to 25 mph	Implicit in sight distance estimates	N/A	Based on compromise between field observations for delayed passes and flying passes in 1940 AASHO policy
Van Valkenburg & Michael (*8*)	Marking	Average speed 10 mph higher than passed vehicle	Average off-peak speed of traffic	85^{th} percentile speed	N/A	N/A	Passenger car—length implicit in field observations of passing distance	Passenger car—length implicit in field observations of passing distance	N/A	N/A	10 mph	20 ft	N/A	Stated critical position concept based on equal pass completion and abort distances, but quantified sight distance based on field observations of pass completions only; assumed critical position with rear bumper of passing vehicle opposite middle of passed vehicle
Weaver & Glennon (*9*)	Design	Design speed	8 to 12 mph less than design speed	Design speed	Implicit in d_2 term	N/A	Passenger car—length implicit in d_2 term	Passenger car—length implicit in d_2 term	Implicit in d_2 term	N/A	8 to 12 mph	Implicit in d_2 term	N/A	Stated critical position concept based on equal pass completion and abort times; quantified sight distance based on a model of pass completions only; assumed critical position occurs with vehicles abreast
Harwood and Glennon (*10*)	Design and Marking	Design speed	10 mph less than design speed	Design speed	N/A	N/A	Passenger car—length implicit in d_2 term	Passenger car—length implicit in d_2 term	N/A	N/A	10 mph	Implicit in d_2 term	N/A	Stated critical position concept based on equal sight distances to complete or abort the passing maneuver; quantified sight distance based on a model of pass completions only; assumed that the passing vehicle could reach the critical position in 2/3 d_2, but did not state where this occurs
Lieberman (*11*)	Design	10 mph faster than passed vehicle	Design speed or 85th percentile speed	Not explicitly stated	Implicit in d_7 term	N/A	Passenger car—length implicit in d_5 term	Passenger car - length implicit in d_5 term	Implicit in d_7 term	N/A	10 mph	1.5 sec	N/A	Uses critical position concept, but assumes that sight distance includes travel distance to critical position plus pass completion distance from critical position; location of critical position is computed explicitly
Saito (*12*)	Marking	85^{th} percentile speed	Included in model, but no explicit value stated	85^{th} percentile speed	N/A	9.7 ft/sec^2	Passenger car—20 ft	Passenger car—20 ft Truck—50 and 55 ft	N/A	0 sec	Included in model, but no explicit value stated	N/A	Included in model, but no explicit value stated	Uses critical position concept based on pass abort maneuver; considered two potential critical positions: head-to-tail and abreast
Ohene & Ardekani (*13*)	Marking	Included in model, but no explicit value stated	5 to 25 mph less than passing vehicle	Same as passing vehicle	2.06 to 2.21 ft/sec^2	6.03 to 9.06 ft/sec^2	Passenger car—length not explicitly stated	Passenger car—length not explicitly stated	1 sec	1 sec	5 to 25 mph	Included in model, but no explicit value stated	N/A	Model parameters not fully defined by authors; model cannot be applied without assumptions
Glennon (*14*)	Design	Design speed	8 to 12 mph less than design speed	Design speed	N/A	8 ft/sec^2	Model includes vehicle length as an input parameter—author used 16-ft passenger car	Model includes vehicle length as an input parameter—author used 16-ft passenger car and 55-, 65-, and 110-ft trucks	N/A	1 sec	8 to 12 mph	1 sec	1 sec	Uses critical position concept based on equal sight distance to complete or abort the passing maneuver; location of critical position is computed explicitly
Harwood and Glennon (*15*)	Design	Design speed	8 to 12 mph less than design speed	Design speed	N/A	8 ft/sec^2	Model includes vehicle length as an input parameter—authors used 19-ft passenger car	Model includes vehicle length as an input parameter—author used 16-ft passenger car and 75-ft truck	N/A	1 sec	8 to 12 mph	1 sec	1 sec	Uses critical position concept based on equal sight distance to complete or abort the passing maneuver; same as Glennon (1988) model with different assumed parameter values for vehicle length
Rilett et al. (*16*)	Design	Design speed	10 mph less than design speed	Design speed	Implicit in d_7 term	Implicit in d_8 term	Model includes vehicle length as an input parameter—authors used 16-ft passenger car	Model includes vehicle length as an input parameter—author used 16-ft passenger car and 66-ft truck	N/A	Included in model, but no explicit value stated	10 mph	1 sec	1 sec	Uses critical position concept, but assumes that sight distance includes travel distance to critical position plus pass completion distance from critical position; specifies minimum speed in pass abort maneuver of 20 mph below design speed; model is not completely described
Hassan et al. (*18*)	Design	Design speed	8 to 12 mph less than design speed	Design speed	N/A	8 ft/sec^2	Model includes vehicle length as an input parameter—authors used 16-ft passenger car	Model includes vehicle length as an input parameter—authors used 16-ft passenger car; trucks were also considered	N/A	Included in model, but no explicit value stated [b]	8 to 12 mph	1 sec	1 sec	Uses critical position concept similar to Glennon (1988) model with two modifications; explicit P-R time for pass abort and pass completion in all cases from abreast position
Wang & Cartmell (*19*)	Design	Maximum passing vehicle speed Included in model, but no explicit value stated	Included in model, but no explicit value stated	Included in model, but no explicit value stated	Included in model, but no explicit value stated	N/A	Implicit in S_2 term	Implicit in S_2 term	Implicit in S_1 term	N/A	10 to 15 mph	Included in model, but no explicit value stated	N/A	Similar to AASHTO model, but with more completely specified kinematic relationships; does not use the critical position concept and does not consider pass aborts

[a] Assumed average speed of passing vehicle is greater than design speed at lower speeds and less than design speed at higher speeds.
[b] Research term has assumed a value of 1 sec.

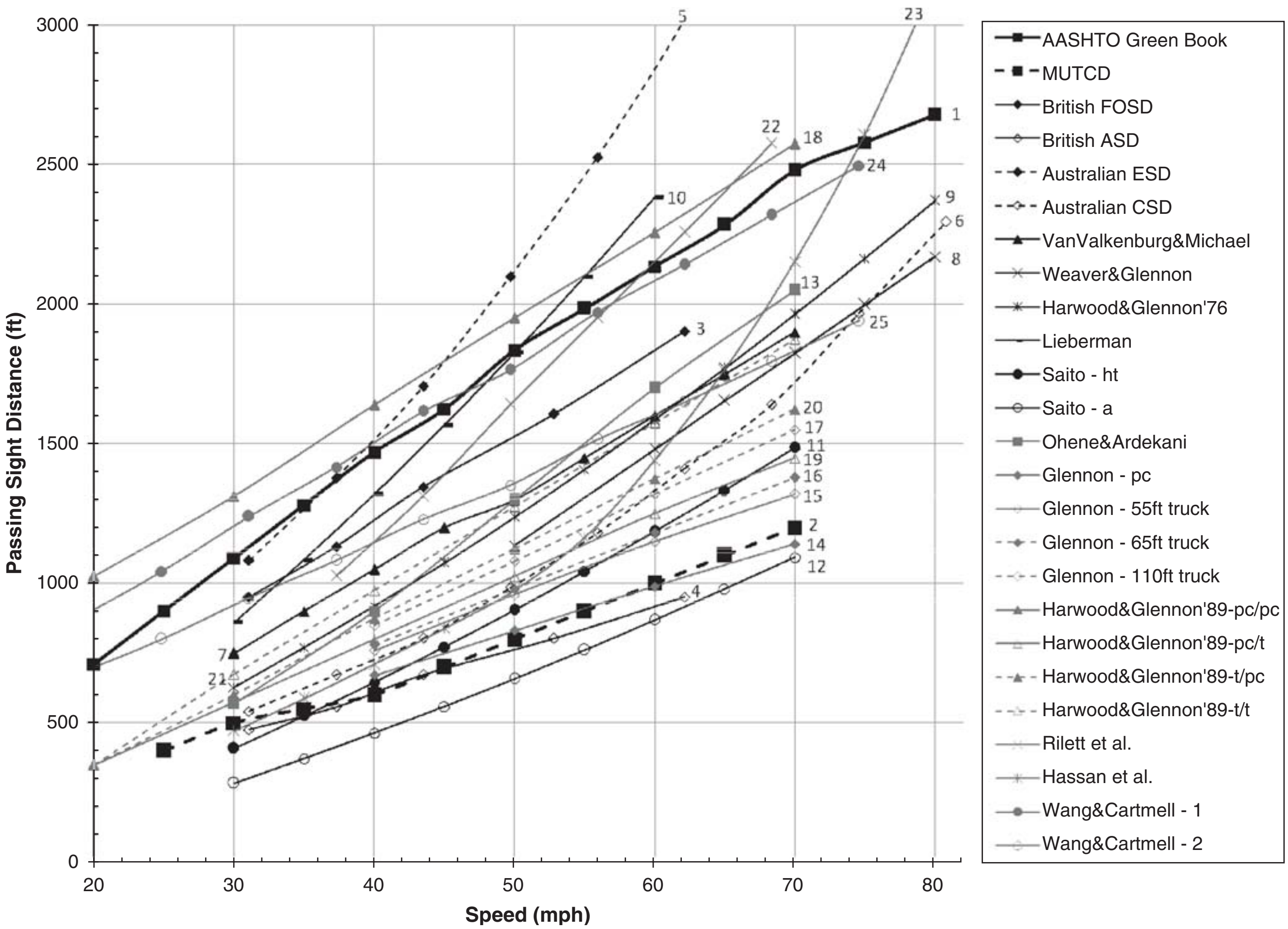

Figure 18. Comparison of PSD values from various PSD models.

Table 21. Comparison of PSD values from various PSD models.

Model	Speed (mph) 30	35	40	45	50	55	60	65	70	75	80
	Passing Sight Distance (ft)										
AASHTO (*1*)	1,090	1,280	1,470	1,625	1,835	1,985	2,135	2,285	2,480	2,580	2,680
MUTCD (*2*)	500	550	600	700	800	900	1,000	1,100	1,200	–	–
British FOSD (*20*)	918	1,071	1,224	1,377	1,530	1,683	1,836	–	–	–	–
British ASD (*20*)	456	533	610	687	764	841	918	–	–	–	–
Australian ESD (*20*)	1,056	1,260	1,504	1,785	2,106	2,465	2,862	3,299	3,773	4,287	4,839
Australian CSD (*20*)	537	619	721	842	984	1,145	1,325	1,526	1,746	1,986	2,245
Van Valkenburg and Michael (*8*)	750	900	1,050	1,200	1,300	1,450	1,600	1,750	1,900	–	–
Weaver and Glennon (*9*)	–	–	–	–	1,135	–	1,480	1,655	1,825	2,000	2,170
Harwood and Glennon (*10*)	628	769	918	1,074	1,238	1,408	1,586	1,772	1,964	2,164	2,371
Lieberman (*11*)	860	1,084	1,320	1,568	1,828	2,099	2,383	–	–	–	–
Saito $_{\text{head-tail}}$ (*12*)	409	524	646	773	905	1,043	1,186	1,334	1,486	–	–
Saito $_{\text{abreast}}$ (*12*)	284	372	463	559	659	763	870	980	1,093	–	–
Ohene and Ardekani (*13*)	570	–	900	–	1,300	–	1,700	–	2,050	–	–
Glennon $_{\text{passenger vehicle}}$ (*14*)	–	–	670	–	830	–	990	–	1,140	–	–
Glennon $_{\text{55-ft truck}}$ (*14*)	–	–	760	–	960	–	1,150	–	1,320	–	–
Glennon $_{\text{65-ft truck}}$ (*14*)	–	–	780	–	980	–	1,180	–	1,380	–	–
Glennon $_{\text{110-ft truck}}$ (*14*)	–	–	850	–	1,080	–	1,320	–	1,550	–	–
Harwood and Glennon $_{\text{pc-pc}}$ (*15*)	525	–	700	–	875	–	1,025	–	1,200	–	–
Harwood and Glennon $_{\text{pc-truck}}$ (*15*)	575	–	800	–	1,025	–	1,250	–	1,450	–	–
Harwood and Glennon $_{\text{truck-pc}}$ (*15*)	600	–	875	–	1,125	–	1,375	–	1,625	–	–
Harwood and Glennon $_{\text{truck-truck}}$ (*15*)	675	–	975	–	1,275	–	1,575	–	1,875	–	–
Rilett et al. $_{\text{16-ft passenger car}}$ (*16*)	–	–	836	1,069	1,312	1,567	1,832	2,109	2,397	–	–
Rilett et al. $_{\text{66-ft truck}}$ (*16*)	–	–	1,152	1,403	1,653	1,903	2,154	2,404	2,654	–	–
Hassan et al. (*18*)	472	588	710	840	976	1,165	1,441	1,767	2,153	2,610	3,155
Wang and Cartmell $_{\text{Apmax1}}$ (*19*)	1,204	1,350	1,496	1,642	1,787	1,933	2,079	2,225	2,371	2,517	–
Wang and Cartmell $_{\text{Apmax2}}$ (*19*)	921	1,035	1,149	1,262	1,376	1,490	1,604	1,717	1,831	1,945	–
Highest PSD value	1,204	1,350	1,504	1,785	2,106	2,465	2,862	3,299	3,773	4,287	4,839
Lowest PSD value	284	372	463	559	659	763	870	980	1,093	1,986	2,170

CHAPTER 4

Field Study of Passing Maneuvers

This chapter presents the results of a field study of passing maneuvers on two-lane highways conducted as part of the research. Together with a related study recently completed in Texas (*28*), the results are intended for use in developing an appropriate model of PSD requirements in passing maneuvers.

Field Study Objectives

The objectives of the field study were to:

- Determine key descriptors of typical passing maneuvers on two-lane highways needed for PSD models including:
  - Distance traveled by the passing vehicle in the opposing lane;
  - Speed differential between the passing and passed vehicles; and
  - Deceleration rate used by the passing vehicle in aborting a passing maneuver.
- Determine how frequently short passing zones of 120 to 240 m (400 to 800 ft) in length are used for passing maneuvers, whether these passing maneuvers contribute substantially to the operational efficiency of a two-lane highway, and whether passing maneuvers in short passing zones are conducted safely.

Field Study Layout

Field data for the research were collected at passing zones on two-lane highways using a combination of traffic classifiers and video recording. Figure 19 shows the layout of the traffic classifiers and video camera for a typical data collection site with marked passing zones in both directions of travel.

As shown in the figure, traffic classifiers were placed upstream of the beginning of the passing zone in each direction of travel and in both directions of travel near the center of the passing zone. Where there was a passing zone in only one direction of travel, the upstream traffic classier for the other direction of travel was omitted.

The traffic classifiers were connected to a pair of tapeswitches placed across the pavement surface in each lane at a distance of 3.1 m (10 ft) from one another. In this configuration, each traffic classifier can provide the following data for every vehicle that passed over the tapeswitches:

- Time of day (clock time);
- Headway to preceding vehicle (sec);
- Speed (mph);
- Number of axles; and
- Axle spacing (ft).

In some cases, the sensors at the center of the passing zone recorded data for passing vehicles passing over the sensors in the opposing direction to normal traffic, but not all passing vehicles were necessarily occupying the opposing lane at this location.

A video also was recorded at each site using a video camera mounted on a high mast to gain a good view of as much of the passing zone as possible. The mast and camera assembly was mounted on a trailer for ease of transportation between sites. The video system used for this research was the Portable Overhead Surveillance Trailer (POST) system owned and operated by the University of Missouri–Columbia (UMC). Figure 20 presents a photograph of the trailer and camera, while Figure 21 illustrates the typical field of view of the camera. A passing maneuver in progress can be seen in Figure 21 at the location marked by a horizontal line in the photograph.

Field Study Procedure

The equipment setup for each study site required approximately two hours. First, a suitable camera location was determined and the video trailer was placed on the roadside, just outside the roadway shoulder, at that location, and the field of

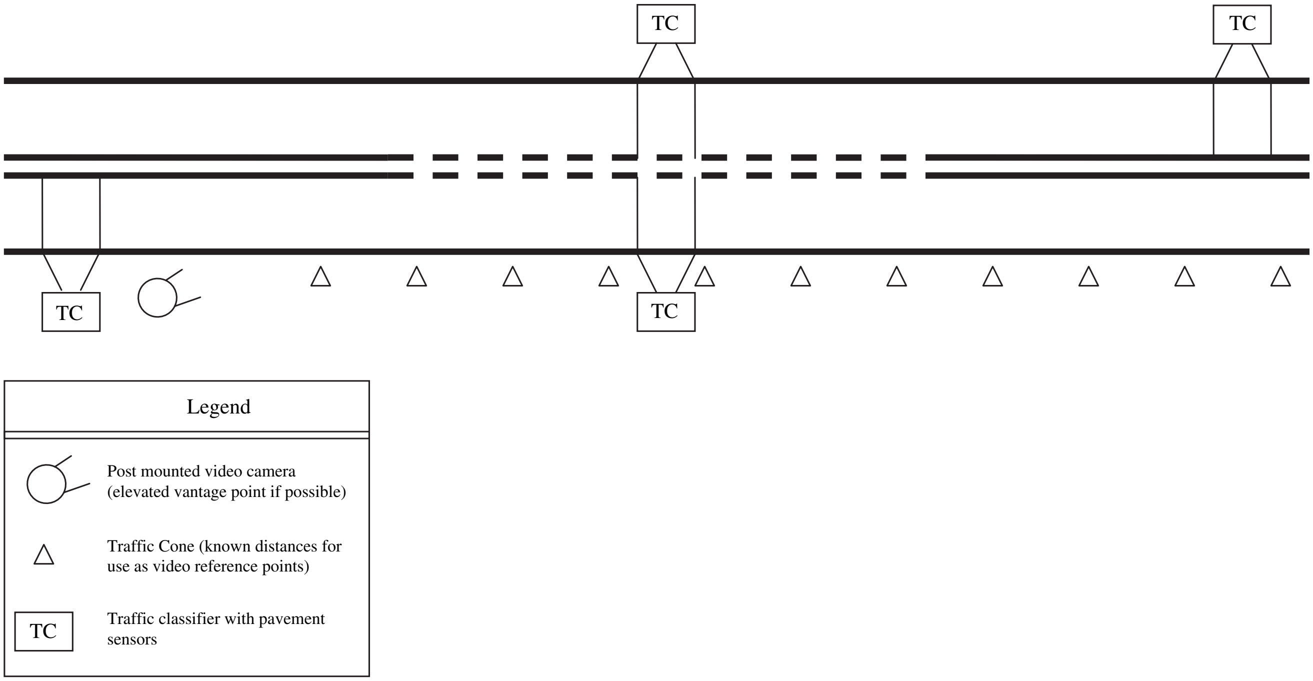

Figure 19. Typical layout for data collection site.

view of the camera was established to include as much of the passing zone(s) of interest as possible. Next, traffic cones were placed along the roadside within the camera field of view at 60 m (200 ft) intervals. Video was recorded with the traffic cones in view for use in determining the distances of vehicles from the camera in subsequent data reduction. After initial recording of the video including the cone locations, the cones were removed from the roadside during most of the study, to avoid attracting the attention of drivers traveling through the study site. Finally, the traffic classifiers were placed at the locations illustrated in Figure 19, all of the equipment was activated, and the study began.

Field Study Sites and Data Collection Activities

Field data were collected at seven sites in Missouri and eight sites in Pennsylvania. The site locations are identified in Table 22. Some sites had passing zones in only one direction of travel, while other sites had passing zones in both direc-

Figure 20. Mast-mounted video camera system used in field data collection.

Figure 21. Passing maneuver in progress as seen in video data.

Table 22. Locations and passing zone lengths for field data collection sites.

Site number	Route	County	Location	Length of passing zone(s)
MO01	US 50	Morgan	Pettis Co Line to Rte A, E of Sedalia	EB—3300 ft; WB—4100 ft
MO02	US 50	Morgan	Approx 8 mi E of Sedalia	EB—5300 ft; WB—5200 ft
MO03	US 63	Osage	4 mi S of Rte T, N of Freeburg	NB—700 ft
MO04	US 63	Maries	1 mi S of County Rd 210, S of Freeburg	NB—1600 ft; SB—2300 ft
MO05	US 63	Maries	5 mi S of Osage Co Line, S of Freeburg	NB—1000 ft; SB—1200 ft
MO06	US 63	Osage	N of Rte E, S of Westphalia	SB—500 ft
MO07	US 63	Osage	S of Rte T, S of Westphalia	NB—600 ft; SB—800 ft
PA01	ALT US 220	Centre	0.25 mi N of US 322, W of State College	NB—3100 ft; SB—3000 ft
PA02	SR 64	Centre	S of SR 26, E of State College	NB—2800 ft; SB—2400 ft
PA03	SR 255	Clearfield	1 mi S of SR 153, N of DuBois	NB—2400 ft; SB—3400 ft
PA04	US 119	Indiana	S of SR 436, S of Punxsutawney	NB—800 ft; SB—800 ft
PA05	US 422	Indiana	2 mi E of SR 403, E of Indiana	EB—800 ft; WB—700 ft
PA06	SR 45	Centre	near Indiam St, E of State College	NB—1700 ft; SB—1300 ft
PA07	SR 45	Centre	1 mi N of SR 144, E of State College	NB—1000 ft; SB—600 ft
PA08	SR 64	Centre	1 mi N of Zion, E of State College	NB—4400 ft; SB—5400 ft

tions of travel. The seven Missouri sites included 12 passing zones; the eight Pennsylvania sites included 16 passing zones. Thus, for the study as a whole, there were 15 sites and 28 passing zones.

Both long passing zones, with passing zone lengths of 300 m (1,000 ft) or more, and short passing zones, with lengths of 120 to 240 m (400 to 800 ft) or more were studied. A total of 19 long passing zones and nine short passing zones were studied.

Field data at the Missouri sites were collected in August and September 2005 and again in November 2005. Field data were collected at the Pennsylvania sites in September and October 2005. Table 23 summarizes the data collection activity at each passing zone. As shown in the table, a total of 187.25 hours of passing-zone operational data were collected. The data collection included 112.75 hours (60 percent) at Missouri sites and 74.50 hours (40 percent) at Pennsylvania sites. A total of 102.50 hours (55 percent) of data were collected at long passing zones and 84.75 hours (45 percent) at short passing zones.

Table 23 also summarizes the traffic flow rates and speeds during the field study period at each passing zone. All of the studies were conducted under daytime, off-peak conditions. The traffic flow rates at the study sites for 15-min periods ranged from 36 to 476 veh/h, with most flow rates in the range from 100 to 250 veh/h. Sites in this range of flow rates were chosen because the objective of the study was to observe passing maneuvers. At sites with higher flow rates, passing demand might have been higher, but passing opportunities would have been limited by higher opposing traffic volumes.

