Passing Sight Distance Criteria

Interim Report

NCHRP Project 15-26
MRI Project 110348

Prepared for

National Cooperative Highway Research Program
Transportation Research Board
National Research Council

Midwest Research Institute

March 2005
Acknowledgment of Sponsorship and Disclaimer

Acknowledgment

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Preface

This interim report was prepared for the National Cooperative Highway Research Program (NCHRP) under the requirements of NCHRP Project 15-26, “Passing Sight Distance Criteria.” The report was prepared by Mr. Douglas W. Harwood, Mr. David K. Gilmore, Ms. Ingrid B. Potts, and Dr. Darren J. Torbic of Midwest Research Institute (MRI) and Dr. Forrest M. Council of BMI-SG. The report presents the results of Phase I of the research and presents a recommended research plan for Phase II. We look forward to discussing the Phase I results and the Phase II work plan with the NCHRP project panel. MRI will not proceed with work in Phase II of the project until receiving NCHRP authorization.

MIDWEST RESEARCH INSTITUTE

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March 2005
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Section 1.
Introduction

1.1 Background

Passing sight distance (PSD) is a key consideration in both 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 2001 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 during 1938 and 1941. Surveys conducted in 1971 and 1978 found that AASHTO values for PSD were conservative, except at passing vehicle speeds above 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 are in need for replacement or modification and whether there is a need to rationalize or reconcile these two separate sets of criteria.

1.2 Research Objectives and Scope

The objectives of the proposed research are to evaluate the design and operational criteria for determining minimum PSD and to modify or develop new PSD criteria. The project scope will include potential modifications to both the PSD design criteria presented in the Green Book and the PSD marking criteria presented in the MUTCD.
1.3 Research Approach

This interim report represents the completion of Phase I of the research. Phase I has included five tasks:

- Task 1: Review Current PSD Criteria and Models
- Task 2: Review Literature and Research in Progress
- Task 3: Identify Factors That Potentially Contribute to PSD Requirements
- Task 4: Critique PSD Criteria and Develop Work Plan
- Task 5: Prepare Interim Report

Phase II of the research will begin upon authorization to proceed by NCHRP. The research in Phase II will consist of four tasks, as follows:

- Task 6: Execute Approved Work Plan
- Task 7: Prepare New or Modified PSD Criteria
- Task 8: Prepare Final Report
- Task 9: Prepare and Deliver Final Presentations

Our recommended approach to these tasks is presented later in this report.

1.4 Organization of This Report

This interim report presents an overview of the work conducted in Phase I of the research. The remainder of this report is organized as follows. Section 2 reviews current PSD criteria for geometric design and marking of passing and no-passing zones. Section 3 presents a review and critique of various alternative PSD models that have been in the literature. Section 4 reviews key PSD-related issues. Section 5 presents potential work plans for data collection and analysis in Phase II. Section 6 describes the work to be performed in Phase II as a whole and addresses priorities and budget allocations for Phase II. Section 7 presents a list of references cited in this interim report.
Section 2. Current Passing Sight Distance Design and Marking Criteria

This section 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.

2.1 AASHTO Green Book Criteria for PSD Design

The current PSD design criteria for two-lane highways in the 2001 Green Book are essentially unchanged from the criteria in the 1954 AASHTO 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:

\[ \text{PSD} = d_1 + d_2 + d_3 + d_4 \]  

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 (i.e., clearance distance)
- \( d_4 \) = distance traveled by an opposing vehicle for two-thirds of the time the passing vehicle occupies the left lane, or \( 2/3 \) 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. The speed of the passed vehicle is up to 22 mph less than the design speed of the 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 \( d_i \) is computed in the Green Book as:

<table>
<thead>
<tr>
<th>Metric</th>
<th>US Customary</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_i = 0.278t_1 \left( v - m + \frac{at_1}{2} \right) )</td>
<td>( d_i = 1.47t_1 \left( v - m + \frac{at_1}{2} \right) )</td>
</tr>
</tbody>
</table>

where:

| \( t_1 \) | time of initial maneuver, s; |
| \( a \) | average acceleration, km/h/s; |
| \( v \) | average speed of passing vehicle, km/h; |
| \( m \) | difference in speed of passed vehicle and passing vehicle, km/h |

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 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:

<table>
<thead>
<tr>
<th>Metric</th>
<th>US Customary</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_2 = 0.278v t_2 )</td>
<td>( d_2 = 1.47v t_2 )</td>
</tr>
</tbody>
</table>

where:

| \( t_2 \) | time passing vehicle occupies the left lane, s; |
| \( v \) | average speed of passing vehicle, km/h |

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 1.38 to 1.51 mph/s.
Figure 1. Elements of Passing Sight Distance for Two-Lane Highways (1)

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

<table>
<thead>
<tr>
<th>Component of passing maneuver</th>
<th>Metric</th>
<th>US Customary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50-65</td>
<td>66-80</td>
</tr>
<tr>
<td></td>
<td>56.2</td>
<td>70.0</td>
</tr>
<tr>
<td>Average passing speed (km/h)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average passing speed (mph)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial maneuver:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a = average acceleration a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t1 = time (sec)a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d1 = distance traveled</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupation of left lane:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t2 = time (sec)a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d2 = distance traveled</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearance length:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d3 = distance traveled a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opposing vehicle:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d4 = distance traveled</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total distance, d1 + d2 + d3 + d4</td>
<td>317</td>
<td>446</td>
</tr>
</tbody>
</table>

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.
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 30 to 70 mph.

The clearance distance (\(d_3\)) is estimated in the Green Book to range from 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 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.