All of the Missouri sites had speed limits of 97 km/h (60 mph). The mean speeds at the Missouri sites ranged from 92 to 103 km/h (57 to 64 mph) and the 85th percentile speeds ranged from 95 to 114 km/h (59 to 71 mph). The Pennsylvania sites had speed limits of 89 km/h (55 mph). The mean speeds at the Pennsylvania sites ranged from 85 to 93 km/h (53 to 58 mph) and the 85th percentile speeds ranged from 95 to 105 km/h (59 to 65 mph).

In addition to the collection of traffic classifier and video data, site characteristics data were recorded, including the locations of passing and no-passing zone pavement markings with respect to the camera, traffic cone, and traffic classifier locations. PSD for each site was measured from construction plans for the Missouri sites and was measured in the field for the Pennsylvania sites.

Field Data Reduction and Analysis

The video data collected using the UMC POST system were reduced using AutoScope technology. The cones placed on the roadside at measured locations at the beginning of the study were used to calibrate the AutoScope images so that the distances of vehicles from the camera could be measured for specific traffic events. The locations for which data were taken for individual passing maneuvers were keyed to traffic events as follows:

- Point A: Before the passing maneuver begins (4 sec before the passing vehicle first encroaches on the left lane).
- Point B: Location where the passing vehicle first encroaches on the left lane.

Table 23. Summary of field data collection by passing zone.

Site number	Direction of travel	Passing zone length: Measured length (mi)	Passing zone length: Length category[a]	Data collection period (hours)	15-min flow rate (veh/h): Mean	15-min flow rate (veh/h): Range	Speed (mph): Mean	Speed (mph): Standard deviation	Speed (mph): 85th percentile
MO01	EB	3,300	Long	4.75	189	140 to 292	57.0	9.8	65
MO01	WB	4,100	Long	4.75	202	160 to 256	60.6	5.6	65
MO02	EB	5,300	Long	11.00	138	92 to 232	63.5	4.7	68
MO02	WB	5,200	Long	11.00	126	64 to 196	62.5	6.2	66
MO03	NB	700	Short	16.00	143	76 to 240	60.0	7.0	65
MO04	NB	1,600	Long	5.75	129	92 to 188	60.0	6.6	65
MO04	SB	2,300	Long	5.75	132	92 to 228	61.2	5.9	65
MO05	NB	1,000	Long	5.25	115	44 to 180	64.2	12.1	71
MO05	SB	1,200	Long	5.25	143	84 to 216	54.6	5.0	59
MO06	SB	500	Short	5.75	149	92 to 232	56.9	5.9	62
MO07	NB	600	Short	18.75	190	36 to 332	57.1	7.1	63
MO07	SB	800	Short	18.75	232	104 to 476	58.1	6.7	64
PA01	NB	3,100	Long	5.00	157	104 to 232	54.8	7.1	61
PA01	SB	3,000	Long	5.00	133	80 to 180	58.0	6.5	62
PA02	NB	2,800	Long	4.75	187	68 to 348	53.2	10.1	61
PA02	SB	2,400	Long	4.75	139	88 to 180	58.1	8.7	65
PA03	NB	2,400	Long	5.25	214	120 to 288	53.1	8.5	59
PA03	SB	3,400	Long	5.25	167	96 to 236	54.3	6.0	60
PA04	NB	800	Short	5.25	166	116 to 200	56.0	6.6	62
PA04	SB	800	Short	5.25	173	136 to 260	54.1	5.5	62
PA05	EB	800	Short	5.00	197	84 to 276	53.7	5.8	59
PA05	WB	700	Short	5.00	211	140 to 312	55.9	6.4	62
PA06	NB	1,700	Long	4.75	214	120 to 324	54.5	6.5	60
PA06	SB	1,300	Long	4.75	172	128 to 268	54.6	8.5	61
PA07	NB	1,000	Long	5.25	260	124 to 340	53.8	6.7	59
PA07	SB	600	Short	5.25	208	124 to 360	54.9	7.7	61
PA08	NB	4,400	Long	4.25	179	152 to 288	55.2	8.0	61
PA08	SB	5,400	Long	4.25					
MO long passing zones				53.50	142	64 to 292	60.6	7.7	67
MO short passing zones				59.25	186	36 to 476	58.1	7.0	64
All MO sites				112.75	165	36 to 476	59.2	7.4	65
PA long passing zones				49.00	176	68 to 348	54.7	7.9	61
PA short passing zones				25.50	191	84 to 360	54.9	6.5	60
All PA sites				74.50	181	68 to 360	54.8	7.5	61
All long passing zones				102.50	159	64 to 348	57.4	8.3	64
All short passing zones				84.75	188	36 to 476	56.9	7.0	63
All sites				187.25	172	36 to 476	57.2	7.7	64

- Point C: Location where the passing and passed vehicles are approximately abreast.
- Point D—Location when the passing vehicle fully returns to its normal lane.

Distances to the vehicles at each point were estimated from the calibrated video; vehicle speeds were determined by measuring the distance to the vehicle 1 sec before and 1 sec after the vehicle reached each point. Video data were used to determine the speed and distance from the camera of both the passing and passed vehicles at Points A through D for individual passing maneuvers. The speed and distance to any opposing vehicle in view also were recorded at Point D.

Video data were reduced to determine the speed and distances of the involved vehicles for as many of the observed passing maneuvers as possible. Data were generally reduced for all passing maneuvers that were completely within the camera field of view and for some passing maneuvers that were partially within the camera field of view. In some cases, the camera position did not permit data to be taken for Point A. In other locations, including the long passing zone sites in Pennsylvania, the distance data from the video were found to be inaccurate because of curvilinear road alignments and were not used. Even where distances could not be measured, the frequency and type of passing maneuvers could be observed in the video and the consequences of passing maneuvers that extended beyond the marked passing zone could be evaluated.

A basic study of traffic performance measures, speeds, times, and distances for passing maneuvers was conducted with the reduced video data for 60 passing maneuvers at long passing zones sites [such as, passing zones with lengths of 300 m (1,000 ft) or more] in Missouri. Studies of driver behavior at long and short passing zones were conducted with the following sample of passing maneuvers:

- 153 passing maneuvers in long passing zones in Missouri;
- 149 passing maneuvers in long passing zones in Pennsylvania;
- 45 passing maneuvers in short passing zones in Missouri; and
- 20 passing maneuvers in short passing zones in Pennsylvania.

Short passing zones are between 120 and 240 m (400 to 800 ft) in length and long passing zones are 300 m (1,000 ft) or more in length.

Seven aborted passing maneuvers were observed and the video data for these maneuvers was used in an investigation of deceleration rates in aborted passes.

Texas Study

A closely related study of passing maneuvers (*28*) was completed in Texas while the current study was underway. However, the Texas data were collected in a distinctly different manner than the data collected in the current study. The field data in the current study include passing maneuvers that occurred in the course of normal traffic operations and were observed from a roadside camera. The Texas study was performed with an impeding vehicle (such as, passed vehicle) operated by the researchers at speeds of 88, 97, and 105 km/h (55, 60, and 65 mph) on a two-lane highway with a 113-km/h (70-mph) speed limit. The observed passing maneuvers involved vehicles whose drivers decided to pass the research vehicle because of its slower speed. The passing maneuvers were observed with cameras mounted on the passed vehicle and distances and speeds were measured from the resulting video.

A total of 105 passing maneuvers were observed in the Texas study. The Texas data were obtained and were analyzed together with the data from the current study.

Traffic Performance Measures for Passing Maneuvers

Traffic performance measures for passing maneuvers were quantified from the long passing zone data collected in the current research and the Texas data described above. Despite the differences in data collection methods between the two studies, the resulting traffic performance measures are very similar. Table 24 compares the results from the current study and the Texas study. The table shows that the mean left-lane travel distances for passing vehicles for the current study and the Texas study are, respectively, 282 and 313 m (926 and 1,026 ft); the mean left-lane travel times are 10.0 and 9.8 sec; and the mean speed differentials between the passing and passed vehicles are 24.8 and 19.8 km/h (15.4 and 12.3 mph). Such differences, as there are between the two studies, generally reflect the differences in study approach in that the data from the current study represent the full range of all observed passing maneuvers at specific sites, while the Texas data reflect passing maneuvers over a narrower range of conditions; all passed vehicle speeds were between approximately 88 and 105 km/h (55 and 65 mph) and the speeds for the Texas study were generally higher than the speeds observed in the current study. This more limited range of conditions generally explains the lower standard deviation of the Texas data.

Each of the parameters shown in the table, and other parameters of interest to the study, are discussed below.

Passing Vehicle Speed at Abreast Position

Table 24 shows that the average passing vehicle speed at the abreast position is 106.4 km/h (66.1 mph) for the current study and 114.2 km/h (71.0 mph) for the Texas study. The higher passing vehicle speed for the Texas study is expected because the Missouri data for the current study were collected on highways with 97-km/h (60-mph) speed limits, while

Table 24. Comparison of traffic performance measures from field data for the current study and the Texas study.

Study	No. of passing maneuvers	Mean	Standard deviation	Minimum value	Maximum value
Passing Vehicle Speed at Abreast Position (mph)					
Current study	60	66.1	9.9	47.1	98.3
Texas study	105	71.0	3.8	62.3	81.6
Combined	165	69.2	7.1	47.1	98.3
Passed Vehicle Speed at Abreast Position (mph)					
Current study	60	50.7	8.6	32.6	70.0
Texas study	105	58.7	3.0	54.0	64.1
Combined	165	55.8	6.9	32.6	70.0
Speed Differential Between Passing and Passed Vehicle (mph)					
Current study	60	15.4	7.0	0.7	33.1
Texas study	105	12.3	3.2	5.1	20.0
Combined	165	13.4	5.1	0.7	33.1
Travel Time in Left Lane for Passing Vehicle (sec)					
Current study	60	10.0	2.8	5.0	19.0
Texas study	105	9.8	2.1	5.6	17.3
Combined	165	9.9	2.4	5.0	19.0
Travel Distance in Left Lane for Passing Vehicle (ft)					
Current study	60	926.2	246.9	402.8	1609.9
Texas Study	105	1,025.9	203.9	640.1	1748.0
Combined	165	989.7	225.0	402.8	1748.0

the Texas data were collected on highways with 113-km/h (70-mph) speed limits.

The mean passing vehicle speed for the current study of 106.4 km/h (66.1 mph) is very close to the 85th percentile speed of 108 km/h (67 mph) for the same sites. Since most highways are designed for speeds equal to or greater than the 85th percentile speed, this suggests that the AASHTO design assumption of passing vehicle speeds up to 19 km/h (12 mph) below the design speed is unrealistic. It should be recognized, however, that the assumed speed of the passing vehicle in the AASHTO design criteria represents the average passing vehicle speed over the entire maneuver while the observed passing vehicle speed from the field studies represents the instantaneous speed at the abreast position, which may be the highest speed during the maneuver.

Passed Vehicle Speed at Abreast Position

Table 24 shows that the average passed vehicle speed at the abreast position is 81.6 km/h (50.7 mph) for the current study and 89.8 km/h (55.8 mph) for the Texas study. As noted above for passing vehicle speed, the higher speed of passed vehicles in the Texas study is consistent with the higher speed limits on the Texas sites.

Speed Differential Between Passing and Passed Vehicle

Table 24 shows that the average speed differential between the passing and passed vehicles is 24.8 km/h (15.4 mph) for the current study and 19.8 km/h (12.3 mph) for the Texas study. The observed speed differentials are larger than the 16 km/h (10 mph) speed differential assumed in the AASHTO design criteria and larger than the 13 km/h (8 mph) at high speeds assumed by Glennon (*14*) and Hassan et al. (*18*). By contrast, the speed differentials between the passing and passed vehicles observed in the field are substantially less than the speed differentials of 32 and 40 km/h (20 and 25 mph) for passing vehicle speeds of 97 and 113 km/h (60 and 70 mph) assumed in the 1940 AASHO passing sight distance warrants on which the MUTCD criteria are based.

Both Glennon (*14*) and Hassan et al. (*18*) have assumed that the speed differential between the passing and passed vehicle decreases as the speed of the highway increases. This hypothesis was investigated by using the combined field data from the current study and the Texas study to develop a regression relationship between speed differential and passed vehicle speed. The resulting relationship is:

$$m = 27.4 - 0.250\ V_i \qquad (57)$$

where

m = speed differential between passing and passed vehicle (mph); and

V_i = speed of passed vehicle at the position abreast of the passing vehicle (mph).

This regression relationship is statistically significant at the 95-percent confidence level and has an R^2 value of 0.12, which means that the relationship explains 12 percent of the variation in the observed values of speed differential.

By contrast, an investigation of the relationship between speed differential and passing vehicle speed indicates that speed differential *increases* with passing vehicle speed. The regression relationship for the combined data from the current study and the Texas study is:

$$m = -6.79 + 0.292\ V_p \tag{58}$$

where

V_p = speed of passing vehicle at the position abreast of the passed vehicle (mph).

This regression relationship is statistically significant at the 95-percent confidence level and has an R^2 value of 0.16, which indicates that the relationship explains 16 percent of the variation in the observed values of speed differential.

The regression relationships in Equations (57) and (58) explain only a limited percentage of the variation in the observed values of speed differential. The Glennon and Hassan et al. studies both recommended that the AASHTO assumption of a constant speed differential, independent of speed, be replaced with an assumption that speed differentials decrease as speed increases. The field data from this study do not show a consistent relationship of this sort. Therefore, it is recommended that speed differential between the passing and passed vehicles that does not vary with speed be retained. The data also suggests that the speed differential in current traffic should be larger than the 16-km/h (10-mph) value assumed by AASHTO.

Travel Time in Left Lane for Passing Vehicle

Table 24 shows that the mean observed travel time spent in the left lane for a passing vehicle (t_2) is 10.0 sec for the current study and 9.8 sec for the Texas study. The combined mean for the data from both studies is 9.9 sec.

AASHTO assumes that the travel time (t_2) for the passing vehicle in the left lane increases with increasing passing vehicle speed. However, the effect of passing vehicle speed on t_2 is not very large, as t_2 ranges from 9.3 sec at an average passing vehicle speed of 56.2 km/h (34.9 mph) to 11.3 sec at an average passing vehicle speed of 99.8 km/h (62.0 mph), as shown in Table 1.

Analysis of the combined field data for the current study and the Texas study found a very weak regression relationship between t_2 and passing vehicle speed (V_p):

$$t_2 = 13.5 - 0.052\ V_p \tag{59}$$

This regression relationship is statistically significant at the 95-percent confidence level, but has a very low R^2 value of 0.02, indicating the passed vehicle speed explains only 2 percent of the variation in time t_2. The coefficient of V_p in Equation (2) indicates a smaller change in t_2 than is assumed by AASHTO and that change is in the opposite direction to that assumed by AASHTO. The authors believe that Equation (59) is too weak to be relied upon.

The field data from this study do not provide any evidence to support the hypothesis that the left-lane travel time (t_2) increases with increasing passed vehicle speed. Therefore, it is recommended that a constant value of t_2, independent of speed, should be used with that value chosen on the basis of the field data:

	15th percentile	Mean	85 percentile
t_2 (sec)	7.5	9.9	12.3

The mean value of 9.9 sec for t_2 is within the 9.3 to 11.3 sec range used in the current AASHTO model. However, a more conservative choice for t_2 based on the field data would be the 85th percentile value of 12.3 sec. The choice of an 85th percentile value for t_2 includes a substantially larger set of drivers than use of the mean.

Travel Distance in Left Lane for Passing Vehicle

Table 24 shows that the average observed travel distance in the left lane for a passing vehicle is 282 m (926 ft) for the current study and 313 m (1,025 ft) for the Texas study. The longer left-lane travel distance for the Texas study is expected because the Missouri data for the current study were collected on 97-km/h (60-mph) highways and the Texas data were collected on 113-km/h (70-mph) highways.

Table 25 compares the field data for the current study and the Texas study to the AASHTO design values for the distance traveled by the passing vehicle in the left lane. For both studies, the observed travel distances in the left-lane are approximately 60 m (200 ft) less than the d_2 distance assumed by AASHTO for the observed average passing vehicle speed. This shorter passing distance is consistent with the speed differentials reported above which are higher than those assumed by AASHTO. Both the shorter passing distances and higher

Table 25. Comparison of observed field values for the distance traveled by the passing vehicle in the left lane (d_2) and AASHTO design values.

	Mean observed speed (mph)		d_2 value (ft)		
Study	Passing vehicle	Passed vehicle	Observed	AASHTO	Difference
Current study	66.1	50.7	927	1,122	195
Texas study	71.0	58.7	1,026	1,220	194

speed differentials can be explained by today's vehicles that are more powerful than those in the 1930s and 1950s when the studies on which the AASHTO criteria are based were performed.

The following regression models show the relationship of left-lane travel distance to passing and passed vehicle speed:

$$d_2 = 607.9 - 5.52\ V_p \qquad (60)$$

$$d_2 = 480.2 - 9.09\ V_i \qquad (61)$$

where

d_2 = distance traveled by the passing vehicle in the left-lane (ft); and

V_p = speed of passing vehicle at the position abreast of the passed vehicle (mph).

While statistically significant at the 95-percent confidence level, the regression relationships have R^2 values of only 0.03 and 0.07, respectively.

Since the regression relationships shown in Equations (60) and (61) are weak, it appears more appropriate to derive values of d_2 from the observed values of t_2 using Equation (3), which is part of the current AASHTO model. Table 25 shows the values of d_2 derived with Equation (3) from the 15th percentile, mean, and 85th percentile values of t_2.

Comparison of mean values from Tables 23 and 25 demonstrates the appropriateness of Table 26. Table 24 shows a mean observed d_2 value of 282 m (926 ft) from the current study for a mean passing vehicle speed (V_p) of 106.4 km/h (66.1 mph). Interpolation in Table 26 indicates a corresponding mean value of d_2 equal to 293 m (960 ft) for the same speed, a difference of less than 4 percent. Similarly, for the Texas study, the mean observed d_2 value is 313 m (1,026 ft) for a mean passing vehicle speed (V_p) of 114.2 km/h (71.0 mph). Interpolation in Table 25 indicates a corresponding value of d_2 equal to 315 m (1,031 ft) for the same speed, a difference of less than 0.5 percent.

The mean left-lane travel distance (d_2) used in passing maneuvers observed in today's traffic, as shown in Table 24, is clearly less than the value used in AASHTO design criteria. However, a case can be made for a more conservative choice than the mean value of d_2. The 85th percentile values of d_2 are about equivalent to those of the current AASHTO design values. The choice of the appropriate percentiles of t_2 and d_2 from Table 26 is addressed in Chapter 5.

Location of the Abreast Position

The field data from the current study was used to determine the location within the passing maneuver of the position where the passing and passed vehicles are abreast. As noted above, the passing vehicle was found, on average, to occupy the left lane for 282 m (926 ft). The average distance traveled by the passing vehicle from the initiation of the passing maneuver to the abreast position is 116 m (380 ft). Thus, the passing vehicle reaches the abreast position 41 percent of the way through the passing maneuver.

Hassan et al. (*18*) noted that in the Glennon model the critical position, from which the sight distances to either complete or abort the pass are equal, can occur with the passing vehicle forward of the passed vehicle. Hassan et al. proposed that PSD requirements should be based on either the abreast potion or the critical position, whichever is reached first in the passing maneuver. Computations with the Glennon and Hassan et al. models indicate that the passing vehicle generally reaches the abreast position prior to reaching the critical position. The field data indicate that the abreast position is reached, on the average, where the passing vehicle has traversed approximately 40 percent of the total left-lane passing distance. Thus, at the abreast position, the passing vehicle, on the average, has 60 percent of the passing maneuver left to complete.

Table 26. Values of d_2 derived from 15th percentile, mean, and 85th percentile values of t_2.

Speed (mph)	t_2 (sec) 15th percentile	Mean	85th percentile	d_2 (ft) 15th percentile	Mean	85th percentile
20	7.5	9.9	12.3	220	290	361
25	7.5	9.9	12.3	275	363	451
30	7.5	9.9	12.3	330	436	541
35	7.5	9.9	12.3	385	508	631
40	7.5	9.9	12.3	440	581	722
45	75	9.9	12.3	495	653	812
50	7.5	9.9	12.3	550	726	902
55	7.5	9.9	12.3	605	799	992
60	7.5	9.9	12.3	660	871	1,082
65	7.5	9.9	12.3	715	944	1,173
70	7.5	9.9	12.3	770	1,016	1,263
75	7.5	9.9	12.3	825	1,089	1,353
80	7.5	9.9	12.3	880	1,162	1,443

Clearance Interval Between Passing and Opposing Vehicle

Of the 60 completed passing maneuvers examined in detail in the current study, seven passing maneuvers (or 12 percent) were completed with opposing vehicles within the video field of view and close enough to the camera for their position and speed to be determined. The clearance distances between the passing and opposing vehicles ranged from 16 to 321 m (52 to 1,055 ft) for these seven maneuvers, and the clearance times ranged from 0.3 to 5.8 sec. One passing maneuver with a clearance distance of 16 m (52 ft) and clearance time of 0.3 sec was the only observed maneuver with a clearance time less than the generally accepted margin of 1 sec.

Aborted Passing Maneuvers

A total of seven aborted passing maneuvers were observed among the 367 total passing maneuvers studied. Thus, approximately 1.9 percent of the passing maneuvers started by drivers were aborted. This finding indicates clearly that drivers do routinely exercise judgment in deciding whether to continue or discontinue a passing maneuver.

In the aborted passing maneuvers, the average time for occupancy of the left lane was 7.1 sec, and ranged from 4.1 to 9.5 sec. If one assumes that the times from pass initiation to abort initiation and from abort initiation to return to the normal lane are equal, then on average drivers proceeded 3.6 sec into the maneuver before beginning to abort the pass. The average completed passing maneuver required the passing vehicle to remain in the left lane for 10 sec, so the pass abort began, on average, when the driver had completed 36 percent of the maneuver. Since the abreast position is normally reached after 40 percent of the maneuver is completed, this indicates that drivers initiated the pass abort before reaching the abreast position, which is what would be expected.

Data for four of the seven aborted passing maneuvers were sufficient to compute the deceleration rates used in the passing maneuvers. The highest instantaneous deceleration rates in these maneuvers ranged from 0.17 m/sec^2 (0.57 ft/sec^2 or 0.02 g) to 5.27 m/sec^2 (17.3 ft/sec^2 or 0.54 g). These data show that a driver can use a broad range of deceleration rates in aborting passing maneuvers. However, the data based on only four aborted passing maneuvers are too limited to serve as a basis for selecting a specific deceleration rate for use in PSD models.

Passing Behavior in Short Passing Zones

This section of the report reviews the passing behavior of drivers in short passing zones with lengths between 120 and 240 m (400 and 800 ft). The objective of this review is to determine whether drivers use short passing zones safely and to determine how much short passing zones contribute to the operational efficiency of a two-lane highway.

Passing Frequency in Short Passing Zones

Table 27 presents a summary of passing frequency in short passing zones with lengths ranging from 120 to 240 m (400 to 800 ft). Passing behavior was observed in short passing zones for 84.75 hours, 59.25 hours at four sites in Missouri and 25.50 hours at five sites in Pennsylvania. The table shows that the volumes and passing behavior at Missouri and Pennsylvania sites were quite similar, so the following discussion is based on the combined data for both states.

During the study period, a total of 15,920 vehicles traveled through the short passing zones in a direction of travel where pavement markings indicate that passing maneuvers are legally permitted. Of these 15,920 vehicles, 4,136 vehicles (or 26 percent) were traveling at headways of 3 sec or less. The HCM (*32*) indicates that the percentage of headways of 3 sec or less at a point on the road can be used to estimate the service measure for a two-lane highway, percent time spent following, which is indicative of passing demand. This does not necessarily mean that 26 percent of the drivers on these roads would actually decide to initiate a passing maneuver if they could, but it is likely that some substantial percentage of them would. Of course, a driver that wants to pass may not be able to pass because of the presence of opposing traffic.

A total of 65 completed passing maneuvers were observed at the short passing zones during the study period or 0.77 passing maneuvers per hour of data. These 65 passing maneuvers represent 0.4 percent of all vehicles and 1.6 percent of vehicles with headways of 3 sec or less in the direction of travel studied. Thus, the frequency of observed passing maneuvers is very low as a proportion of the total traffic stream and as a proportion of vehicles with short headways whose drivers may have an interest in passing.

For comparative purposes, Table 28 shows comparable data for passing zones that exceed 300 m (1,000 ft) in length. The length of the long passing zones ranges from 300 to 1,650 m (1,000 to 5,400 ft). Passing behavior in long passing zones was observed for 102.50 hours, 53.50 hours at eight sites in Missouri and 49.00 hours at ten sites in Pennsylvania. As in the case of the short passing zones, the data for long passing zones show that the traffic volumes and passing frequencies at the Missouri and Pennsylvania sites are quite comparable.

A total of 16,252 vehicles traveled through the long passing zones in a direction of travel where pavement markings indicate that passing is legally permitted. Of these 16,252 vehicles, 3,848 vehicles (or 24 percent) were traveling at headways of 3 sec or less.

Table 27. Summary of passing frequency in short passing zones.

Site number	Direction of travel	Length of passing zone (ft)	Duration of study period (hours)[a]	No. of vehicles observed in study direction	Mean flow rate (veh/h)		Range of flow rates in study direction[b] (veh/h)	Vehicles with short headways in study direction[b]		Observed passing maneuvers in study direction		
					Study direction	Opposing direction		Number	Percent of all vehicles	Number	Percent of all vehicles	Percent of vehicles with short headways[b]
MO03	NB	700	16.00	2,283	143	162	76-240	525	23.0	11	0.5	2.1
MO06	SB	500	5.75	858	149	112	92-232	166	19.3	2	0.2	1.2
MO07	NB	600	18.75	3,568	190	232	36-332	1,333	37.4	15	0.4	1.1
MO07	SB	800	18.75	4,346	232	190	104-476	940	21.6	17	0.4	1.8
PA04	NB	800	5.25	874	166	173	116-200	205	23.5	7	0.8	3.4
PA04	SB	800	5.25	909	173	170	136-260	225	24.7	8	0.9	3.6
PA05	WB	800	4.75	937	197	211	84-276	271	28.9	3	0.3	1.1
PA05	EB	700	5.00	1,053	211	197	140-312	197	18.7	0	0.0	0.0
PA07	SB	600	5.25	1,092	208	260	124-360	274	25.1	2	0.2	0.7
MO	Combined	–	59.25	11,055	186	188	36-476	2,964	26.9	45	0.4	1.5
PA	Combined	–	25.50	4,865	191	202	84-360	1,172	24.1	20	0.4	1.7
All	Combined	–	84.75	15,920	188	192	36-476	4,136	26.0	65	0.4	1.6

[a] Includes only complete 15-min periods.
[b] Vehicles with headways less than or equal to 3 sec.

Table 28. Summary of passing frequency in long passing zones.

Site number	Direction of travel	Length of passing zone (ft)	Duration of study period (hours)[a]	No. of vehicles observed in study direction	Mean flow rate (veh/h)		Range of flow rates in study direction[b] (veh/h)	Vehicles with short headways in study direction[b]		Observed passing maneuvers in study direction		
					Study direction	Opposing direction		Number	Percent of all vehicles	Number	Percent of all vehicles	Percent of vehicles with short headways[b]
MO01	EB	3,300	4.75	897	189	202	140-292	226	25.2	17	1.9	7.5
MO01	WB	4,100	4.75	958	202	189	160-256	277	28.9	18	1.9	6.5
MO02	EB	5,300	11.00	1,519	138	126	92-232	349	23.0	53	3.5	15.2
MO02	WB	5,200	11.00	1,385	126	138	64-196	257	18.6	28	2.0	10.9
MO04	NB	1,600	5.75	741	129	132	92-188	171	23.0	10	1.3	5.8
MO04	SB	2,300	5.75	760	132	129	92-228	202	26.6	10	1.3	5.0
MO05	NB	1,000	5.25	603	115	143	44-180	126	20.9	10	1.7	7.9
MO05	SB	1,200	5.25	752	143	115	84-216	209	27.8	7	0.9	3.3
PA01	NB	3,100	5.00	783	157	133	104-232	145	18.5	6	0.8	4.1
PA01	SB	3,000	5.00	664	133	157	80-180	101	15.2	11	1.7	10.9
PA02	NB	2,800	4.75	890	187	139	68-348	245	27.5	3	0.3	1.2
PA02	SB	2,400	4.75	660	139	187	88-180	145	22.0	38	5.8	26.2
PA03	NB	2,400	5.25	1,124	214	167	120-288	329	29.3	25	2.2	7.6
PA03	SB	3,400	5.25	879	167	214	96-236	198	22.5	20	2.2	10.1
PA06	NB	1,700	4.75	1,018	214	172	120-324	213	20.9	3	0.3	1.4
PA06	SB	1,300	4.75	819	172	214	128-268	227	27.7	16	2.0	7.0
PA07	NB	1,000	5.25	1,039	260	208	124-340	251	24.2	8	0.8	3.2
PA08	SB	5,400	4.25	761	179	184	152-288	177	23.3	19	2.5	10.7
MO	Combined	–	53.50	7,615	142	142	64-292	1,817	23.9	153	2.0	8.4
PA	Combined	–	49.00	8,637	176	178	68-348	2,031	23.5	149	1.7	7.3
All	Combined	–	102.50	16,252	159	159	64-348	3,848	23.7	302	1.9	7.8

[a] Includes only complete 15-min periods.
[b] Vehicles with headways less than or equal to 3 sec.

A total of 302 passing maneuvers were observed at the long passing zones during the study period or 2.95 passing maneuvers per hour of data. These 302 passing maneuvers represented 1.9 percent of all vehicles and 7.8 percent of vehicles with headways of 3 sec or less in the direction of travel studied. The frequency of passing in the long passing zones is substantially higher than in the short passing zones.

Table 29 compares the passing frequencies for short and long passing zones. It is evident that, as a proportion of the traffic stream as a whole and a proportion of vehicles with short headways, about four times as many passing maneuvers occur in long passing zones as in short passing zones.

Table 29 also shows a comparison in passing frequency between the four longest short passing zones [all 240 m (800 ft) in length] and the four shortest long passing zones [all were 300 to 400 m (1,000 to 1,300 ft) in length]. The table shows that 300- to 400-m (1,000- to 1,300-ft) passing zones contribute about 2.5 times as many passing maneuvers to the roadway as 240 m (800 ft) passing maneuvers.

The small difference in passing zone length of 60 to 150 m (200 to 500 ft) between 240-m (800-ft) and 300- to 400-m (1,000 to 1,300 ft) passing zones appears to make a substantial difference in the utilization of passing zones for passing maneuvers. This finding is not surprising given the indication in Table 29 that the mean distance traveled (d_2) in passing maneuvers on high-speed highways is 302 m (990 ft) and that the average distance traveled by the passing vehicle in passing maneuvers in short passing zones is 273 m (894 ft). Thus, a typical high-speed passing maneuver cannot be completed within a passing zone that is 240 m (800 ft) or less in length, but can be completed within a longer passing zone.

The data summarized in Tables 27 through 29 suggest that passing zones from 120 to 240 m (400 to 800 ft) in length do not contribute much operationally to a two-lane highway and might be removed without any substantial effect on traffic operational level of service. It is likely that passing zones from 120 to 240 m (400 to 800 ft) in length only can be used legally to pass slow-moving vehicles. (The extreme case would be passing a slow-moving farm tractor or a flying pass where the passing vehicle has a substantial speed advantage over the passed vehicle.) A case could be made for keeping short passing zones to facilitate passing of slow-moving vehicles as long as there was no detrimental effect on safety from use of the short passing zones for higher speed passing maneuvers. This issue is addressed below through an examination of how drivers actually use short passing zones.

Passing Maneuver Locations with Respect to Passing and No-Passing Zone Markings

Table 30 summarizes the locations of passing maneuvers in short passing zones with respect to the passing and no-passing zone markings. The data in Table 30 addresses 53 of the 65 passing maneuvers shown in Table 27; passing maneuvers for which the entire maneuver was not visible from the camera location had to be omitted from the table.

Table 30 shows that out of 53 observed passing maneuvers in short passing zones, only two passes (4 percent) were completed legally within the marked passing zone. A total of 17 passing maneuvers (32 percent) started before the beginning of the marked passing zone (known as jumping) and 49 passing maneuvers (92 percent) were completed beyond the end of the marked passing zone (known as clipping). A total of 15 passing maneuvers (28 percent) started in advance of the marked passing zone and were completed beyond the end of the marked passing zone (jumping and clipping in the same maneuver).

Because of the typical camera position in long passing zones, passing maneuvers that started in advance of the marked passing zones were not observed. However, the end of the marked passing zone was visible in most long passing zones and, out of 56 observed passing maneuvers, only 12 maneuvers (21 percent) extend beyond the end of the marked passing zone. Thus, in short passing zones with lengths of 240 m (800 ft) or less 92 percent of passing maneuvers extended into the marked no-passing zone, while in long passing zones with lengths of 300 m (1,000 feet) or more, only 21 percent of passing maneuvers extended into the marked no-passing zone. In the shortest long passing zones, with lengths in the range from 300 to 400 m (1,000 to 13,00 ft), the percentage of passing maneuvers extending into the marked no-passing zone had an intermediate value of 45 percent.

Table 31 shows that 88 percent of passing maneuvers in short passing zones involved a left-lane travel distance (d_2) that was longer than the length of the marked passing zone. In other words, these passing maneuvers could not have been made completely within the marked passing zone, regardless of where they began and ended. As documented above, such maneuvers are more likely to be completed beyond the end of the marked passing zone than started before the beginning of the marked passing zone.

Table 31 also shows a summary of the locations and sight distances at the completion of passes that extended into marked no-passing zones (such as, passing maneuvers that involved clipping at the end of short passing zones). The 48 passing maneuvers completed in a no-passing zone extended 6 to 250 m (20 to 830 ft) beyond the end of the marked passing zone. The sight distances at the locations where passes were completed beyond the end of a marked passing zone ranged from 120 to 480 m (410 to 1,570 ft). The Missouri sites had 96 km/h (60 mph) speed limits, while the Pennsylvania sites had 88 km/h (55 mph) speed limits, with corresponding MUTCD minimum passing sight distances of 300 and 270 m (1,000 and 900 ft), respectively. So the passing maneuvers

Table 29. Comparison of passing frequency for short and long passing zones.

Passing zone length category	Range of passing zone lengths (ft)	Duration of study period (hours)[a]	Number of vehicles observed in study direction	Vehicles with short headways in study direction[b]		Observed passing maneuvers in study direction		
				Number	Percent of all vehicles	Number	Percent of all vehicles	Percent of vehicles with short headways[b]
Short	400-800	84.25	15,920	4,136	26.0	65	0.4	1.6
Long	1,000-5,400	102.50	16,252	3,848	23.7	302	1.9	7.8
Longest short zones	800	34.00	7,066	1,641	23.2	35	0.5	2.1
Shortest long zones	1,000-1,300	20.50	3,213	813	25.3	41	1.3	5.0

[a] Includes only complete 15-min periods.
[b] Vehicles with headways less than or equal to 3 sec.

Table 30. Summary of passing maneuver beginning and end locations for short passing zones.

				Number (percentage) of passing maneuvers					
Site number	Direction of travel	Length of passing zone (ft)	Total number of observed passing maneuvers	Legal passing maneuver (all within passing zone)	Start before zone; end within zone	Start within zone; end beyond zone	Start before zone; end beyond zone	All maneuvers starting before zone	All maneuvers ending beyond zone
MO03	NB	700	11	1 (9.1)	0 (0.0)	7 (63.6)	3 (27.3)	3 (27.3)	10 (90.9)
MO06	SB	500	2	0 (0.0)	0 (0.0)	0 (0.0)	2 (100.0)	2 (100.0)	2 (100.0)
MO07	NB	600	13	0 (0.0)	0 (0.0)	9 (69.2)	4 (30.8)	4 (30.8)	13 (100.0)
MO07	SB	800	15	1 (6.7)	0 (0.0)	13 (86.7)	1 (6.7)	1 (6.7)	14 (93.3)
PA04	NB	800	5	0 (0.0)	2 (40.0)	0 (0.0)	3 60.0)	5 (100.0)	3 (60.0)
PA04	SB	800	5	0 (0.0)	0 (0.0)	4 (80.0)	1 (20.0)	1 (20.0)	5 (100.0)
PA05	NB/WB	100	0	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
PA07	SB	600	2	0 (0.0)	0 (0.0)	1 (50.0)	1 (50.0)	1 (50.0)	2 (100.0)
MO	Combined	–	41	2 (4.9)	0 (0.0)	29 (70.7)	10 (24.4)	10 (24.4)	39 (95.1)
PA	Combined	–	12	0 (0.0)	2 (16.7)	5 (41.7)	5 (41.7)	7 (10.6)	10 (83.3)
All	Combined	–	53	2 (3.8)	2 (3.8)	34 (64.2)	15 (28.3)	17 (32.1)	49 (92.4)

Table 31. Summary of location and sight distance at completion of passing maneuvers beyond the end of short passing zones.

Site number	Direction of travel	Length of passing zone (mi)	Total number of observed passing maneuvers	Number (percentage) of passing maneuvers ending beyond the passing zone	Distances beyond end of passing zone at completion of passing maneuvers (ft)	Passing sight distance from location at which passing maneuver was completed beyond the end of passing zone	Percentage of passing maneuvers with d_2 longer than passing zone[a]	Percentage of passing maneuvers with abreast position beyond end of passing zone[a]
MO03	NB	700	11	10 (90.9)	40-520	1,290-520	90.0	30.0
MO06	SB	500	2	2 (100.0)	120-530	630-410	100.0	0.0
MO07	NB	600	13	13 (100.0)	180-780	790-560	84.6	30.8
MO07	SB	800	15	14 (93.3)	110-830	790-430	92.9	7.1
PA04	NB	800	5	3 (60.0)	110-510	1,570-1,130	100.0	0.0
PA04	SB	800	5	5 (100.0)	20-660	1,320-750	60.0	20.0
PA05	WB	700	0	0 (0.0)	–	–	–	–
PA07	SB	600	1	1 (100.0)	50	1,120	100.0	0.0
MO	Combined	–	41	39 (95.1)	40-830	1,290-410	89.7	20.5
PA	Combined	–	11	9 (81.8)	20-660	1,570-750	77.8	11.1
All	Combined	–	52	48 (92.3)	20-830	1,570-410	87.5	18.8

[a] Based only on passing maneuvers that were completed beyond the end of the passing zone.

extended, in some cases, into a region with less than half the MUTCD minimum passing sight distance.

The final column of Table 31 shows that in nine of the 55 passing maneuvers (17 percent) in short passing zones, the abreast position occurred beyond the end of the passing zone in the marked no-passing zone.

Table 32 shows comparable data to Table 31 for long passing zones. The table shows that only 11 of the 52 observed passing maneuvers extended beyond the end of the marked passing zones. Most of the 11 passing maneuvers extended into the region with passing sight distance only marginally below the MUTCD minimum values. Only two of those 11 passing maneuvers extended into regions with extremely limited sight distance—160 m (510 ft). Table 32 shows that none of the passing maneuvers in long passing zones had left-lane travel distances (d_2) that exceeded the length of the marked passing maneuver and that there were only 2 out of 52 passing maneuvers (4 percent) in long passing zones in which the abreast position occurred beyond the end of the passing zone in the marked no-passing zone.

Table 32. Summary of location and sight distance at completion of passing maneuvers beyond the end of long passing zones.

Site number	Direction of travel	Length of passing zone (mi)	Total number of observed passing maneuvers	Number (percentage) of passing maneuvers ending beyond the passing zone	Distances beyond end of passing zone at completion of passing maneuvers (ft)	Passing sight distance from location at which passing maneuver was completed beyond the end of passing zone	Percentage of passing maneuvers with d_2 longer than passing zone[a]	Percentage of passing maneuvers with abreast position beyond end of passing zone[a]
MO01	EB	3,300	6	0 (0.0)	–	–	–	–
MO02	EB	5,300	16	0 (0.0)	–	–	–	–
MO02	WB	5,200	9	0 (0.0)	–	–	–	–
MO05	NB	1,000	3	3 (100.0)	70-520	880-510	0.0	33.0
MO05	SB	1,200	3	2 (66.7)	310-350	800-740	0.0	0.0
PA06	NB	1,700	2	2 (100.0)	230-700	1,370-900	0.0	0.0
PA06	SB	1,300	8	2 (25.0)	20-130	1,220-1,110	0.0	50.0
PA07	NB	1,000	5	2 (40.0)	90-660	1,750-1,540	0.0	0.0
MO	Combined	–	37	5 (13.5)	70-590	880-510	0.0	20.0
PA	Combined	–	15	6 (38.8)	20-700	1,750-900	0.0	14.3
All	Combined	–	52	11 (21.8)	20-700	1,750-510	0.0	16.6

[a] Based only on passing maneuvers that were completed beyond the end of the passing zone.

While there is concern that a substantial number of the passing maneuvers in short passing zones and a few of the passing maneuvers in long passing zones extended into areas of limited PSD, no close conflicts between passing vehicles and opposing vehicles were observed, except for one maneuver in a long passing zone with clearance distance of 16 m (52 ft) and a clearance time of 0.3 sec.

Contribution of Short Passing Zones to the Operational Efficiency of a Two-Lane Highway

The contribution of short passing zones to the operational efficiency of two-lane highways was evaluated with the TWOPAS model. TWOPAS is the state-of-the-art microscopic traffic operational simulation model for two-lane highways (*29, 30, 31*) and was used in the development of the traffic operational assessment procedures for two-lane highways in the *Highway Capacity Manual* (HCM) (*32*).

Two scenarios were evaluated with TWOPAS. Both scenarios involved a 4.8-km (3.0-mi) two-lane level, tangent road section. In Scenario 1, the road was initially marked with no-passing zones throughout and then the following alternative passing zone markings were evaluated:

- One 120-m (400-ft) passing zone in each direction of travel;
- One 150-m (500-ft) passing zone in each direction of travel;
- One 180-m (600-ft) passing zone in each direction of travel;
- One 210-m (700-ft) passing zone in each direction of travel;
- One 240-m (800-ft) passing zone in each direction of travel; and
- One 300-m (1,000-ft) passing zone in each direction of travel.

These configurations are illustrated in Figure 22. In the TWOPAS model, unlike the real world, drivers obey the passing and no-passing zone markings, so these alternative passing zone markings provide progressively more passing zone length in which to complete passing maneuvers. Passing maneuvers in marked passing zones are not limited by sight distance (since a level, tangent alignment was selected), but they are limited by opposing traffic.

Scenario 2 uses the same short passing zone configurations as shown above for Scenario 1, but also includes two 920-m (3,000-ft) passing zones in each direction of travel. Thus, the roadway for Scenario 2 provides passing opportunities in addition to short passing zones that also were included in Scenario 1.

For both scenarios, all of the passing zone alternatives were evaluated for the following traffic volumes:

- 100 veh/h in each direction of travel;
- 200 veh/h in each direction of travel;
- 300 veh/h in each direction of travel;
- 400 veh/h in each direction of travel;
- 500 veh/h in each direction of travel; and
- 600 veh/h in each direction of travel.

This covers the entire range of traffic volumes observed in the field studies and some higher volumes, as well. In all cases, the directional split of traffic was 50/50, with 5 percent trucks and no recreational vehicles. A free-flow speed of 97 km/h (60 mph) was specified for passenger cars with a free-flow speed of 93 km/h (58 mph) for trucks. For each passing-lane configuration and traffic volume evaluated, five replicate runs were made with the TWOPAS model, with each run simulating 60 min of traffic operations. Each of the five replicate runs used a different random number seed to generate the entering traffic stream; therefore, the traffic performance measures for the five runs differ slightly, as would be the case for a real-world site observed on five different days. The same sequence of five replicates was run for each passing-zone and traffic volume alternative, so an identical sequence of vehicles and drivers was evaluated for each alternative. The reported results are based on the average results from the five runs.

Table 33 presents the traffic performance measures from the TWOPAS simulation model results for Scenario 1. In Scenario 1, the only passing opportunities on the 4.8-km (3.0-mi) roadway occur in one short passing zone in each direction of travel. The length of the passing zones is varied systematically as shown in Figure 22 and Table 33. The traffic performance measures included in the table are percent time spent following, average travel speed, level of service (based on the HCM service thresholds), and passing rate (passes per hour). The results in the table show that none of the passing zone alternatives contributes much to the traffic operational performance of the two-lane highway. For short passing zones with lengths of 0 to 240 m (0 to 800 ft), percent time spent following and average travel speed show only normal (essentially random) fluctuations and the level of service is unaffected by the progressively longer passing lanes. Only for the two 300-m (1,000-ft) passing lanes is there an indication that the presence of the passing lane may reduce percent time spent following and that effect is observed only for the lowest traffic volume level (100 veh/h in each direction of travel).