### 2.2 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.

The MUTCD PSD criteria are substantially less than the Green Book PSD design criteria. For example, at a speed of 60 mph, the AASHO and MUTCD PSD criteria are 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). These earlier AASHTO 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.
Table 2. Passing Sight Distance for Design of Two-Lane Highways (1)

<table>
<thead>
<tr>
<th>Design speed (km/h)</th>
<th>Metric</th>
<th>Passed vehicle</th>
<th>Passing vehicle</th>
<th>Lost vehicle</th>
<th>Passed vehicle</th>
<th>Rounding for design</th>
<th>US Customary</th>
<th>Passed vehicle</th>
<th>Passing vehicle</th>
<th>Rounding for design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metric</td>
<td>Passed vehicle</td>
<td>Passing vehicle</td>
<td>Calculated</td>
<td>Rounded for design</td>
<td>Design speed (mph)</td>
<td></td>
<td>Passed vehicle</td>
<td>Passing vehicle</td>
<td>Rounding for design</td>
</tr>
<tr>
<td>30</td>
<td>200</td>
<td>29</td>
<td>44</td>
<td>200</td>
<td>200</td>
<td>20</td>
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<td>47</td>
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<td>670</td>
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<td>2281</td>
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</tr>
<tr>
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<td>812</td>
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<td>815</td>
<td>70</td>
<td>54</td>
<td>64</td>
<td>2479</td>
<td>2480</td>
</tr>
</tbody>
</table>

1. NCHRP PROJECT 15-26 INTERIM REPORT.DOC
Table 3. Minimum Passing Sight Distance for Marking Passing and No-Passing Zones on Two-Lane Highways (2)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Minimum passing sight distance (m)</th>
<th>U.S. Customary</th>
<th>Minimum passing sight distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>85th percentile speed or posted or statutory speed limit (km/h)</td>
<td></td>
<td>85th percentile speed or posted or statutory speed limit (mph)</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>140</td>
<td>25</td>
<td>450</td>
</tr>
<tr>
<td>50</td>
<td>160</td>
<td>30</td>
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<td>180</td>
<td>35</td>
<td>550</td>
</tr>
<tr>
<td>70</td>
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</tr>
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</tr>
<tr>
<td>90</td>
<td>280</td>
<td>50</td>
<td>800</td>
</tr>
<tr>
<td>100</td>
<td>320</td>
<td>55</td>
<td>900</td>
</tr>
<tr>
<td>110</td>
<td>355</td>
<td>60</td>
<td>1,000</td>
</tr>
<tr>
<td>120</td>
<td>395</td>
<td>65</td>
<td>1,100</td>
</tr>
</tbody>
</table>

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 400 ft by stating that, where two no-passing zones come within 400 ft of one another, the no-passing barrier stripe should be continued between them.

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

![Comparison of PSD Values for Green Book and MUTCD Models](image)

**Figure 3. Comparison of PSD Values for Green Book and MUTCD Models**

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.

- Neither the *Green Book* nor the MUTCD models contain a vehicle length term that would allow consideration of different vehicles types (e.g., 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. In fact, 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.

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 (d₀ through d₄) is extremely conservative, since it assumes that very early in the passing maneuver, the passing driver is committed to complete the pass. In fact, observation of two-lane highway operations shows that passing drivers frequently abort passing maneuvers.

While the MUTCD PSD criteria are not based on an explicit assumption about the passing situation represented, it will be demonstrated in Section 3 of this report 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 (i.e., 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 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 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 has also been incorporated in research on passing sight distance requirements published in 1982, 1983, 1988, 1989, 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 Section 3 of the interim report.

### 2.4 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. 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 counties 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.
Table 5 presents the PSD criteria used in geometric design in comparison to the criteria used in Canada, Britain, Australia, Austria, Germany, and Greece, 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 4, 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 at which 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 from which 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 at which 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
### Table 5. Passing Sight Distance Criteria Used in Geometric Design in Several Countries (20)

<table>
<thead>
<tr>
<th>Country</th>
<th>Design situation</th>
<th>Design or operating speed (km/h)</th>
<th>Based on distance shown in Figure 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Australia</td>
<td>ESD—beginning of PSD</td>
<td>AH</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>CSD—end of PSD</td>
<td>CF</td>
<td>–</td>
</tr>
<tr>
<td>Austria</td>
<td>beginning and end of PSD</td>
<td>BG</td>
<td>–</td>
</tr>
<tr>
<td>Britain</td>
<td>FOSD—beginning of PSD</td>
<td>BG</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>ASD—end of PSD</td>
<td>1/2 BG</td>
<td>–</td>
</tr>
<tr>
<td>Canada</td>
<td>beginning and end of PSD</td>
<td>AF</td>
<td>–</td>
</tr>
<tr>
<td>Germany</td>
<td>beginning and end of PSD</td>
<td>BG</td>
<td>–</td>
</tr>
<tr>
<td>Greece</td>
<td>beginning and end of PSD</td>
<td>BG</td>
<td>–</td>
</tr>
<tr>
<td>South Africa</td>
<td>beginning and end of PSD</td>
<td>AF</td>
<td>–</td>
</tr>
<tr>
<td>United States</td>
<td>beginning and end of PSD</td>
<td>AF</td>
<td>217</td>
</tr>
</tbody>
</table>

Note: Australian CSD and British FOSD and ASD values (see test 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.
assumption that the Australian equivalent of ASD is equal to an estimate of distance CF
in Figure 4.

![Figure 5. Passing Sight Distance Criteria Used in Geometric Design in Several Countries (20)](image)

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.

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 that is 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.

**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.

**Table 6