The passing rates show that some passing maneuvers begin to occur when the passing zone length reaches 150 m (500 ft) and passing rates then increase slightly as the passing zone length increases. The observed passing rate for short passing zones from the field study is 0.77 passes per hour for one passing zone or 1.54 passes per hour for two passing zones. Thus, the simulation results show substantially lower passing rates than the field data, most likely because the model will not simulate illegal passes (jumping or clipping), while such maneuvers do occur in the real world.

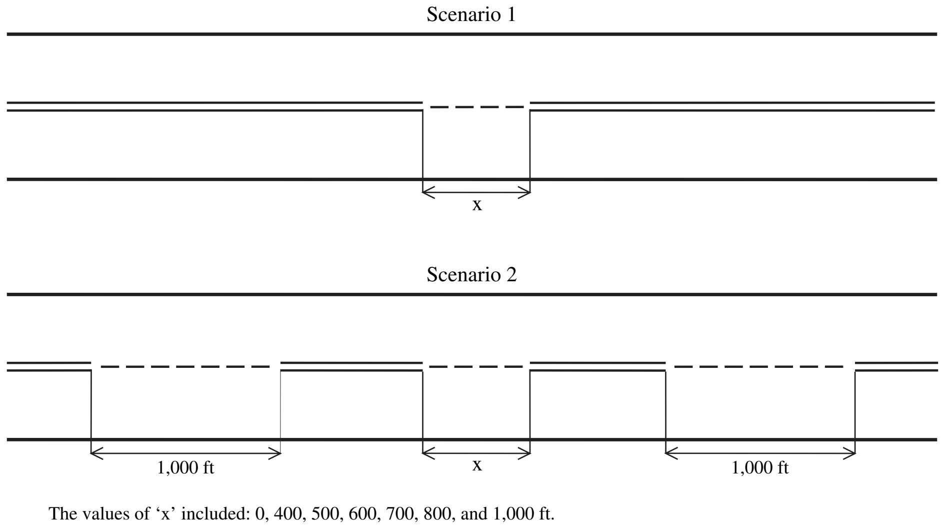

Figure 22. Passing zone alternatives considered in TWOPAS simulation study.

Table 33. Results of TWOPAS simulation study for short passing zones (Scenario 1).

Traffic volume (veh/h)		Length of passing zones in a 3-mi road section						
Dir 1	Dir 2	None	2 @ 400 ft	2 @ 500 ft	2 @ 600 ft	2 @ 700 ft	2 @ 800 ft	2 @ 1,000 ft
PERCENT TIME SPENT FOLLOWING								
100	100	40.2	42.0	39.0	39.8	42.1	40.8	37.1
200	200	48.7	48.9	48.9	48.5	47.7	49.4	48.3
300	300	54.4	53.5	55.2	54.7	53.2	56.1	54.6
400	400	60.2	60.0	60.7	61.1	60.6	59.9	59.8
500	500	66.0	66.8	65.7	66.0	66.6	65.9	66.5
600	600	71.3	72.1	71.1	71.4	71.4	70.9	71.4
AVERAGE TRAVEL SPEED (mph)								
100	100	59.1	59.3	59.8	59.6	59.3	59.4	59.9
200	200	59.0	58.8	58.9	58.8	58.9	58.9	58.8
300	300	58.6	58.5	58.3	58.4	58.6	58.2	58.4
400	400	58.1	58.0	58.0	57.9	58.0	57.9	58.1
500	500	57.6	57.5	57.7	57.6	57.5	57.7	57.6
600	600	57.2	56.9	57.2	57.1	57.0	57.2	56.9
LEVEL OF SERVICE (HCM 2000) (*32*)								
100	100	B	B	B	B	B	B	B
200	200	B	B	B	B	B	B	B
300	300	C	C	C	C	C	C	C
400	400	C	C	C	C	C	C	C
500	500	D	D	D	D	D	D	D
600	600	D	D	D	D	D	D	D
PASSING RATE (passes/hr)								
100	100	0.0	0.0	0.0	0.0	0.2	0.4	0.8
200	200	0.0	0.0	0.0	0.0	0.2	0.4	1.0
300	300	0.0	0.0	0.0	0.2	0.4	0.2	2.0
400	400	0.0	0.0	0.2	0.0	0.2	0.4	1.6
500	500	0.0	0.0	0.0	0.0	0.0	0.6	1.8
600	600	0.0	0.0	0.0	0.0	0.0	0.8	1.6

Table 34. Results of TWOPAS simulation study for short passing zones (Scenario 2).

Traffic volume (veh/h)		Length of passing zones in a 3-mi road section							
			Two 3,000-ft passing zones in each direction of travel plus:						
Dir 1	Dir 2	None	None	2 @ 400 ft	2 @ 500 ft	2 @ 600 ft	2 @ 700 ft	2 @ 800 ft	2 @ 1,000 ft
PERCENT TIME SPENT FOLLOWING									
100	100	40.2	35.3	35.1	38.7	36.2	35.2	36.6	36.0
200	200	48.7	47.6	48.7	45.4	46.0	47.1	45.0	36.0
300	300	54.4	52.4	53.5	54.4	54.3	52.0	54.0	46.4
400	400	60.2	60.0	59.1	59.5	60.5	59.6	59.1	59.1
500	500	66.0	65.4	65.4	65.4	64.8	65.5	65.5	66.2
600	600	71.3	71.1	70.6	70.5	70.8	71.0	71.1	70.6
AVERAGE TRAVEL SPEED (mph)									
100	100	59.1	60.2	60.0	59.7	59.9	60.0	59.9	59.8
200	200	59.0	59.2	59.0	59.4	59.4	59.3	59.3	59.8
300	300	58.6	58.8	58.6	58.4	58.6	58.8	58.7	59.3
400	400	58.1	58.0	58.2	58.0	58.1	58.2	58.1	58.1
500	500	57.6	57.6	57.7	57.7	57.7	57.7	57.5	57.5
600	600	57.2	57.1	57.1	57.2	57.2	57.1	56.9	57.1
LEVEL OF SERVICE (HCM 2000) (*32*)									
100	100	B	B	B	B	B	B	B	B
200	200	B	B	B	B	B	B	B	B
300	300	C	C	C	C	C	C	C	B
400	400	C	C	C	C	C	C	C	C
500	500	D	D	D	D	C	D	D	D
600	600	D	D	D	D	D	D	D	D
PASSING RATE (passes/hr)									
100	100	0.0	20.6	22.8	23.0	26.5	24.4	22.6	21.0
200	200	0.0	32.8	38.6	33.2	31.0	37.4	33.8	21.0
300	300	0.0	35.8	30.0	29.6	29.4	30.4	29.2	35.2
400	400	0.0	23.2	25.0	26.0	28.0	24.0	24.0	27.6
500	500	0.0	19.8	16.6	18.4	21.2	21.2	18.8	19.8
600	600	0.0	11.4	13.2	16.0	12.2	20.6	16.0	17.0

Table 34 shows a comparable summary of results for Scenario 2, which includes two 920-m (3,000-ft) passing zones in each direction of travel, as well as the short passing zones included in Scenario 1. The results show that there is a general reduction in percent time spent following as passing zone length increases at the traffic volume level of 100 veh/h in each direction of travel; this can be explained by the long passing zones allowing faster vehicles to pass and catch up with slower vehicles, creating more passing opportunities at the longer passing zones. However, this effect is not evident at traffic volume levels higher than 100 veh/h in each direction of travel and there is no overall indication that the presence of the short passing zones affects either average travel speed or level of service.

The passing rate data in Table 34 show that the highest passing rates occur in the traffic volume range from 200 to 300 veh/h, confirming the strategy used in selecting field sites. However, there is no indication of any consistent effect on passing rate of increasing the length of the short passing zones. It is evident that most passes on the roadway for Scenario 2 occur in the long passing zones and the presence of the short passing zones has only a minor influence on passing rates.

Overall, the results in Tables 33 and 34 confirm that short passing zones with lengths of 120 to 240 m (400 to 800 ft) do not contribute much to the traffic operational efficiency of two-lane highways.

CHAPTER 5

Assessment of Potential Revisions to Current Passing Sight Distance Criteria

This chapter reviews the current state of knowledge about a number of key PSD-related issues and assesses the need for revision of current passing sight distance criteria. This assessment is based on published literature and the field study results reported in Chapter 4.

The key issues reviewed in this section are:

- What level of safety concerns are present on two-lane highways related to passing maneuvers and/or PSD?
- Are the current AASHTO and MUTCD models appropriate?
- Are the parameter values used in the AASHTO and MUTCD models appropriate?
- Is it appropriate to continue to use different PSD models for design and marking?
- Should larger and longer vehicles such as trucks be considered in PSD criteria?
- Should older drivers be considered in PSD criteria?
- Do drivers understand passing and no-passing zone markings?
- What driver judgments are involved in passing maneuvers and how good are drivers at making those judgments?
- Is the current MUTCD minimum passing zone length appropriate?
- Should the current AASHTO and/or MUTCD models be replaced and, if so, what alternative model(s) are most appropriate?

Each of these issues is addressed below.

Safety Concerns Related to Passing Maneuvers and Passing Sight Distance

The first and most basic issue in considering the appropriateness of current PSD criteria is the safety performance of two-lane roads designed and marked under current PSD criteria. If the overall level of accident experience for passing maneuvers on two-lane highways is minimal, the case can be made that major changes in PSD criteria are not needed. However, consideration would still need to be given to the potential for safety improvement from marginal changes in PSD criteria or from related issues such as the minimum length of passing zones and to the need for a consistent rationale for PSD criteria.

In 1992, in the FHWA project, *Study Designs for Passing Sight Distance Requirements*, Hughes et al. (*33*) recommended a basic accident study focused on accidents related to passing maneuvers. Such a study was subsequently conducted with data from FHWA's Highway Safety Information System (HSIS) (*34*). This study included a key advance in thinking, in that accidents related to turning maneuvers at intersections were excluded. Typically, accidents associated with turning maneuvers at intersections that are coded by police officers as passing-related involve not passing maneuvers in the opposing lane of traffic, but through vehicles using the shoulder to go around vehicles stopped or slowing in the through lane waiting to make a turn (*35*); such accidents do not involve PSD.

Using data from three participating HSIS states, this study found that accidents related to passing maneuvers constitute a relatively small proportion—approximately 2 percent—of accidents on rural two-lane roads. Table 35 presents a summary of the distribution of collision types for passing-related accidents. Averaged over the three states, approximately 42 percent of the passing-related accidents were rear-end or same-direction sideswipe collisions, 13 percent were head-on or opposite direction sideswipe collisions, 30 percent were single-vehicle accidents (primarily run-off-road accidents), and 15 percent were of other or unknown types. Some of each of the collision types may be related to PSD.

The data in Table 35 contradict the common belief that passing-related accidents on two-lane roads are primarily head-on accidents. Furthermore, it should be recognized that

Table 35. Distribution of collision types for passing-related accidents (*34*).

Collision type	Percentage of total passing-related accidents			
	State A	State B	State C	Average
Single-vehicle run-off-road	25.5[a]	34.1	30.7	30.1
Sideswipe passing	31.9	12.1[b]	31.7[c]	25.3
Sideswipe meeting	8.2	3.1[b]	8.7[c]	6.5
Rear end	12.2	25.2	12.2[c]	16.5
Head-on	6.4	6.7	6.4[c]	6.5
Other/unknown	15.8	18.8	10.8	15.1

[a] Run-off-road accidents in State A include 13.6 percent of accidents in which a vehicle ran off the right side of the road and 11.9 percent of accidents in which a vehicle ran off the left side.
[b] Sideswipe accidents for State B have been split between sideswipe passing and sideswipe meeting in proportion to State A data.
[c] Sideswipe, rear-end, and head-on accidents for State C have been split in proportion to State A data.

not every passing-related accident is necessarily the results of limited PSD. Many passing-related accidents may occur due to interactions between the passing and passed vehicles with no oncoming vehicle present. Thus, an unknown percentage of accidents on rural two-lane highways, but definitely less than 2 percent, are related to PSD.

In one state, the locations of passing-related accidents were reviewed on photolog videodiscs, and it was found that 90 percent of the passing-related accidents on two-lane rural roads occurred in marked passing zones, while 10 percent occurred outside of marked passing zones.

Passing-related accidents were found to be more severe than non-passing-related accidents. The HSIS data show that approximately 13.9 percent of passing-related accidents involve a fatality or serious injury, as compared to 9.4 percent of all accidents on rural two-lane highways. Thus, if passing-related accidents constitute 2 percent of all accidents, they may constitute 3 percent of fatal and serious injury accidents.

Fatality Analysis Reporting System (FARS) data for 2003 indicate there are approximately 13,000 fatal accidents per year at nonintersection locations on the nearly 3,000,000 miles of rural two-lane undivided roads in the United States. The HSIS research (*34*) indicates that approximately 3 percent of these fatalities, or 390 fatal accidents per year, may be related to passing maneuvers on these roads. An unknown proportion of these 390 fatal accidents per year may be related to PSD and, therefore, potentially susceptible to correction through modification to PSD criteria. Approximately 1,000,000 of the 3,000,000 miles of rural two-lane highways have marked centerlines that include passing and no-passing zone markings.

These data do not suggest there are major safety issues on two-lane highways related to PSD. While the safety performance of some passing zones might be changed at the margins by modifications in PSD criteria, it appears unlikely that changes in PSD criteria could bring about a major change in the safety performance of two-lane roads, even if the change in PSD criteria were found to be justified for other reasons.

Appropriateness of Current MUTCD and AASHTO Models

The following discussion addresses the appropriateness of the current MUTCD and AASHTO models. Even if there are no large overall safety issues related to passing maneuvers or PSD, it is important that the MUTCD and AASHTO models for PSD be well documented and easily explained as relevant to driver behavior and safety needs. Reviews of the MUTCD and AASHTO models are presented below.

MUTCD Model

The MUTCD marking criteria for passing and no-passing zones (see Table 3) are very familiar to traffic engineers. However, the model and assumptions on which the MUTCD criteria are based are not at all familiar to most practicing traffic engineers because the model is represented in tabular rather than equation form and because the model appeared in a 1940 AASHO publication (*6*) and has not been widely reproduced since. Nevertheless, the criteria based on this 1940 AASHO model are still used today in marking passing and no-passing zones on nearly every two-lane highway in the United States that has a marked centerline.

Concern has been raised in Chapter 2 that the 1940 AASHO PSD values represent a subjective compromise between distances computed for flying passes and distances computed for delayed passes and, thus, do not represent any particular passing situation. This is a concern because it appears nonconservative to rely to any extent on values for flying pass maneuvers in setting PSD requirements since delayed passes obviously require greater maneuver distance and longer sight distance.

The critical position concept is important to understanding the PSD criteria in the MUTCD because models that use the critical position concept come close to reproducing the MUTCD criteria and models that do not use the critical position concept result in much longer PSD criteria.

Figure 23 illustrates the sight distance needs of the driver of the passing vehicle in making a passing maneuver. As the passing maneuver begins, the PSD needed to complete the maneuver is at a maximum ($d_1 + 2d_2 + d_3$) and continually decreases throughout the maneuver until it reaches zero at the point where the passing driver completes the pass and returns to the normal lane. This return to the normal lane occurs at a distance $d_1 + d_2$ from the point where the passing maneuver began. As the passing maneuver begins, the PSD needed to abort the maneuver is zero and continually increases throughout the passing maneuver. Figure 23 is a conceptual representation in which the changes in PSD with distance traveled by the passing vehicle is shown as a linear function, but these relationships are, in fact, nonlinear. The critical position is the point where the sight distances needed to complete or abort the passing maneuver are equal. If a conflicting vehicle appears before the passing driver reaches the critical position, the correct decision for the passing driver is to abort the passing maneuver. If a conflicting vehicle appears after the passing driver reaches the critical position, the correct decision for the passing driver is to complete the passing maneuver. PSD criteria must, at a minimum, ensure that:

- Any passing driver who has not yet reached the critical position has sufficient PSD to abort the passing maneuver;
- Any passing driver who is beyond the critical position has sufficient PSD to complete the passing maneuver; and
- Any passing driver who is at the critical position has sufficient PSD to either complete or abort the passing maneuver.

In fact, if the passing driver always makes the right decision, the third item above (PSD for the driver at the critical position) is most critical.

In fact, the MUTCD criteria agree quite closely with recent PSD models, like those of Glennon (*14*) and (at lower speeds) Hassan et al. (*18*), which are both based on the concept of a critical position in the passing maneuver. Figure 16 compares the MUTCD criteria to the PSD values suggested by the Glennon (*14*) and Hassan et al. (*18*) models.

Despite past critiques that the MUTCD criteria are incorrect or unsupported, it may be that they have been about right all along, but for the wrong reason. The MUTCD criteria appear to agree quite closely with PSD values that recognize that the passing driver has the option to abort the passing maneuver up to the point in the passing maneuver when it would require less PSD to complete the passing maneuver. An explanation of this sort seems inevitable; otherwise, it would be hard to explain the documented relatively safe passing operations of two-lane highways.

The comparison shown in Figure 16 suggests that the MUTCD criteria (or values very close to them) might be retained, but with the Glennon (*14*) or Hassan et al. (*18*) model offered as the rationale for the criteria, rather than relying on the 1940 AASHO guide (*6*). Two factors that differ between the Glennon and Hassan et al. models will need to be resolved, especially the Hassan et al. model's assurance of pass completion from the abreast position, which results in increased PSD values at higher speeds.

Hassan et al. (*18*) maintain that a weakness of the Glennon model (*14*) is that the critical position in a passing maneuver can occur at a stage of the maneuver when the front of the passing vehicle is ahead of the front of the passed vehicle. Hassan et al. state that, while it may make theoretical sense for the passing driver to abort a passing maneuver from a position forward of the passed vehicle, it is unlikely as a practical matter that most drivers would do so. This appears to be a

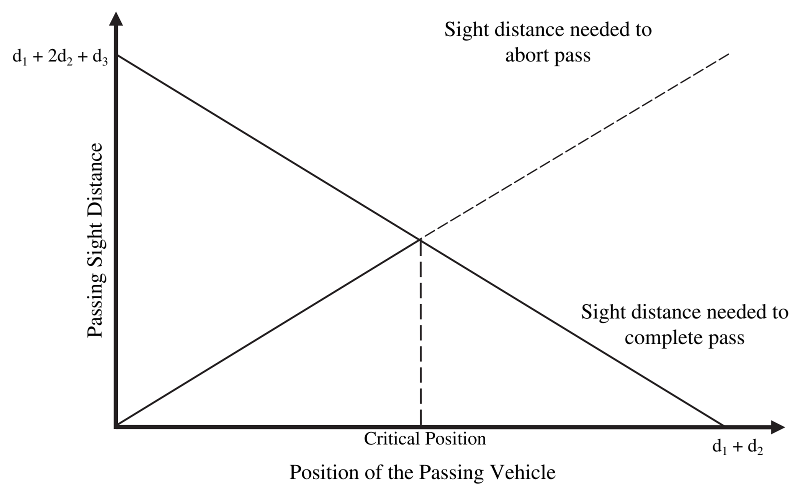

Figure 23. Conceptual representation of the changes in sight distance needed to complete or abort a passing maneuver as the passing maneuver progresses.

reasonable assumption. Thus, the Hassan et al. model changes the definition of the critical position to be the first of the following two positions to be reached:

- Position where the front bumpers of the passing and passed vehicle are abreast of one another
- Position where the sight distances needed by the passing driver to complete or abort the passing maneuver are equal

This approach appears to be conservative, providing some insurance against a "wrong" decision by the passing driver.

Hassan et al. (*18*) also maintain that the PSD model should include an explicit term for the perception-reaction time (p_a) needed for the driver of the passing vehicle to decide to abort a passing maneuver. If an oncoming vehicle is in sight before the passing driver reaches the abreast position, no additional perception-reaction time for the abort decision is needed. However, if the oncoming vehicle appears at the moment the passing driver reaches the abreast position, it is reasonable to assume that perception-reaction time could carry the passing driver forward of the abreast position while the decision to abort the pass was being made. The inclusion of perception-reaction time for the pass abort decision appears reasonable and, in fact, the Glennon model implicitly assumed a 1-sec perception-reaction time.

The similarity of the MUTCD criteria to the Glennon (*14*) and Hassan et al. (*18*) models suggests that the MUTCD criteria, together with normal enforcement practices, are very safety conservative in the treatment of the end of a passing zone. Most state laws and enforcement practices use the short-zone marking concept, meaning that it is illegal for a passing driver ever to operate to the left of a no-passing zone barrier stripe; all passing maneuvers must legally be completed before the passing zone ends. Thus, current PSD marking criteria make it safe for a passing driver to be in the critical position (such as, abreast or slightly ahead of the passed vehicle) at the end of the passing zone and still have sufficient sight distance to complete the passing maneuver. Current marking practices are very conservative because they can safely accommodate not only legal passing maneuvers, but also the illegal maneuver of completing a pass beyond the beginning of the no-passing zone barrier stripe.

Figure 24 illustrates the conservative nature of current short zone marking practices. Passing maneuvers must legally end at the beginning of the no-passing barrier stripe. However, passing maneuvers can be safely completed for a distance (designated in some PSD models as d_6) downstream of the beginning of the no-passing zone. Thus, the distance d_5 in Figure 24 is a buffer area that represents a key margin of safety in passing maneuvers. Within this buffer area, it is safe to complete a passing maneuver, but illegal to do so in most U.S. states.

The excellent safety record of passing maneuvers reported above is likely the result of a combination of two factors:

- Prudent driver decisions about initiating, completing, and aborting passing maneuvers; and
- Marking and enforcement practices that provide a buffer area downstream of every passing zone where completion of passing maneuvers is safe but not permitted.

There are only limited exceptions to the favorable enforcement practice represented by the short zone marking concept. The long-zone marking concept, in which passing maneuvers begun in a passing zone can be legally completed in a no-passing zone, was used more extensively in the past and was advocated by Van Valkenburg and Michael (*8*) in 1971. A 1978 review of current practice (*36*) found that 44 states used the short-zone marking concept and six states used the long-zone marking concept for passing and no-passing zone enforcement. A review of state laws and driver license manuals as part of the current research found that today only three states (Idaho, Illinois, and Wyoming) formally use the long-zone marking concept for enforcement. There appears to be one additional

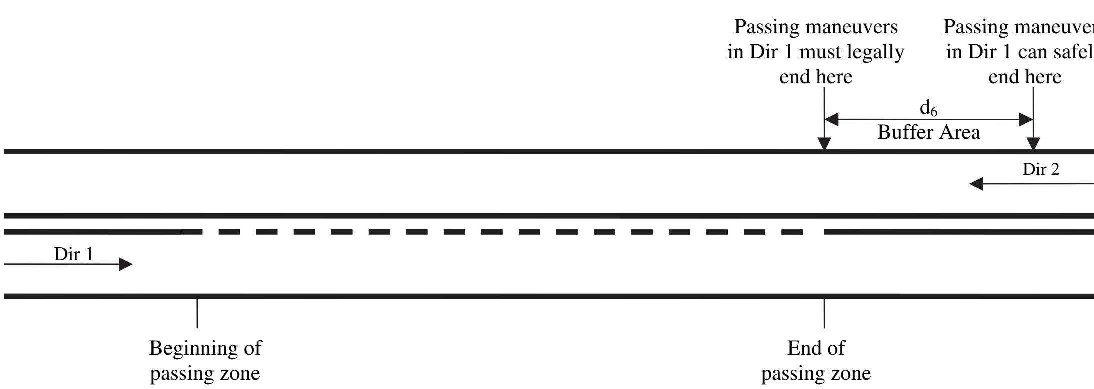

Figure 24. Buffer area downstream of a passing zone where it is safe, but not legal, to complete a pass.

state (Vermont) in which all passing and no-passing zone markings are considered advisory rather than legal requirements. Thus, the favorable short-zone enforcement environment is in effect in 46 of the 50 states. It is not clear to what extent drivers in Idaho, Illinois, Vermont, and Wyoming behave differently than drivers in other states or are even aware that their state laws differ from the norm. The long-zone marking concept does not appear to be in sufficiently wide use today to constitute a factor that should affect national policy concerning PSD criteria.

Some past researchers (*36, 37*) have recommended introducing a third level of passing and no-passing pavement markings for the buffer area shown in Figure 24. For example, a dotted marking alongside the existing centerline has been suggested to identify an area where passes could legally be completed but not initiated. The research team does not recommend this approach because it would be difficult to educate motorists on the meaning of the new marking, there would be costs involved in installing it, state laws would have to be changed accordingly, and there is no current evidence of a safety problem that needs to be addressed. Rather, the research team believes that the buffer area created by the current short-zone marking approach to marking provides a key margin of safety that promotes safe passing maneuvers.

AASHTO Model

The AASHTO model is the most widely understood PSD model because it is explicitly and prominently presented in the *Green Book* (*1*). This model is presented in Equation (1) and the resulting PSD values are shown in Figure 2 and Table 2. Many engineers who are familiar with the model may not fully understand or fully appreciate that the AASHTO model is used exclusively in design and is not used in marking passing and no-passing zones.

The AASHTO model is an extremely conservative model of PSD needs for the passing maneuver. If the distance d_4 in Equation (1) were set equal to d_2, instead of equal to $\frac{2}{3}$ d_2, it would be possible for the passing driver to see a clear roadway ahead in the opposing direction of travel, initiate a passing maneuver, never again look for opposing vehicles, and complete the passing maneuver with adequate clearance to any opposing vehicle that might subsequently appear. (Such nonobservant driving behavior is not recommended.) The only theoretical risks to such a maneuver would be from the passed vehicle or an opposing vehicle traveling faster than expected.

The choice of the value of the d_4 term in the AASHTO model as equal to $\frac{2}{3}$ d_2 rather than d_2 is presumed to provide an opportunity for the passing driver to abort the passing maneuver once it is in progress. Published alternative models such as those developed by Glennon (*14*) and Hassan et al. (*18*) show that PSD values much lower than those obtained from the AASHTO model can be used for passing if the passing driver makes correct judgments about when to abort the passing maneuver or if the consequences of making an incorrect judgment can be limited.

The AASHTO model also is very conservative in that the portion of the roadway with sufficient PSD is considered to end at the point where the available PSD drops below the PSD value specified by the AASHTO model. At this point, there is still nearly enough PSD available for a passing driver to initiate and complete a passing maneuver with minimal expectation of oncoming traffic. This implies that the actual extent of roadway where passing maneuvers can be completed safely is substantially longer than suggested by the AASHTO model. The buffer area present in passing zones marked in accordance with the MUTCD criteria is substantially larger in PSD design with the AASHTO criteria, since the AASHTO PSD criteria use longer PSD values.

The use of long PSD values in design can mislead the designer into believing that only a small percentage of roadway length has sufficient PSD for passing. In fact, when marked in accordance with the MUTCD PSD criteria, a roadway may have substantially greater length with marked passing zones than is suggested by the design PSD criteria.

While the AASHTO model is very conservative, the text of the *Green Book* does not fully communicate this. The *Green Book* text in several places refers to "minimum passing sight distance" and the caption of *Green Book* Exhibit 3-5 refers to "safe passing sight distance." This language may be interpreted to imply that PSD values less than those specified by the AASHTO model are unsafe. This language is a potential tort liability concern for highway agencies given that much shorter PSD values from the MUTCD are used to mark passing and no-passing zones on two-lane highways.

The provision of longer sight distances in the design process may be desirable to provide more and better passing opportunities on the completed road that might be possible if the MUTCD criteria served as the basis for design. The appropriateness of using different models for design and marking of passing sight distance is considered. Specific alternatives to the current AASHTO PSD models are identified later in this chapter.

Another concern with the AASHTO model is that the data used to quantify parameters d_1 and d_2 (and, therefore, d_4 as well) are very dated. The values of these parameters are based on field studies conducted between 1939 and 1941 and validated by another study conducted in 1958 (*3, 4, 5*). Conditions on U.S. roads have changed markedly since the 1930s, 1940s, and 1950s. Today's vehicles are much more powerful than vehicles of that older era and are clearly capable of accelerating and passing in shorter distances.

Parameter Values Used in PSD Models

Based on the review of PSD models in Chapter 3 of this report, the most important parameters to be considered in PSD models are as follows:

- Speeds for passing and passed vehicles (V_p and V_i) in relation to design speed (V_d) and 85th percentile speed (V_{85});
- Speed differential between the passing and passed vehicles (m);
- Time spent by the passing vehicle in the left lane (t_2);
- Distance traveled by the passing vehicle in the left lane (d_2);
- Distance traveled by the passing vehicle from the beginning of the passing maneuver to the position where the passing driver is committed to complete the pass (d_5);
- Distance traveled by the passing vehicle from the position where the passing driver is committed to pass to the end of the passing maneuver (d_6);
- Deceleration rate used in aborting a passing maneuver (d_a);
- Length of passing vehicle (L_p);
- Length of passed vehicle (L_i);
- Headway between passing and passed vehicles before and after the passing and pass abort maneuvers (h_1);
- Clearance time between passing and oncoming vehicles (h_0); and
- Perception-reaction time required for the passing driver to decide to abort the passing maneuver (p_a).

Each of these parameter values is addressed in the following material. Table 36 compares the values of selected parameters used in deriving the current AASHTO and MUTCD models to those recommended in recent research and in the current study.

Speed of Passing Vehicle (V_p)

Both the current AASHTO and MUTCD models assume that the passing vehicle travels during the passing maneuver at an average speed that is less than the design speed of the roadway. Current field data suggest that this assumption is unrealistic. Field data collected as part of the current research on highways with 97-km/h (60-mph) speed limits found that the average passing vehicle speed at the abreast position was 106.4 km/h (66.1 mph), which is very close to the 85th percentile speed of 108 km/h (67 mph) for the same roads. It is recommended that future design criteria assume a passing vehicle speed equal to the design speed and that marking criteria assume a passing vehicle speed equal to the 85th percentile speed of traffic. The AASHTO *Green Book* (*1*) recognizes anticipated operating speed, typically represented by the 85th percentile speed of traffic, as one consideration in selecting the design speed for a roadway. Other factors considered in selecting the design speed of a roadway are terrain and the functional classification of the roadway. The MUTCD (*2*) uses the 85th percentile speed of traffic as the primary basis for marking criteria, but the posted or statutory speed limit may be used as the basis for marking criteria when the 85th percentile speed is not known.

Speed of Passed Vehicle (V_i)

Virtually every PSD model makes the assumption that the passed vehicle travels at constant speed and that the behavior of the driver of the passed vehicle is unaffected by the traffic

Table 36. Summary of current and recommended values for key parameters in PSD models.

Parameter	Current AASHTO value (*1*)	Current MUTCD value (*6*)	Recommended by Glennon (*14*)	Recommended by Hassan et al. (*18*)	Recommended in this study
Speed differential between passing and passed vehicle (V_d)	10 mph	10 to 25 mph	8 to 12 mph	6.9 to 12.9 mph	12 mph
Time spent by passing vehicle in the left lane (t_2)	9.3 to 11.3 sec	–	–	–	12.3 sec
Deceleration rate used in aborting a passing maneuver (d_a)	–	–	8 ft/sec^2	5 to 7 ft/sec^2	11.1 ft/sec^2
Length of passing vehicle (L_p)	–	–	16 ft	16 ft	19 ft
Length of passed vehicle (L_i)	–	–	16 ft	16 ft	19 ft
Headway between passing and passed vehicles before and after the passing and pass abort maneuvers (h_i)	–	–	1.0 sec	1.0 sec	1.0 sec
Minimum clearance interval between passing and opposing vehicles at the completion of the passing maneuver (h_o)	–	–	1.0 sec	1.0 sec	1.0 sec
Perception-reaction time required for the passing driver to decide to abort the passing maneuver (P_a)	–	–	1.0 sec	–	1.0 sec

situation as the passing maneuver proceeds. Of course, if a potential collision impends, it is likely that the drivers of the passed and opposing vehicles would take evasive action (for example, braking or moving to the shoulder). The potential for such evasive action, if incorporated in a model, would normally be expected to reduce the PSD needed, but it also is possible for evasive action to work counter to the actions of the passing driver (for example, braking by the passed vehicle after the passing driver has decided to abort the pass). Weaver and Woods (*36*) state that passing drivers often say that the drivers of passed vehicles speed up, but they comment that the available field data does not show this to be the case.

Speed Differential Between Passing and Passed Vehicles (m)

The value of the speed differential between the passing and passed vehicles (m) has been suggested by Glennon (*14*) and others to range from 13 to 19 km/h (8 to 12 mph), with lower speed differentials at higher speeds. Thus, Glennon would suggest a speed differential of 13 km/h (8 mph) for high-speed passes. Field data collected in this study suggest that the speed differential for high-speed passes in today's traffic is in the range from 3.6 to 4.6 km/h (12 to 15 mph). Since the Glennon and Hassan et al. models suggest that the PSD values are not very sensitive to speed differential, a constant speed differential of 3.6 km/h (12 mph) across all speed ranges is recommended. This implies that the passed vehicle speed (V_i) assumed in design criteria should be 3.6 km/h (12 mph) less than the design speed of the road and the passed vehicle speed assumed in marking criteria should be 3.6 km/h (12 mph) less than the 85th percentile speed of traffic.

Time Spent by the Passing Vehicle in the Left Lane (t_2)

The current AASHTO model for PSD design assumes that the time spent by the passing vehicle in the left lane (t_2) varies from 9.3 sec at an average passing vehicle speed of 56.2 km/h (34.9 mph) to 11.3 sec at an average passing vehicle speed of 99.8 km/h (62.0 mph), as shown in Table 1. The field data from the current study and the Texas study (*28*) indicate that t_2 is not substantially influenced by speed (see Chapter 4). Therefore, the use of a t_2 value that does not vary with speed is recommended. The distance traveled by the passing vehicle in the left lane (d_2) is a linear function of passing vehicle speed and, therefore, will remain strongly influenced by speed.

The observed values of t_2 from the field data are:

	15th percentile	Mean	85th percentile
t_2 (sec)	7.5	9.9	12.3

The mean value for t_2 of 9.9 sec falls toward the lower end of the range of 9.3 to 11.3 sec assumed in the current AASHTO PSD model. Indeed, for mean passing vehicle speeds of 106.4 km/h (66.1 mph) from the current study and 114.2 km/h (71.0 mph) from the Texas study, the corresponding AASHTO values of t_2 would be at the upper end of the range (11.3 sec). Thus, one could make the case that today's more powerful vehicles have reduced t_2 compared to the field studies from 1939 through 1958 on which the AASHTO model is based (*3, 4, 5*). However, since design should generally be based on more conservative criteria than operations, it is recommended that the 85th percentile value of 12.3 sec for t_2 be used in design.

Distance Traveled by the Passing Vehicle in the Left Lane (d_2)

The distance traveled by passing vehicles in the left lane (d_2) was measured in several older studies from 1938 to 1968 (*3, 4, 5, 38*). The new field data summarized in Tables 23 and 24 suggest that d_2 might be decreased in today's traffic if the mean observed values of d_2 observed in the field were used. Instead, the 85th percentile value for travel time spent by the passing vehicle in the left lane (t_2) equal to 12.3 sec will be used in design. Corresponding values of d_2 as a function of speed can then be computed with Equation (3). Computed 85th percentile values of d_2 for a range of speeds from 32 to 129 km/h (20 to 80 mph) are shown in Table 26.

Distance Traveled by the Passing Vehicle from the Beginning of the Passing Maneuver to the Point Where the Passing Driver is Committed to Complete the Pass (d_5)

The field data presented in Chapter 4 indicate that the distance traveled by the passing vehicle from the beginning of the passing maneuver to the abreast position is 40 percent of distance d_2. Hassan et al. (*18*) recommend the use of the abreast position, rather than the critical position, as the location at which the driver is committed to complete the pass. Therefore, it is recommended that d_5 be determined as:

$$d_5 = 0.4\ d_2 \tag{62}$$

Distance Traveled by the Passing Vehicle from the Point Where the Passing Driver is Committed to Complete the Pass to the End of the Passing Maneuver (d_6)

The distance traveled from the abreast position to the end of the passing maneuver can be estimated as the remaining portion of d_2 not included in d_5 (see above), or 60 percent of distance d_2. Therefore, it is recommended that d_6 be determined as:

$$d_6 = 0.6\ d_2 \tag{63}$$

and, therefore, it follows from Equations (62) and (63) that:

$$d_2 = d_5 + d_6 \quad (64)$$

As illustrated in Figure 24, based on the passing zone marking and enforcement practices of most states, d_6 also represents the length of a buffer area present at the downstream end of each marked passing zone. Passes can be completed illegally, but safely, in this buffer area if three conditions apply:

- Passing vehicle reached the abreast position before reaching the end of the marked passing zone;
- Passing vehicle is traveling at the speed assumed for it in the PSD model, or a greater speed; and
- Any opposing vehicle that may be present is traveling at the speed assumed for it in the PSD model, or a lesser speed.

Deceleration Rate Used in Aborting a Passing Maneuver (d_a)

The deceleration rate (d_a) for aborting a passing maneuver has been recommended by Glennon (*14*) to be 2.4 m/sec^2 (8 ft/sec^2) for a passenger car. The use of a constant deceleration rate, independent of speed, is consistent with the recommendations of Fambro et al. (*27*) concerning stopping sight distance, which have been incorporated in the AASHTO *Green Book* (*1*) beginning in 2001. Based on the Fambro work, the *Green Book* stopping sight distance criteria now incorporate a controlled deceleration rate of 3.4 m/sec^2 (11.1 ft/sec^2), rather than the speed-dependent locked-wheel braking coefficient that was previously used in the *Green Book.* Since the deceleration rate now used in stopping sight distance criteria represents controlled braking, it seems very appropriate for use in PSD criteria, as well. The presence of an oncoming vehicle coming directly toward the passing vehicle in the same lane is surely at least as great a motivation for rapid deceleration as an object or stalled vehicle in the roadway ahead. Therefore, a deceleration rate in pass abort maneuvers of 3.4 m/sec^2 (11.1 ft/sec^2), independent of speed, is recommended for use in PSD models. A larger deceleration rate in pass abort maneuvers of 3.4 m/sec^2 (11.1 ft/sec^2), independent of speed, is recommended for use in PSD models. A larger deceleration rate might be justified, but this would require data for a larger set of pass abort maneuvers than available from this research (see Chapter 4).

Length of Passing Vehicle (L_p) and Passed Vehicle (L_i)

Previous researchers (*14, 18*) have recommended the use of 4.9 m (16 ft) for the length of the passing and passed vehicles in PSD models. Relatively few passenger cars in today's fleet are longer than 4.9 m (16 ft). However, the length of the AASHTO passenger car design vehicle is 5.8 m (19 ft) and, unless the length of this design vehicle is changed, it does not appear appropriate to use a shorter vehicle length in PSD design criteria. In any case, the PSD values in the Glennon (*14*) and Hassan et al. (*18*) models are not very sensitive to the difference in vehicle length between 4.9 and 5.8 m (16 and 19 ft).

Headway Between Passing and Passed Vehicles Before and After the Passing and Pass Abort Maneuvers (h_1)

The headway between the passing and passed vehicles before and after the maneuver and the clearance time between the passing and passed vehicles are recommended to have values of 1 sec, consistent with the recommendations of Glennon (*14*) and Hassan et al. (*18*).

Minimum Clearance Interval Between Passing and Opposing Vehicles at the Completion of the Passing Maneuver (h_0)

The recommended minimum clearance interval between the passing vehicle and an opposing vehicle at the completion of a passing maneuver (or the completion of a passing abort maneuver) is 1 sec. This value also has been used by both Glennon (*14*) and Hassan et al. (*18*) and corresponds to a clearance distance of 11 m (37 ft) at 40 km/h (25 mph) and 31 m (103 ft) at 113 km/h (70 mph). It should also be remembered that the enforcement practices of most states provide a buffer area of length d_5 at the end of each passing zone, so a clearance interval of 1 sec would normally arise only in passing maneuvers that extend beyond the length of a marked passing zone.

Perception-Reaction Time Required for the Passing Driver to Decide to Abort the Passing Maneuver (p_a)

The perception-reaction time for the passing driver to decide to abort a passing maneuver (p_a) was included in the Hassan et al. (*18*) model, but Hassan et al. did not recommend a value for this parameter. Perception-reaction time is not critical when the view of the roadway ahead is clear (since perception of an opposing vehicle in view by the passing driver can take place continuously while the passing maneuver is in progress), but becomes critical when sight distance is limited.

The perception-reaction times used in design and operations models generally range from 0.9 to 2.5 sec, depending on the type of situation to be detected by the driver and whether the situation was an alerted condition or a surprise. The most conservative value of perception-reaction time used in design is 2.5 sec, used in the AASHTO design criteria for stopping sight distance. Detecting an object in the roadway ahead, which could occur anywhere at any time, is clearly a surprise condition. Wortman and Matthias (*39*) determined perception-reaction times in a traffic control situation, from the onset of a yellow signal interval to the appearance of vehicle brake lights as 0.9 sec for an alerted 85th-percentile perception-reaction time and 1.3 sec for a surprise 85th-percentile reaction time. Clearly, the perception-reaction time in a PSD context is an alerted condition.

Monitoring the potential appearance of an opposing vehicle in the same traffic lane during a passing maneuver in progress is perhaps the most alerted of all possible conditions encountered by a driver on the roadway. Where PSD limits the view of the roadway ahead, a passing driver would be clearly expected to recognize the risk posed by oncoming vehicles and to direct a good share of their attention accordingly to the location where an opposing vehicle might potentially appear. Because of the alerted nature of this condition, the authors of the current report recommend a value of perception-reaction time (p_a) of 1 sec for the decision to abort a passing maneuver.

Use of Different PSD Models for Design and Marking

Current practice uses different PSD models in highway design and in marking of passing and no-passing zones. An assessment has been made of whether this practice is warranted.

Research in the FHWA HSIS program presented earlier in this chapter (*29*) has demonstrated that the U.S. highway system operates with relatively few accidents related to passing maneuvers and PSD. Thus, there appears to be little doubt that the highway system can be operated safely with passing and no-passing zones marked with the current MUTCD criteria, which correspond closely to the PSD values from the Glennon (*14*) and Hassan et al. (*18*) models.

Increasing the current MUTCD PSD criteria to equal the AASHTO criteria, or some intermediate value, does not appear desirable because it would decrease the frequency and length of passing zones on two-lane highways. This would decrease the traffic operational level of service and might encourage illegal passes at locations where passing maneuvers are currently legal. Given the favorable safety record of passing-related accidents on two-lane highways, the research team would consider recommending an increase in the current MUTCD PSD criteria only if a strong safety rationale for the change were identified and if a cost-effectiveness analysis showed an economic justification for such a change.

The central question concerning the need for design PSD criteria that differ from the PSD criteria used for marking is whether part of the good safety performance of passing maneuvers on the two-lane highway system results from the use of longer PSD values in the design process, even though the shorter MUTCD values are used to mark the passing and no-passing zones on the completed road.

It is difficult to determine what impact may result from the current use of the longer AASHTO PSD values in design, since design policy does not specify any particular proportion of the roadway length that must have adequate PSD. The selection of this proportion is a project design decision that is left to the responsible highway agency or designer. However, there is no research which indicates that crash frequency differs from marked passing zones with PSD above and below the AASHTO PSD criteria. Thus, it appears that the primary benefits of using longer PSD values in design are in operational efficiency (such as, more and longer passing zones) rather than in safety.

Since different PSD values are used for design than for marking, it is not customary to consider as part of the design process the proportion of the length of the completed highway that will have marked passing zones or the frequency, length, and spatial distribution of those marked zones. While such a determination may have been difficult in the past, modern CAD technology should make this much easier today. Consideration should be given to making a review of anticipated passing and no-passing zone markings, and their implication for traffic operations, a routine part of the design process for projects on two-lane highways.

Consideration of Larger and Longer Vehicles in PSD Criteria

The PSD requirements for passing larger and longer vehicles, such as trucks, have been addressed by Glennon (*14*), Rilett et al. (*16*), and Hassan et al. (*18*). The PSD values from these analyses have been illustrated in Figures 13, 15, and 16, respectively. Harwood and Glennon (*15*) have considered passenger cars and trucks as both the passing and passed vehicles (see Figure 14).

The results show clearly that it takes more PSD to pass a long truck than to pass a passenger car. Harwood and Glennon (*15*) indicate that, at 97 km/h (60 mph), it takes 313 m (1,025 ft) of sight distance for a passenger car to pass another passenger car and 381 m (1,250 ft) of sight distance for a passenger car to pass a 23-m (75-ft) truck. Comparable values for a truck to pass a passenger car and a truck to pass another truck are 419 and 480 m (1,375 and 1,575 ft), respectively.

Truck drivers have substantially higher eye heights than passenger cars. This provides truck drivers an advantage over passenger car drivers at vertical sight limitations, but there is no comparable advantage for truck drivers at horizontal sight limitations. Because higher truck driver eye heights provide more sight distance, Harwood and Glennon (*15*) found that (except in some highly unusual cases) a truck can safely pass a passenger car on any vertical curve on which a passenger car can safely pass a truck.

Given the longer PSD needed to pass a truck, should the PSD criteria used for marking be changed to address passing of trucks rather than passing of passenger cars? Previous consideration of this issue by the research team and by others (*26*) concluded that consideration of trucks in setting PSD criteria would not be justified because this would shorten or eliminate passing zones that can be used safely for a passenger car to pass another passenger car and would, thus, reduce the highway level of service. The extent of the reduction in level of service is assessed in Chapter 4 of this report.

Ultimately, the safety of passing maneuvers on two-lane highways is dependent on judgments by passing drivers and potential passing drivers. There is no reason to believe that passing drivers will attempt to pass trucks at locations where such maneuvers would be unsafe, just because a passing zone where it is safe to pass a passenger car is marked.

There may, however, be a good rationale for considering trucks in other ways in PSD design. For example, there may be a rationale for increasing the percentage of roadway length with adequate PSD, requiring a longer minimum length of PSD region on roads with substantial truck percentages, or requiring more PSD in the early portions of passing zones on roads with substantial truck volumes.

Consideration of Older Drivers in PSD Criteria

Older drivers have reduced perception-reaction times, reduced visual acuity, reduced peripheral vision, and reduced ability to judge distances and speeds (*40–45*), all of which indicate that an older driver may need more time, distance, and sight distance than a younger driver to complete a passing maneuver. However, it is logical that older drivers are less likely than younger drivers to make passes on two-lane highways because older drivers often travel at lower speeds and are generally less aggressive than younger drivers. Typically, one would expect to find older drivers in the passed vehicle, rather than the passing vehicle, on a two-lane highway. Thus, consideration of the abilities of older drivers in setting PSD criteria for marking passing maneuvers may not be justified if, even after the change, older drivers still make very few passing maneuvers.

The FHWA *Highway Design Handbook for Older Drivers and Pedestrians* (*40*) implies (but does not explicitly state) that the AASHTO PSD criteria, rather than the MUTCD criteria, should be used to mark passing and no-passing zones so as to better accommodate older drivers on two-lane highways. However, in NCHRP Project 20-7 (118), Potts et al. (*46*) recommended caution in implementing this recommendation. Such a change would clearly reduce the number and length of passing zones and the traffic operational efficiency of two-lane roads, but might provide no benefit if, despite the longer sight distance in the passing zones that remain, older drivers were still reluctant to pass. There is no indication of any documented safety concern for older drivers on two-lane highways that needs to be addressed through a change in PSD criteria.

Driver Understanding of and Compliance with Passing and No-Passing Zone Markings

A driver-related issue of concern is the effect that impatience or frustration over inability to pass may have on driver behavior. Hostetter and Seguin (*47*) have stated that, when forced to follow a slow-moving vehicle for up to 8 km (5 mi), almost 25 percent of drivers made an illegal pass in a no-passing zone. This indicates the importance of not changing PSD criteria in a way that eliminates too many current passing zones because there is a clear indication that illegal passing maneuvers will increase.

A study by Bacon et al. (*48*) was undertaken in the 1960s to determine how drivers in Michigan understand and act at no-passing zones. Their research found that only 30 percent of the sample (424 respondents) claimed to observe no-passing zones according to enforcement intentions. Field observations in Michigan indicated that clipping of the start of a no-passing zone occurred in 14 to 17 percent of passing maneuvers (*36, 49*). Comparable field data in the current study indicated clipping in 21 percent of passing maneuvers in passing zones of 300 m (1,000 ft) or more in length and clipping in 92 percent of passing maneuvers in passing zones of 120 to 240 m (400 to 800 ft) in length.

Driver Judgments In Passing Maneuvers

It is evident that the safety of passing maneuvers relies on the ability of the passing driver to make two key judgments:

- Judgment 1: The decision whether to initiate a passing maneuver in any particular road and traffic situation
- Judgment 2: The decision whether to continue or abort a passing maneuver when an opposing vehicle appears or when the end of the passing zone or the region of sufficient PSD approaches

Aborted passing maneuvers are not rare events; they are observed quite commonly on two-lane highways. Given the relatively safe record of passing maneuvers on two-lane highways, drivers must either be fairly adept at making both Judgment 1 and Judgment 2 or the consequences of making poor judgments must be minimal. Indeed, it can be argued that Judgment 2 is the most critical for safety on a two-lane highway because good exercise of Judgment 2 can make up for a mistake in Judgment 1.

Thus, there is a good case that both pass initiation decisions and pass continuation/abort decisions have a role in establishing PSD criteria. Furthermore, it is likely that pass continuation/abort decisions are the more important of the two types of decisions.

There are a number of older studies in the literature that address the ability of drivers to estimate speeds and distances and make judgments needed in passing. These studies are reviewed below. Unfortunately, none of these studies focused specifically on the abort/continue decision which appears to be the critical element in passing maneuvers.

Research conducted by Gordon and Mast (*38*) was concerned with the ability of drivers to judge the distance required to overtake and pass. Their results (government car and own car) are shown in Figure 25 compared with previous results by Matson, Forbes, and Greenshields (*50*), Prisk (*4*), and Crawford (*51*).

Jones and Heimstra (*52*) performed studies to determine how accurately drivers estimate clearance time. They found that many subjects were not capable of accurately judging the last safe moment for passing without causing the approaching vehicle to take evasive action.

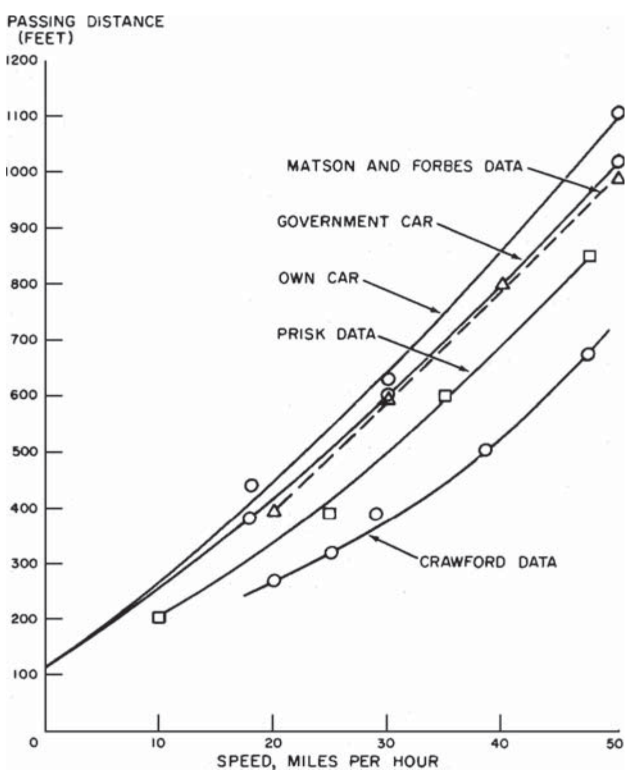

Figure 25. Passing distance in relation to speed (4, 10, 38, 50, 51).

Farber and Silver (*53, 54, 55, 56*) defined requirements for the overtaking and passing maneuver. The major findings of their studies were that drivers judged distance accurately in passing situations, but that their ability to judge speed variables was marginal. Subjects could not discriminate even grossly different opposing vehicle speeds. Ability to judge time available to pass was substantially improved when the need to judge opposing vehicle speed was eliminated.

Research was conducted by Hostetter and Seguin (*47*) to determine the singular and combined effects of impedance distance, impedance speed, passing sight distance, and traffic volume on driver acceptance of passing opportunities. In general, sight distance was found to be the major determinant of the probability that a driver would accept a passing opportunity. The probability of a pass increased as the sight distance increased.

Cassel and Janoff (*57*) used a mathematical simulation model to study passing maneuvers. It simulated the movement of vehicular traffic for various road geometry and traffic volume conditions. Results of simulation runs indicate that (a) when drivers were given knowledge of opposing vehicle speed on tangents, there appeared to be an increase in safety but the average speed was reduced, so that a significant loss in time occurred; and (b) as the percentage of no-passing zones increased, there was a decrease in throughput as indicated by average speed, time delay, and number of passes.

Weaver and Woods (*36*) indicate that their human factors research, including interviews with drivers, found that drivers almost universally understand that it is illegal to extend a passing maneuver into a no-passing zone. Despite this knowledge of the law, a substantial proportion of drivers do, at times, extend passing maneuvers into passing zones when they perceive it is safe to do so. Thus, there is evidence in the literature that drivers fully understand the law and also flout the law at times; this is consistent with driver behavior toward speed limits.

The research findings described here present something of a conundrum. In older research, drivers were found to be somewhat poor at making the judgments required for passing maneuvers, particularly judgments about opposing vehicle speed, but the safety record of passing maneuvers is very good. This suggests that passing maneuvers occur in a relatively forgiving environment. First, while drivers are relatively poor in making passing judgments, many drivers may inherently understand this and make very conservative decisions about passing. Second, the buffer area provided downstream of each passing zone provides a margin of safety against collisions resulting from poor driver judgments.

Since the current level of safety in passing maneuvers appears to be good, a key goal of the research should be to provide assurance that no changes recommended in the research would adversely affect current level of safety.

Minimum Length of Marked Passing Zones

Two studies have addressed driver behavior in short passing zones as related to the minimum length of marked passing zones: a study by Jones (*7*) and the current study. Each of these studies is discussed below.

Results from Study by Jones

A study by Jones (*7*), done in 1970 in conjunction with the Weaver and Glennon (*9*) study, was undertaken to prove that the MUTCD allowance of a 120-m (400-ft) passing zone length was inadequate. Although this study was not rigorous, it shed light on the relationship of marking practice and actual highway operations.

The Jones study evaluated the use and safety of short passing zones on two-lane highways in Texas. Three short passing zones of 120, 200, and 270 m (400, 640, and 880 ft) were chosen. The three sites had similar ADT volumes and geometrics and reasonably similar lengths of no-passing stripe on the approach to zone 490 and 670 m (1,600 to 2,200 ft). In addition, two longer zones having lengths of 500 and 790 m (1,640 and 2,600 ft) were studied for comparative purposes. The posted speed limit for all five Texas sites at the time of study was 113 km/h (70 mph).

The study included a subjective evaluation of the proportion of passing opportunities that resulted in completed passes. A passing opportunity was defined as a situation whereby a vehicle entered one study area trailing another vehicle within four car-lengths (approximately 24 m or 80 ft) and was, in the judgment of the observer, awaiting a chance to pass the lead vehicle.

An average of 125 such passing opportunities occurred at each of the three short zones during the study period.

Figure 26 shows the results of the evaluation of passing zone use. Fewer than 9 percent of the passing opportunities were accepted at each of the three short passing zones. By contrast, the 500-m (1,640-ft) zone had 22.8 percent use, and the 790-m (2,600-ft) zone had 41.0 percent use. These results, though based on limited observation, cast doubt on any claim that short passing zones add substantially to the level of service on two-lane highways.

Additional data about each passing opportunity that resulted in a passing maneuver were collected at the three short zones. The safety of the return of the passing vehicle to the right lane at the completion of the maneuver was subjectively rated on a severity scale of 0 to 2 based on the following definitions:

Rating	**Definition**
0	Smooth return from passing lane to normal operating lane.
1	Forced return in which the passing driver apparently realized that the remaining sight distance was less than adequate.
2	Violent return in which the passed vehicle or an opposing vehicle was forced to brake or move to the shoulder.

Also, the location of the return to the right lane was recorded for each completed pass.

Figure 27 shows the distribution of severity ratings for the return maneuvers of completed passes for each of the three short zones. The proportion of observed hazardous maneuvers decreased as the zone length increased. Forced or violent returns occurred in 63 percent of the passes on the 120-m

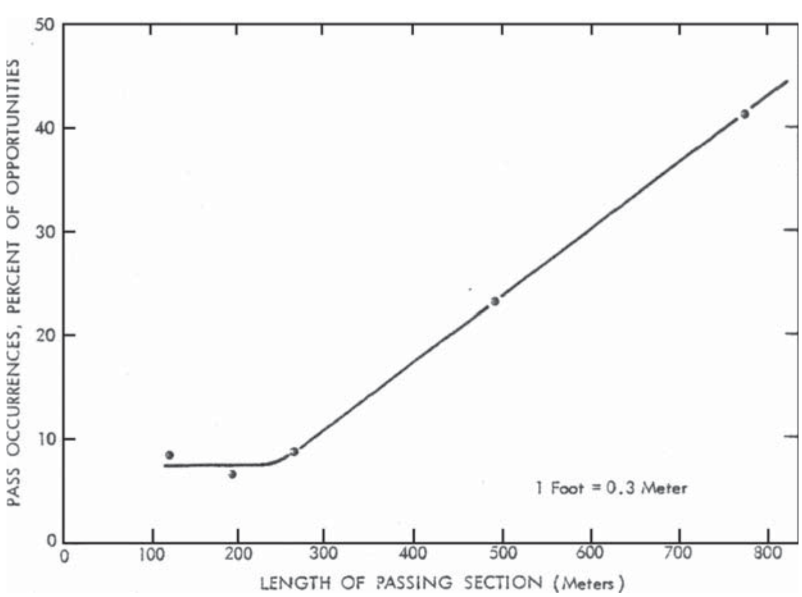

Figure 26. Driver acceptance of passing opportunities (7, 10).

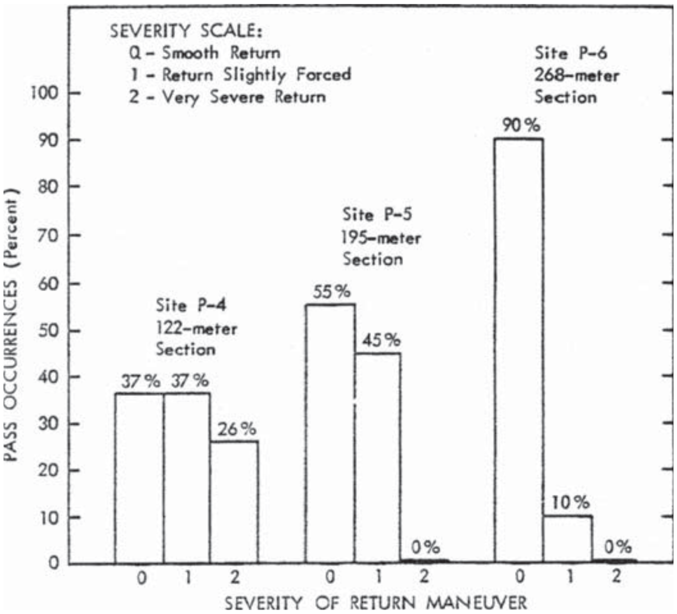

Figure 27. Return maneuver severity rates (7, 10).

(400-ft) zone, 45 percent of the passes for the 200-m (640-ft) zone, and 10 percent of the passes for the 270-m (880-ft) zone. Only the results for the 270-m (880-ft) zone appear tolerable under any reasonable safety standard.

The point of return of passing vehicles to the right lane also was recorded as an indication of safety and legality. The laws governing highway operation in most states require a driver to complete a pass before entering a no-passing zone. On this basis, all 11 of the observed passes on the 120-m (400-ft) section were illegal. In 5 of these 11 passes, the passing vehicle did not return to the right lane until more than 120 m (400 ft) after the beginning of the no-passing stripe. Only one pass out of nine on the 200-m (640-ft) passing zone and two of the 10 passes observed on the 270-m (880-ft) passing zone were legal. For all three study sites, the drivers who penetrated the no-passing zone entered an area of extremely restricted sight distance.

Results of the Jones study indicate that most drivers are reluctant to use passing zones shorter than 270 m (880 ft) long. The overwhelming majority of drivers who did use such zones did so illegally.

Results of Current Study

Results of the current study relevant to the issue of short passing zones with lengths of 120 to 240 m (400 to 800 ft), in comparison to long passing zones with lengths of 300 m (1,000 ft) or more, have been presented in Chapter 4. Specifically, the current study found that:

- There is very little passing activity in short passing zones. The observed passing rate was 0.77 passes per hour in short passing zones, as compared to 2.95 passes per hour in long passing zones. Only 0.4 percent of all vehicles and 1.6 percent of vehicles with headways of 3 sec or less make passing maneuvers in short passing zones, as compared to 1.9 and 7.8 percent of vehicles, respectively in long passing zones.
- The percentage of passing maneuvers completed legally within the marked passing zone was only 4 percent in short passing zones.
- The percentage of passing maneuvers that extended beyond the passing zone into the marked no-passing zone was 92 percent for short passing zones and 21 percent for long passing zones.
- In 19 percent of the passing maneuvers that extended beyond the end of a short passing zone into a marked no-passing zone, the abreast position occurred in the marked no-passing zone; the comparable value for long passing zones was 17 percent. The passing maneuvers in which the abreast position occurred beyond the end of the marked passing zone constituted 15 percent of all maneuvers in short passing zones and only 4 percent of all maneuvers in long passing zones.
- In 88 percent of passing maneuvers that extended beyond the end of a short passing zone into a marked no-passing zone, the left-lane distance for the passing vehicle (d_2) exceeded the length of the passing zone; in long passing zones there were no maneuvers for which d_2 exceeded the length of the passing zone.

The need for a change in the MUTCD criteria for minimum length of passing zone is addressed in the following material.

Potential Alternative PSD Models

The choice of appropriate PSD models for design and marking involves all of the considerations discussed in Chapters 2 through 4 and in the preceding sections of Chapter 5. The following discussion addresses the need for changes in the PSD criteria for marking passing and no-passing zones, the minimum length of marked passing zones, and the PSD criteria for use in design of two-lane highways.

PSD Criteria for Marking Passing and No-Passing Zones

With respect to PSD criteria for marking passing and no-passing zones, there is a natural interest in replacing the 1940 AASHO model on which the current MUTCD (*2*) criteria are based, because the model lacks credibility as a rationale for PSD criteria. On the other hand, there is a very substantial cost to any proposed change in PSD criteria for marking, since this could require remeasuring sight distance for every two-lane road in the United States that has centerline markings. Such a large task should only be recommended if this action would have clear, documentable safety benefits and would be cost-effective.

The review of alternative PSD models in Chapter 3 of this report found two credible models, both based on the critical position concept or a variation of the critical position concept and both providing PSD values quite close to the current MUTCD criteria. These models are those developed by Glennon (*14*) and Hassan et al. (*18*). The Glennon model is presented in Equations (21) and (22) and the Hassan et al. model in Equations (25) through (30). These models have been considered as alternative approaches to the development of PSD criteria for marking passing and no-passing zones. The recommended parameter values and assumptions for both models are:

- The speeds of the passing vehicle (V_p) and the opposing vehicle (V_o) are equal and represent the 85th percentile speed of the highway (V_{85}).
- The speed differential (m) between the passing and passed vehicle is 19 km/h (12 mph), independent of the speed of the passing vehicle. The passed vehicle travels at this constant speed throughout the entire maneuver.
- The passing vehicle has sufficient acceleration capability to reach the specified speed difference relative to the passed vehicle by the time it reaches the critical position or the position abreast of the passed vehicle.
- The lengths of the passing and passed vehicles (L_p and L_i, respectively) are 5.8 m (19 ft), equivalent to the AASHTO PC design vehicle.
- The maximum sight distance during a passing maneuver is required at the critical position in the passing maneuver. The passing driver will abort the passing maneuver at any time until the critical position is reached if a potentially conflicting vehicle appears in view. Once beyond that point, the driver will complete the passing maneuver. The Glennon model assumes that the critical position is the position where the sight distances needed to complete or abort the passing maneuver are equal. The Hassan et al. model assumes that the critical position occurs at the position when the passing and passed vehicles are abreast or the position at which the sight distances needed to complete or abort the pass are equal, whichever occurs first.
- The passing driver's perception-reaction time (p_a) in deciding to abort a passing maneuver is 1 sec.
- If a passing maneuver is aborted, the passing vehicle will use a deceleration rate of 3.4 m/sec^2 (11.1 ft/sec^2) until returning to its normal lane behind the passed vehicle.
- For a completed pass, the space headway between the passing and passed vehicles at the completion of the maneuver is 1 sec. This is implicit in the Glennon model and a formal parameter (h_1) in the Hassan et al. model.
- For an aborted pass, the space headway between the passing and passed vehicles at the completion of the maneuver is 1 sec. This is implicit in the Glennon model and a formal parameter (h_1) in the Hassan et al. model.
- The minimum clearance between the passing and opposing vehicles at the point when the passing vehicle returns to its own lane is 1 sec. This is implicit in the Glennon model and a formal parameter (h_0) in the Hassan et al. model.

The rationale for the parameter values presented above has been presented earlier in this chapter.

Table 37 presents PSD values determined with the Glennon and Hassan et al. models, incorporating the parameter values specified above, in comparison to the current MUTCD PSD criteria. The table shows that the PSD values from the Glennon model are less than the current MUTCD criteria for all speeds. The PSD values from the Hassan et al. model are less than the current MUTCD criteria for all speeds of 72 km/h (45 mph) or less and exceed the current MUTCD criteria for all speeds of 80 km/h (50 mph) or more. The maximum difference between the MUTCD and Hassan et al. PSD values is 40 m (132 ft) at 113 km/h (70 mph).

A key question for this research is whether a change in the MUTCD PSD criteria for marking passing and no-passing zones should be recommended on the basis of Table 37. The assumptions of the Hassan et al. model concerning the critical position may be slightly more realistic than the Glennon model, but they are only assumptions and are not documented

Table 37. Comparison of MUTCD PSD criteria to PSD values from the Glennon and Hassan et al. models.

85th percentile speed (mph)	PSD value (ft)		
	MUTCD	Glennon	Hassan et al.
25	450	356	301
30	500	442	392
35	550	527	490
40	600	611	594
45	700	695	704
50	800	778	819
55	900	862	940
60	1000	945	1066
65	1100	1028	1197
70	1200	1111	1332

with field observations. Thus, both the Glennon and Hassan et al. models appear useful in assessing current PSD marking practice. The Hassan model would suggest increasing the MUTCD PSD criteria by 6 to 40 m (20 to 130 ft) for roads with 85th percentile speeds of 80 km/h (50 mph) and above. The 1994 HSIS study (*34*) suggests that less than 2 percent of accidents on two-lane highways involve passing maneuvers and only a portion of those accidents are related to PSD. Thus, there is no indication of a PSD-related safety problem on two-lane highways and no reason to suppose that a small increase in PSD criteria would have any discernable safety benefit. Furthermore, the cost of such a change would be substantial, as PSD would need to be remeasured on every two-lane road with an 85th percentile speed of 80 km/h (50 mph) or more. Therefore, no change is recommended in the PSD values presented in the MUTCD and shown in Table 3 of this report. A recent Canadian study (*58*), based on literature review and expert opinion but not on new field data, reached a similar recommendation concerning Canadian PSD marking practices.

While no change in the current MUTCD PSD values is recommended, it is recommended that documentation on the MUTCD web site, or in a publication like the *Traffic Control Devices Handbook* (*59*), present both the Glennon (*14*) and Hassan et al. (*18*) models as the rationale for the MUTCD PSD criteria.

Minimum Length of Marked Passing Zones

The field data collected for this study indicate a potential need to increase the minimum 120-m (400-ft) length of marked passing zones which is implied, but not explicitly stated in guidance provided in the MUTCD. Field studies in short passing zones with lengths of 120 to 240 m (400 to 800 ft) indicate that 92 percent of maneuvers in such passing zones are completed beyond the end of the marked passing zone. At times, these passing maneuvers extend beyond the buffer area for safe (but illegal) completion of passes that exists at the end of each marked passing zone. These findings are not surprising given that the average length of passing maneuvers in these short passing zones is 273 m (894 ft).

It can also be documented that passing zones with lengths of 120 to 240 m (400 to 800 ft) add little to the traffic operational efficiency. Only 0.4 percent of all vehicles and 1.6 percent of vehicles with headways of 3 sec or less pass in short passing zones. Comparable passing percentages for comparable passing zones with length of 300 m (1,000 ft) or more are 1.9 percent of all vehicles and 7.8 percent of vehicles with headways of 3 sec or less. A traffic simulation study for two-lane highways with the TWOPAS models showed that the few passing maneuvers that occur in short passing zones contribute little to the traffic operational efficiency and level of service of a two-lane highway.

A key issue that deserves attention is whether there is support for a tentative recommendation to increase the MUTCD guideline for the minimum length of passing zone on two-lane highways from 120 m (400 ft) to 240 m (800 ft) for two-lane highways with speeds of 70 km/h (45 mph) or more. This value would roughly correspond to the minimum length of a high-speed passing maneuver. For highways with speeds less than 70 km/h (45 mph), the minimum passing zone length could increase from its current value of 120 m (400 ft) to 240 m (800 ft) with increasing speed as shown in Table 38. This change would be less expensive to implement than changing PSD marking criteria because the change would require remarking of some but not all passing zones, and because only passing zone length and not sight distance would need to be measured.

If short passing zones with lengths of 120 to 240 m (400 to 800 ft) were eliminated on two-lane highways, a concern is this would unnecessarily eliminate some legal passing maneuvers by reducing the opportunity for some flying passes and some passes of slow-moving vehicles such as farm tractors. Elimination of such passing opportunities may not be acceptable to the motoring public and might lead to illegal passing maneuvers where legal maneuvers could previously be performed. There is no available information about whether there

Table 38. Potential guidance for minimum length of marked passing zones.

Metric		U.S. Customary	
85th percentile speed or posted or statutory speed limit (km/h)	Minimum passing zone length (m)	85th percentile speed or posted or statutory speed limit (mph)	Minimum passing zone length (ft)
40	140	20	400
50	180	30	550
60	210	35	650
70	240	40	750
80	240	45	800
90	240	50	800
100	240	55	800
110	240	60	800
120	240	65	800
		70	800

is, in fact, any crash pattern associated with passing maneuvers in short passing zones with lengths of 120 to 240 m (400 to 800 ft). While the FHWA HSIS study (*34*) establishes that there is no general safety concern related to passing maneuvers on two-lane highways, there has been no comparable investigation that has focused on short passing zones. Pending further research on the safety of short passing zones, no change in the MUTCD 120-m (400-ft) minimum passing zone length is recommended.

The recent Canadian study (*59*) of passing sight distance design and marking recommended that the current 100 m (328 ft) minimum passing zone length used in Canada be increased using a minimum length that varies as a function of the operating speed and the assumed speed differential between the passing and passed vehicles. The authors consider the 85th percentile d_2 values shown in Table 37 to be preferable to the Canadian approach of revising minimum passing zone length criteria, because operating speeds are generally known on a site-specific basis, but speed differentials between passing and passed vehicles are not. Furthermore, the field data collected in this study indicate the left-lane travel distance of the passing vehicle (d_2) does not vary as a function of passed vehicle speed and speed differential.

PSD Criteria for Design

Six alternatives for determining PSD criteria for application in design were assessed in the research:

- Alternative 1: Retain the current AASHTO *Green Book* (*1*) criteria.
- Alternative 2: Update the parameter values in the AASHTO model to match the values used above with the Glennon and Hassan et al. models for marking criteria.
- Alternative 3: Use the same PSD criteria for geometric design specified in the MUTCD (*2*) for marking passing and no-passing zones.
- Alternative 4: Use an approach in which the PSD criteria for design are equal to the PSD criteria used for marking plus a quantity X to be determined:

$$PSD = PSD_{MUTCD} + X \tag{65}$$

where
PSD_{MUTCD} = sight distance used by the MUTCD for marking passing and no-passing zones.

In this concept, X could be equal to the distance traveled by the passing vehicle from the start of the passing maneuver to the critical position (d_5), as recommended by Lieberman (*11*). Or, X could have one value for a typical two-lane road and a larger value for a road with substantial truck volumes. It is likely that appropriate values of X should increase with increasing speed.

- Alternative 5: Use the same PSD criteria for design and marking, but require longer minimum passing zone lengths (or minimum lengths for regions with adequate PSD for passing) for all passing zones. In most terrain, this should result in passing zones with more PSD at the beginning of the zone.
- Alternative 6: Use a concept based on British or Australian practice, in which a longer sight distance (similar to current design criteria) is used to define the beginning of a region of adequate PSD and a shorter sight distance (similar to current marking criteria) is used to define the end of a region of adequate PSD.

Each of these alternative approaches to PSD design is assessed below.

Alternative 1: Current AASHTO Model

The evaluation of Alternative 1, retention of the current AASHTO design criteria, raises the following issues:

- The AASHTO PSD model is so extremely conservative that consideration of alternatives is appropriate. The model assumes that once initiated, passing maneuvers will be aborted, if at all, only very early in the maneuver. This does not match field observations of actual driver behavior.
- Two-lane highways with passing and no-passing zones marked in accordance with the MUTCD PSD criteria have been shown to operate very safely (*34*). The MUTCD PSD values are approximately half of those recommended by AASHTO for design.
- Exhibit 3-5 in the AASHTO *Green Book* (*1*) labels the AASHTO design values as representing "safe passing sight distance." This implies that PSD values less than the AASHTO design values may be unsafe, which is unfortunate because all two-lane highways in the U.S. are marked with the lower PSD values presented in the MUTCD. Two-lane highways marked with these criteria have been shown to operate very safely (*34*).
- Most engineers do not understand the derivation of the AASHTO and MUTCD PSD criteria or the reason that they differ. Neither the AASHTO *Green Book* or the MUTCD explain these differences.
- Design criteria are often intentionally set more conservatively than operational criteria. In the case of PSD, the more conservative AASHTO design criteria function primarily to encourage longer passing sections, resulting in greater operational efficiency (such as, improved level of service) than might be achieved if the MUTCD criteria were used in design. There is no evidence that longer PSD values than provided by the MUTCD criteria are needed for safety.

- Even if the AASHTO and MUTCD PSD criteria remain different, it would be desirable for them to have a defined relationship or an explicit rationale for how and why they are different. And, it would be desirable for that relationship or rationale to be fully explained in the AASHTO *Green Book,* the MUTCD, or other supporting document(s).
- Design PSD criteria could be set at some intermediate level between the current AASHTO and MUTCD criteria, while still providing favorable safety and traffic operational efficiency.
- The AASHTO PSD criteria, by themselves, do not assure long passing zones or increased operational efficiency on a two-lane highway because design policies do not specify any minimum percentage of road length over which the AASHTO PSD criteria must be met. The cost of providing PSD varies greatly from one project to another and, therefore, it would be impractical to set a general policy for the minimum percentage of road length for which PSD is provided, so AASHTO policy leaves this decision to individual highway agencies and individual designers. The decision by designers as to what length of the project will have above-minimum PSD appears to be much more important in determining the operational efficiency of the roadway than the PSD criteria used.
- The need for an explicit check of the operational efficiency of any proposed two-lane highway design should be emphasized in the *Green Book.* The importance of the percentage of roadway length with PSD should be emphasized in the *Green Book* as an explicit design check. It would be highly desirable for the *Green Book* to encourage the designer to check the anticipated percentage of roadway length with marked passing zones; it is hard to envision how the design process can be successful without explicitly considering the passing and no-passing zones that will be marked on the completed roadway and the operational effects of those markings.

Based on issues discussed above, consideration of PSD design criteria as alternatives to the current AASHTO criteria appears appropriate.

Alternative 2: Update Parameter Values in the Current AASHTO Model

Alternative 2 involves updating the parameter values in the AASHTO model to match those used in this report with the Glennon and Hassan et al. models for marking criteria. Specifically, the assumptions are:

- Average speed of the passed vehicle is equal to the design speed of the highway.
- Speed differential between the passing and passed vehicles is 19 km/h (12 mph) independent of design speed.
- Left-lane travel time for the passing vehicle is equal to the 85th percentile value of 12.3 sec.
- Minimum clearance interval between passing and opposing vehicles at the end of the maneuver is 1 sec.

Table 39 shows the computed PSD for Alternative 2. The PSD values are about the same as the current AASHTO PSD values at design speed of 64 km/h (40 mph) and below and exceed the current AASHTO values for speeds of 72 km/h (45 mph) and above. Thus, at higher speeds, these criteria are even more conservative than the current AASHTO criteria.

Alternative 3: Use the Same PSD Criteria for Both Design and Marking

Alternative 3 suggests that the current MUTCD PSD marking criteria, which have been recommended above for retention, be used for design and marking. The consideration of Alternative 3 is appropriate because there is every indication that two-lane highways operate safely under current PSD marking criteria, so there is no clear safety rationale for a requirement to consider longer sight distances in design. Adoption of Alternative 3 would have the advantage in that it would require the designer to look directly at how the completed highway will be marked and will operate. However, Alternative 3 would remove any cushion for operational efficiency or safety provided by the design process in ensuring that the completed highway has more PSD and longer passing zones than the minimum necessary. This cushion may be important to traffic operations in future years if, for example, new intersections providing access to new development shorten or eliminate some passing zones. For these reasons, Alternative 3 is not recommended. The remainder of this assessment

Table 39. PSD criteria for alternative 2 (updated parameter values in the AASHTO model).

Design speed (mph)	Current AASHTO design PSD criteria (ft) $d_1+d_2+d_3+d_4$	Updated AASHTO design PSD criteria (ft) $d_1+d_2+d_3+d_4$
20	710	720
25	900	910
30	1,090	1,100
35	1,280	1,290
40	1,470	1,500
45	1,625	1,700
50	1,835	1,900
55	1,985	2,110
60	2,135	2,320
65	2,285	2,520
70	2,480	2,720
75	2,580	2,920
80	2,680	3,120

focuses on PSD design criteria between the current AASHTO and MUTCD criteria.

Alternative 4: Use Marking PSD Criteria Plus a Specified Increment for Design

Alternative 4 would use design PSD criteria based on the marking PSD criteria plus a specified increment of distance, as shown in Equation (65). The most logical increment of distance to consider is d_5, the travel distance for the passing vehicle from the beginning of the passing maneuver to the abreast position. Thus, Equation (65) would be recast as:

$$PSD = PSD_{MUTCD} + d_5 \quad (66)$$

Values of d_5 for use in design can be estimated from Equations (3) and (62). The inclusion of d_5 in Equation (66) would assure that each passing section provided in accordance with the design PSD criteria would have sufficient sight distance for a driver entering the passing section to see beyond the d_2 distance required to complete the passing maneuver, to see the entire roadway needed to reach the abreast position, and to see the entire roadway the MUTCD PSD criteria require the driver to be able to see from the abreast position. The PSD criteria based on Alternative 4 and Equation (66) do not provide sufficient PSD to permit the passing driver to know that no potentially conflicting vehicle will appear in the opposing lane during the maneuver, but even the current AASHTO design PSD criteria do not assure that.

Table 40 shows the derivation of the Alternative 4 PSD criteria based on Equation (66) and compares those criteria to the current MUTCD and AASHTO criteria and the 85th percentile d_2 distances.

Alternative 5: Use Design PSD Criteria Based on the Larger Value of the Marking PSD Criteria and Distance d_2

The concept for Alternative 5 is to base design PSD on the larger value of the marking PSD criteria and the 85th percentile value of distance d_2. This assures that the passing driver initiating a passing maneuver not only has the sight distance required for a marked passing zone, but also can see the road ahead for the entire 85th percentile distance to be traversed by the passing vehicle. In fact, the 85th percentile value of d_2 is always the longer of these two distances.

Table 41 shows the derivation of the Alternative 5 PSD criteria and compares those criteria to the current MUTCD and AASHTO criteria and the 85th percentile d_2 distance.

Alternative 6: Longer PSD at Beginning of PSD Region than at the End of the PSD Region

Alternative 6 is an interesting possibility. This alternative, which is actually used in geometric design in Britain and Australia, requires greater sight distance to begin a passing zone (or a region of PSD sufficient for passing) than to end a passing zone (or a region of PSD sufficient for passing). This concept has the potential to tie together the disparate design and marking criteria into a unified method of looking at PSD needs; for example, design PSD criteria could define the beginning of a region of adequate PSD and marking PSD criteria could define the end of a region of adequate PSD.

Table 42 presents candidate PSD criteria for the beginning and end of a region with PSD sufficient for passing. The PSD criteria for the beginning of the passing region are based on

Table 40. Derivation of PSD criteria for alternative 4.

Design speed (mph)	Current marking PSD criteria (ft)[a]	d_5 (ft)[b]	Candidate PSD criteria for Alternative 4 (ft)[c]: Computed	Candidate PSD criteria for Alternative 4 (ft)[c]: Rounded for design	Current design PSD criteria (ft)[d]	85th percentile value of distance d_2 (ft)[e]
20	400	145	545	545	710	361
25	450	181	631	635	900	451
30	500	217	717	720	1,090	541
35	550	253	803	805	1,280	631
40	600	289	889	890	1,470	722
45	700	325	1,025	1,025	1,625	812
50	800	362	1,162	1,165	1,835	902
55	900	398	1,298	1,300	1,985	992
60	1,000	434	1,434	1,450	2,135	1,082
65	1,100	470	1,570	1,600	2,285	1,173
70	1,200	506	1,706	1,750	2,480	1,263
75	1,300	542	1,842	1,850	2,580	1,353
80	1,400	579	1,979	2,000	2,680	1,443

[a] Based on MUTCD (*2*).
[b] Derived from Equations (3) and (62).
[c] Derived from Equation (66).
[d] Based on AASHTO *Green Book* (*1*).
[e] Based on Table 25.

Table 41. Derivation of PSD criteria for alternative 5.

Design speed (mph)	Current marking PSD criteria (ft)[a]	85th percentile value of distance d_2 (ft)[b]	Candidate PSD criteria for Alternative 5 (ft)[c]		Current design PSD criteria (ft)[d]
			Computed	Rounded for design	
20	400	361	400	400	710
25	450	451	451	500	900
30	500	541	541	550	1,090
35	550	631	631	650	1,280
40	600	722	722	750	1,470
45	700	812	812	850	1,625
50	800	902	902	950	1,835
55	900	992	992	1,000	1,985
60	1,000	1,082	1,082	1,100	2,135
65	1,100	1,173	1,173	1,200	2,285
70	1,200	1,263	1,263	1,300	2,480
75	1,300	1,353	1,353	1,400	2,580
80	1,400	1,443	1,443	1,450	2,680

[a] Based on MUTCD (*2*).
[b] Based on Table 25.
[c] Larger of marking PSD criteria or 85th-percentile value of d_2.
[d] Based on AASHTO *Green Book* (*1*).

the Alternative 4 criteria. The PSD criteria for the end of the passing region are based on the current marking PSD criteria.

A variation of Alternative 6 would be to use the current AASHTO design PSD criteria for the beginning of a passing region.

Comparison of Alternatives

Table 43 compares the PSD values for the five alternatives discussed above and also includes the AASHTO *Green Book* design values for stopping sight distance. All of these sight distances are also compared in Figure 28.

There is no evidence of any safety basis for choosing among these alternatives. Two-lane highways can be operated safely with any of the PSD criteria shown in Table 43. The primary considerations in selecting PSD criteria are operational efficiency and construction cost. The longest PSD criteria in Table 43 are the current AASHTO design criteria, and they would be expected to provide the greatest operational efficiency, if no other considerations mattered. However, the designers choice for a given project of the percentage of roadway length over which above-minimum PSD will be provided very likely has more effect on the operational efficiency of the completed highway than the PSD criteria.

Table 42. Candidate PSD criteria for alternative 6.

Design speed (mph)	PSD criterion (ft) for: Beginning of passing section[a]	End of passing section[b]
20	545	400
25	635	450
30	720	500
35	805	550
40	890	600
45	1,025	700
50	1,165	800
55	1,300	900
60	1,450	1,000
65	1,600	1,100
70	1,750	1,200
75	1,850	1,300
80	2,000	1,400

[a] Alternative 4 in Table 40.
[b] MUTCD PSD criteria from Table 3.

Construction cost is clearly a factor that influences PSD design. Relatively few new two-lane highways are being constructed today; most two-lane highway projects involve reconstruction or rehabilitation. Several highway agencies have indicated that they consider it impractical to make additional expenditures to achieve the *Green Book* PSD values in design given that the completed roadway will be marked in accordance with the MUTCD PSD values. One highway agency that has constructed new two-lane highway corridors in hilly terrain found that it would be less expensive to construct a four-lane highway than to achieve a high percentage of the roadway length with *Green Book* PSD values.

Since highway agencies are reluctant to incur increased construction costs to provide the full *Green Book* PSD values, any potential traffic operational benefits from longer passing zones and longer sight distances are not being achieved. It appears most reasonable to adopt Alternative 3 and use in design the same MUTCD PSD values used to mark passing and no-passing zones on two-lane highways. This will provide desirable consistency between design and marking practice. Potential text revisions to incorporate the MUTCD PSD criteria in the *Green Book* are presented in the following material.

The recent Canadian study (*58*) of PSD design and marking criteria came to a similar conclusion that the use of longer PSD values in design could be only justified on the basis of

Table 43. Comparison of alternative sight distance values.

Designor operating speed (mph)	Alternative 1: Current AASHTO design PSD criteria (ft) $d_1+d_2+d_3+d_4$	Alternative 2: Updated AASHTO design PSD criteria (ft) $d_1+d_2+d_3+d_4$	Alternative 3: MUTCD PSD criteria[a] (ft) PSD_{MUTCD}	Alternative 4: MUTCD PSD criteria plus d_5[b] (ft) $PSD_{MUTCD+d_5}$	Alternative 5: Tentative minimum passing zone length (ft) d_2	AASHTO SSD criteria (ft)
20	710	720	400[c]	545	400	115
25	900	910	450	635	500	155
30	1,090	1,100	500	720	550	200
35	1,280	1,290	550	805	650	250
40	1,470	1,500	600	890	750	305
45	1,625	1,700	700	1,025	850	360
50	1,835	1,900	800	1,165	950	425
55	1,985	2,110	900	1,300	1,000	495
60	2,135	2,320	1,000	1,450	1,100	570
65	2,285	2,520	1,100	1,600	1,200	645
70	2,480	2,720	1,200	1,750	1,300	730
75	2,580	2,920	1,300[c]	1,850	1,400	820
80	2,680	3,120	1,400[c]	2,000	1,450	910

[a] Sight distance for end of passing section for Alternative 6.
[b] Sight distance for beginning of passing section for Alternative 6.
[c] Estimated because outside of speed range used in the MUTCD.

operational efficiency rather than safety. However, that study recommended that the current Canadian PSD values used in design be left unchanged.

Recommended Changes to the AASHTO *Green Book*

Appendix A presents recommended text for revision of the PSD discussion on pages 118 to 126 of the AASHTO *Green Book* (*1*). The text revisions focus on replacement of the current design PSD criteria with the MUTCD PSD criteria used in marking passing and no-passing zones. The revised text also recommends that passing zones shorter than the guidelines shown in Table 37 not be considered in determining the percentage of roadway length with minimum PSD for traffic operational evaluations. The text revisions in Appendix A are recommended for consideration by the AASHTO Technical Committee on Geometric Design.

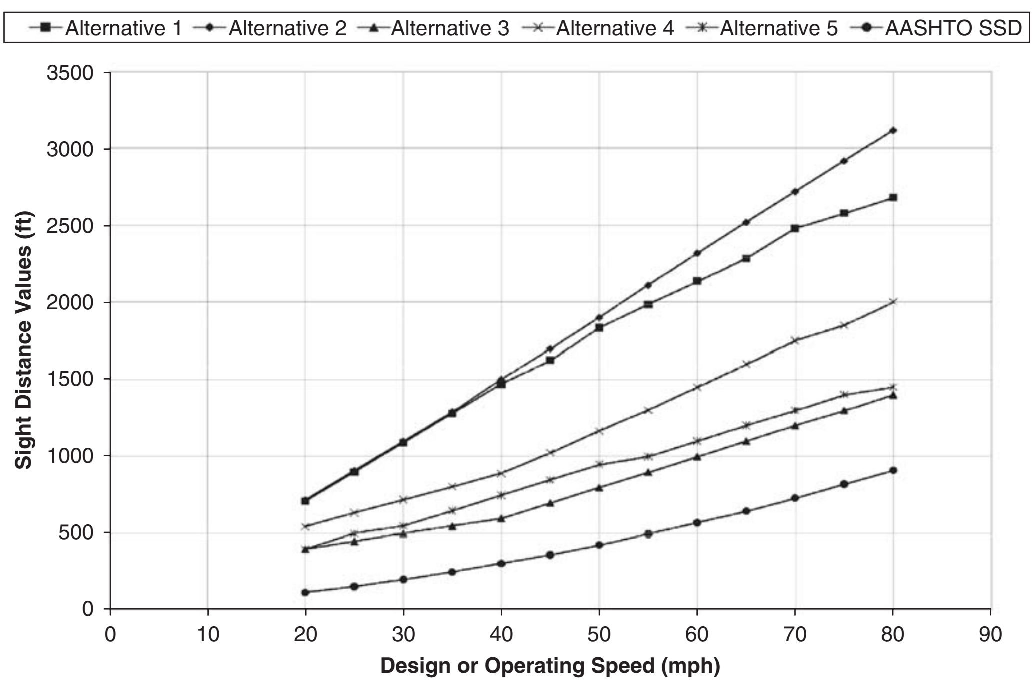

Figure 28. Comparison of alternative sight distance values.

CHAPTER 6

Conclusions and Recommendations

The conclusions and recommendations of the study are presented below.

General

1. The operational efficiency of many two-lane highways depends on the opportunity for faster drivers to pass slower drivers. Where faster drivers encounter a slower driver but are unable to pass, platoons form and the level of service of the two-lane highway deteriorates.
2. PSD is provided in the design of two-lane highways to provide opportunities for faster drivers to pass where gaps in opposing traffic permit. Passing and no-passing zones are marked in the centerline of two-lane highways to indicate where it is legal for drivers to make such passing maneuvers.
3. PSD design for two-lane highways are based on criteria in the AASHTO *Green Book* (*1*) that were derived from older data and have been unchanged for many years. These design PSD criteria are presented in Table 1.
4. Marking of passing and no-passing zones is based on PSD criteria presented in the MUTCD (*2*). The MUTCD criteria are based on the values in a 1940 AASHO guide and represent a subjective compromise between sight distances computed for flying passes and sight distances computed for delayed passes. The marking PSD criteria, presented in Table 3, are substantially less than the PSD criteria used in design.
5. The MUTCD provides guidance on minimum passing zone length of 120 m (400 ft) by stating that, where successive no-passing zones come within 120 m (400 ft) of one another, the no-passing-zone marking should be continued between them.

Alternative Models

6. At least 12 published sources over the period from 1971 to 1998 have proposed alternative models that represent the PSD needs of passing drivers for application to design and/or marking. These alternative models make varying assumptions about the appropriate theoretical form of PSD models and the parameters used in those models.
7. The alternative models that appear to most appropriately represent the PSD needs of passing drivers are those developed by Glennon (*14*) and Hassan et al. (*18*). Both of these models recognize that, in the early stages of a passing maneuver, the passing driver can easily and safely abort the passing maneuver. However, there is a critical position in the passing maneuver beyond which the driver is committed to complete the pass. Glennon modeled the critical position as the location when the sight distances needed to safely complete or abort the pass are equal. Hassan et al. noted that Glennon's critical position often occurs when the passing vehicle has moved in front of the passed vehicle and proposed that the critical position should be either the position where the front bumpers of the two vehicles are abreast or the position where the sight distances to complete or abort the pass are equal, whichever is reached first by the passing vehicle.

Field and Safety Study Results

8. Field studies conducted in Missouri and Pennsylvania as part of the current research, together with field data from a recent Texas study (*28*), can be used to characterize driver behavior and quantify traffic performance measures for passing maneuvers.
9. The mean speeds of passing vehicles observed in the current study were nearly equal to the 85th percentile speed for all traffic at the same sites. This suggests that the assumption in the AASHTO design criteria that the average speed of the passing vehicle is up to 19 km/h (12 mph) below the design speed of the highway is unrealistic.
10. The speed differential between the passing and passed vehicles at the position where the two vehicles are abreast is not strongly influenced by the speeds of the involved vehicles. Current AASHTO design criteria are based on

a speed differential of 16 km/h (10 mph), but the field data suggest that a value equal to 19 km/h (12 mph) would be more appropriate.

11. Current AASHTO design criteria are based on the assumption that the travel time in the left lane for a passing maneuver varies between 9.3 and 11.3 sec, with longer left-lane travel times at higher speeds. Field data show that the mean time spent in the left-lane during passing maneuvers on high-speed highways is 9.9 sec and the 85th percentile time spent in the left-lane is 12.3 sec. Furthermore, the field data do not indicate any variation of left-lane travel time with speed.
12. Field data indicate that the abreast position in a passing maneuver, beyond which the passing driver is committed to complete the pass, occurs after approximately 40 percent of the total left-lane distance has been traveled. Thus, once the first 40 percent of the passing maneuver is completed, the passing driver is committed to complete the remaining 60 percent of the passing maneuver.
13. Safety research by FHWA (*34*) found that less than 2 percent of total accidents (and probably about 3 percent of severe accidents) at nonintersection locations on two-lane highways are related to passing maneuvers. Furthermore, not all of the crashes that involve passing maneuvers are necessarily related to PSD. These findings strongly suggest that passing zones on two-lane highways established with the existing MUTCD PSD criteria generally operate safely.
14. Application of the field study results in the Glennon model produces PSD values that are equal to or slightly less than the MUTCD PSD values. Application of the field study results in the Hassan et al. model produces PSD values that are less than the MUTCD values at speeds of 72 km/h (45 mph) or less and greater than the MUTCD values by only 6 to 40 m (19 to 132 ft) at speeds of 80 km/h (50 mph) or more. These small differences in PSD, together with the good safety record for passing maneuvers on existing two-lane highways, do not indicate any need to modify the current MUTCD PSD criteria.
15. Laws and enforcement practices of most states require that passing maneuvers be completed before the end of a marked passing zone. However, the Glennon and Hassan et al. models provide sufficient sight distance for a passing driver to be in the critical position abreast of (or in the case of the Glennon model slightly ahead of) the passed vehicle at the end of a passing zone marked in accordance with the MUTCD and still complete the passing maneuver safely. There is, in effect, a buffer area at the end of each marked passing zone where it is safe, but not legal, for drivers to complete passing maneuvers. Some drivers (about 21 percent of passing drivers in longer passing zones) do extend passing maneuvers into this buffer area. But the buffer area makes current marking practices conservative and provides a margin of safety against collisions between passing and opposing vehicles that goes beyond the clearance times and distances assumed in PSD models. The presence of this buffer area is still another explanation of why the current MUTCD PSD criteria provide for safe passing operations on two-lane highways and should be retained.

Recommendations

16. Trucks require more PSD than passenger cars to pass slower vehicles. However, it would be impractical to base the passing and no-passing zone markings on the PSD requirements of trucks, because this would eliminate many passing zones used safely by passenger cars. Ultimately, the safety of passing maneuvers on two-lane highways depends more on the judgments of passing drivers concerning the traffic situation and the capabilities of their vehicles. All available evidence indicates that most drivers exercise good judgment in evaluating passing situations.
17. Older drivers clearly drive less aggressively than the driving population as a whole. The PSD at which an older driver would initiate a passing maneuver may well be greater than for a younger driver. However, there is no indication that older drivers look for passing opportunities or make passing maneuvers frequently. Typically, one would expect to find older drivers in the passed vehicle, not the passing vehicle, in a two-lane highway passing maneuver. There does not appear to be any need to make changes to the marking criteria for passing and no-passing zones on two-lane highways specifically for older drivers.
18. Although short passing zones with lengths of 120 to 240 m (400 to 800 ft) contribute little to the traffic operational efficiency of two-lane roads, they may be used for flying passes and for passing slower moving vehicles such as farm tractors. In the absence of any indication that such short zones result in poor safety performance on two-lane highways, no change in the MUTCD 120-m (400-ft) minimum passing zone length guideline is recommended.
19. The MUTCD PSD criteria used for marking of passing and no-passing zones on two-lane roads are also recommended for use in PSD design. This will provide desirable consistency between PSD design and marking practices. The research found that two-lane highways can be safely designed with any set of PSD criteria used in marking passing and no-passing. The longer PSD criteria currently presented in the AASHTO *Green Book* might provide improved traffic operational efficiency, but are often considered to be impractical.
20. Modifications to the text of the AASHTO *Green Book* are recommended in Appendix A to implement Recommendation 19.

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APPENDIX A

Revised Text on Passing Sight Distance for the AASHTO *Green Book*

This appendix presents revised text on passing sight distance for consideration by AASHTO for inclusion in the AASHTO Policy on Geometric Design of Highways and Streets (*1*), commonly known as the *Green Book.* This text could replace the PSD discussion that appears on pages 118 to 126 of the current *Green Book.*

Passing Sight Distance for Two-Lane Highways

Criteria for Design

Most roads and many streets are two-lane, two-way highways on which vehicles frequently overtake slower moving vehicles. Passing maneuvers in which faster vehicles move ahead of slower vehicles must be accomplished on lanes regularly used by opposing traffic. If passing is to be accomplished safely, the passing driver should be able to see a sufficient distance ahead, clear of traffic, so that the passing driver can decide whether to initiate and to complete the passing maneuver without cutting off the passed vehicle before meeting an opposing vehicle that appears during the maneuver. When appropriate, the driver can return to the right lane without completing the pass if he or she sees opposing traffic is too close when the maneuver is only partially completed. Many passing maneuvers are accomplished without the driver being able to see any potentially conflicting vehicle at the beginning of the maneuver. An alternative to providing passing sight distance is found later in this chapter in the section on "Passing Lanes."

Minimum passing sight distances for use in design are based on the minimum sight distances presented in the MUTCD (**6**) as warrants for no-passing zones on two-lane highways. Design practice should be most effective when it anticipates the traffic controls (i.e. passing and no-passing zone markings) that will be placed on the highways. The safety of passing operations on two-lane highways is ultimately determined by the judgments of drivers in initiating and completing passing maneuvers in response to the driver's view of the road ahead provided by available passing sight distance and the passing and no-passing zone markings. Recent research has shown that the MUTCD passing sight distance criteria result in good safety performance for passing maneuvers on two-lane highways. (**6A**).

Design Values

The design values for passing sight distance are presented in Exhibit 3-4 and are shown in comparison to stopping sight distance criteria in Exhibit 3-5. It is apparent from the comparison in Exhibit 3-5 that the accommodation of passing maneuvers on a two-lane highway requires more sight distance than the stopping sight distance that is provided continuously along the highway.

Research has verified that the passing sight distance values in Exhibit 3-4 are consistent with field observation of passing maneuvers (**6A**). This research used two theoretical models for the sight distance needs of passing drivers; both models were based on the assumption that a passing driver will abort the passing maneuver and return to his or her normal lane behind the passed vehicle if a potentially conflicting vehicle comes into view before reaching a critical position in the passing maneuver beyond which the passing driver is committed to complete the maneuver. The Glennon model (**6B**) assumes that the critical position occurs where the passing sight distance to complete the maneuver is equal to the sight distance needed to abort the maneuver. The Hassan et al. model (**6C**) assumes that the critical position occurs where the passing sight distances to complete or abort the maneuver are equal or where the passing and passed vehicles are abreast, whichever occurs first.

Minimum passing sight distances for design of two-lane highways incorporate certain assumptions about driver behavior. Actual driver behavior in passing maneuvers varies widely. To accommodate these variations in driver behavior,

Metric				US Customary			
Design speed (km/h)	Assumed speeds (km/h) Passed vehicle	Passing vehicle	Passing sight distance (m)	Design speed (mph)	Assumed speeds (mph) Passed vehicle	Passing vehicle	Passing sight distance (ft)
30	11	30	120	20	8	20	400
40	21	40	140	25	13	25	450
50	31	50	160	30	18	30	500
60	41	60	180	35	23	35	550
70	51	70	210	40	28	40	600
80	61	80	245	45	33	45	700
90	71	90	280	50	38	50	800
100	81	100	320	55	43	55	900
110	91	110	355	60	48	60	1,000
120	101	120	395	65	53	65	1,100
130	111	130	440	70	58	70	1,200
				75	63	75	1,300
				80	68	80	1,400

Exhibit 3-4. Passing sight distance for design of two-lane highways.

the design criteria for passing sight distance should accommodate the behavior of a high percentage of drivers, rather than just the average driver. The assumptions made in applying the Glennon and Hassan et al. models (**6b, 6C**) are as follows:

1. The speeds of the passing and opposing vehicles are equal and represent the design speed of the highway
2. The passed vehicle travels at uniform speed and the speed difference between the passing and passed vehicles is 19 km/h [12 mph]
3. The passing vehicle has sufficient acceleration capability to reach the specified speed difference relative to the passed vehicle by the time it reaches the critical position, which generally occurs about 40 percent of the way through the passing maneuver
4. The lengths of the passing and passed vehicles are 5.8 m [19 ft], as shown for the PC design vehicle in Chapter 2
5. The passing driver's perception-reaction time in deciding to abort a passing vehicle is 1 sec
6. If a passing maneuver is aborted, the passing vehicle will use a deceleration rate of 3.4 m/sec2 [11.1 ft/sec2], the same deceleration rate used in stopping sight distance design criteria
7. For a completed or aborted pass, the space headway between the passing and passed vehicles is 1 sec
8. The minimum clearance between the passing and opposing vehicles at the point at which the passing vehicle returns to its normal lane is 1 sec

The application of the passing sight distance models using these assumptions is presented in NCHRP Report ___ (**6A**).

Passing sight distance for use in design should be based on a single passenger vehicle passing a single passenger vehicle. While there may be occasions to consider multiple passings, where two or more vehicles pass or are passed, it is not practical to assume such conditions in developing minimum design criteria. Research has shown that longer sight distances are often needed for passing maneuvers then the passed vehicle, the passing vehicle, or both, are trucks (**6D**). Longer sight distances occur in design and such locations can accommodate an occasional multiple passing maneuver or a passing maneuver involving a truck.

Effect of Grade on Passing Sight Distance

Appreciable grades may affect the sight distance needed for passing. However, if the passing and passed vehicles are on a downgrade, the opposing vehicle is on an upgrade, and vice versa, so the effects of the grade on the acceleration capabilities of the vehicle may offset. Passing drivers generally exercise good judgment about whether to initiate and complete passing maneuvers. Where frequent slow-moving vehicles are present on a two-lane highway upgrade, a climbing lane may be provided to provide opportunities to pass the slow-moving vehicles without limitations due to sight distance and opposing traffic (see the section on Climbing Lanes in this chapter).

Frequency and Length of Passing Sections

Sight distance adequate for passing should be encountered frequently on two-lane highways. Each passing section along a length of roadway with sight distance ahead equal to or greater than the minimum passing sight distance should be as long as practical. The frequency and length of passing sections for highways depend, principally on the topography, the design speed of highway, and the cost; for streets, the spacing of intersections is the principal consideration.

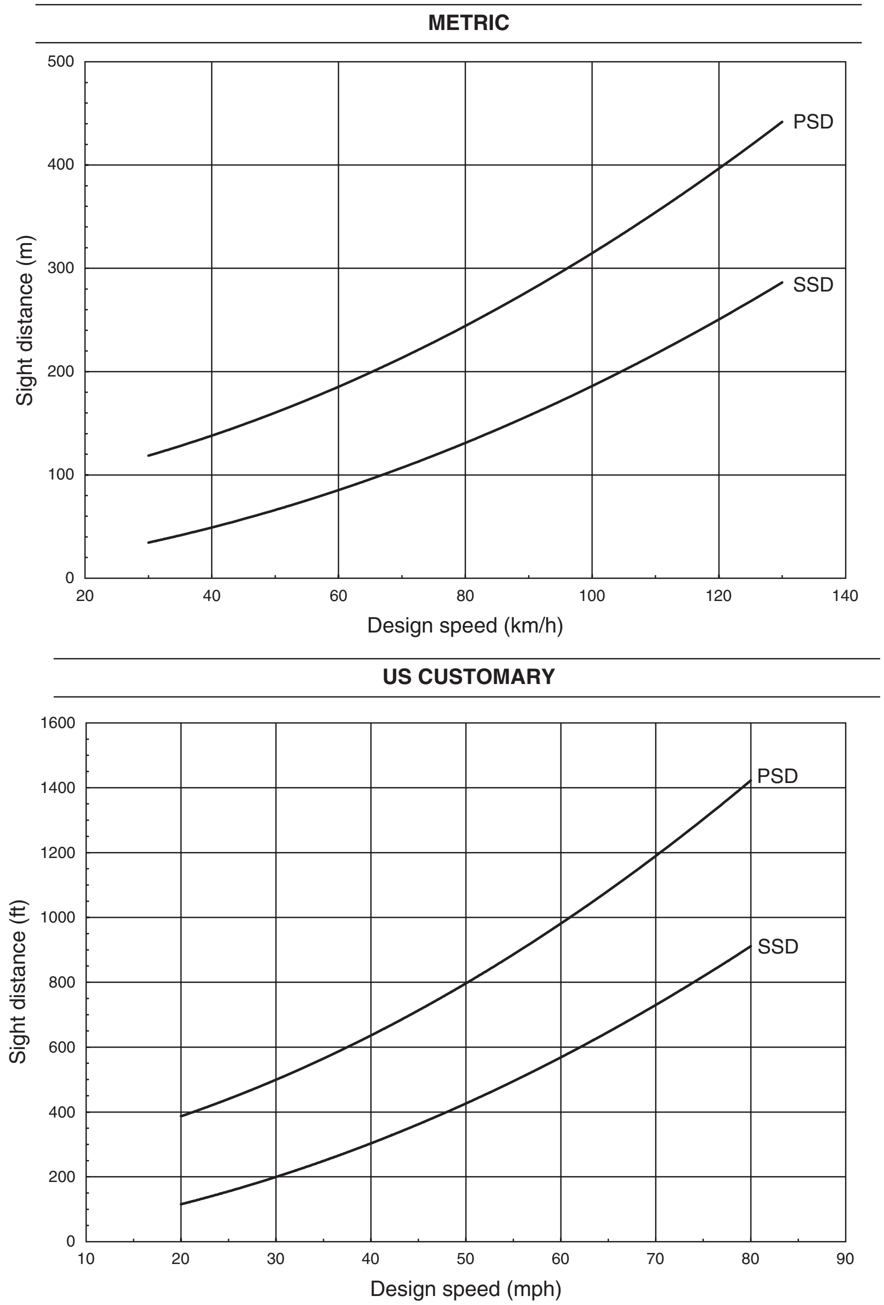

Exhibit 3-5. Comparison of design values for passing sight distance and stopping sight distance.

It is not practical to directly indicate the frequency with which passing sections should be provided on two-lane highways due to the physical and cost limitations. During the course of normal design, passing sections are provided on almost all highways and selected streets, but the designer's appreciation of their importance and a studied attempt to provide them can usually ensure others at little or no additional cost. In steep mountainous terrain, it may be more economical to build intermittent four-lane sections or passing lanes with stopping sight distance on some two-lane highways, in lieu of two-lane sections with passing sight distance. Alternatives are discussed later in this chapter in the section on Passing Lanes.

The passing sight distances shown in Exhibit 3-4 are sufficient for a single or isolated pass only. Designs with infrequent passing sections will not assure that opportunities for passing are available. Even on low-volume roadways, a driver desiring to pass may, on reaching the passing section, find vehicles in the opposing lane and thus be unable to use the passing section or at least may not be able to begin to pass at once.

The importance of frequent passing sections is illustrated by their effect on the level of service of a two-lane, two-way highway. The procedures in the *Highway Capacity Manual* (**14**) to analyze two-lane, two-way highways base the level-of-service criteria on two measures of effectiveness—percent time spent following and average travel speed. Both of these criteria are affected by the lack of passing opportunities. The HCM procedures show, for example, up to a 19 percent increase in the percent time spent following when the directional split is 50/50 and no-passing zones comprise 40 percent of the analysis length compared to a highway with similar traffic volumes and no sight restrictions. The effect of restricted passing sight distance is even more severe for unbalanced flow and where the no-passing zones comprise more than 40 percent of the length.

There is a similar effect on the average travel speed. As the percent of no-passing zones increases, there is an increased reduction in the average travel speed for the same demand flow rate. For example, a demand flow rate of 800 passenger cars per hour incurs a reduction of 3.1 km/h (1.9 mph) when no-passing zones comprise 40 percent of the analysis length compared to no reduction in speed on a route with unrestricted passing.

The HCM procedures indicate another possible criterion for passing sight distance design on two-lane highways that are several miles or more in length. The available passing sight distances along this length can be summarized to show the percentage of length with greater-than-minimum passing sight distance. Analysis of capacity related to this percentage would indicate whether or not alignment and profile adjustments are needed to accommodate the design hourly volume (DHV). When highway sight distances are analyzed over the whole range of lengths within which passing maneuvers are made, a new design criterion may be evaluated. Where high traffic volumes are expected on a highway and a high level of service is to be maintained, frequent or nearly continuous passing sight distances should be provided.

The HCM procedures and other traffic models can be used in design to determine the level of service that will be provided by the passing sight distance profile for any proposed design alternative. The level of service provided by the proposed design should be compared to the highway agency's desired level of service for the project and, if the desired level of service is not achieved, the feasibility and practicality of adjustments to the design to provide additional passing sight distance should be considered. Passing sections shorter than 120 to 240 m (400 to 800 ft) have been found to contribute little to improving the traffic operational efficiency of a two-lane highway. In determining the percentage of roadway length with greater-than-minimum passing sight distance, passing sections shorter than the minimum lengths shown in Exhibit 3-6 should be excluded from consideration.

Sight Distance for Multilane Highways

It is not necessary to consider passing sight distance on highways or streets that have two or more traffic lanes in each direction of travel. Passing maneuvers on multilane roadways are expected to occur within the limits of the traveled way for each direction of travel. Thus, passing maneuvers that involve crossing the centerline of four-lane undivided roadways or crossing the median of four-lane roadways should be prohibited.

Multilane roadways should have continuously adequate stopping sight distance, with greater-than-design sight distances preferred. Design criteria for stopping sight distance vary with vehicle speed and are discussed in detail at the beginning of this chapter.

Metric		U.S. Customary	
85th percentile speed or posted or statutory speed limit (km/h)	Minimum passing zone length (m)	85th percentile speed or posted or statutory speed limit (mph)	Minimum passing zone length (ft)
40	140	20	400
50	180	30	550
60	210	35	650
70	240	40	750
80	240	45	800
90	240	50	800
100	240	55	800
110	240	60	800
120	240	65	800
		70	800

Exhibit 3-6. Minimum passing zone lengths to be included in traffic operational analyses.

References

6. U.S. Department of Transportation, *Manual on Uniform Traffic Control Devices for Streets and Highways,* Federal Highway Administration, 2003.

6A. Harwood, D. W., D. K. Gilmore, K. R. Richard, J. M. Dunn, and C. Sun, *Passing Sight Distance Design Criteria,* NCHRP Report ___, Transportation Research Board, 2007. [Include NCHRP report number for this report, when published.]

6B. Glennon, J. C., "New and Improved Model of Passing Sight Distance on Two-Lane Highways," *Transportation Research Record 1195,* Transportation Research Board, 1998.

6C. Hassan, Y., S. M. Easa, and A. O. Abd El Halim, "Passing Sight Distance on Two-Lane Highways: Review and Revision," *Transportation Research Part A,* Vol. 30, No. 6, 1996.

6D. Harwood, D. W., and J. C. Glennon, "Passing Sight Distance Design for Passenger Cars and Trucks," *Transportation Research Record 1208,* Transportation Research Board, 1989.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation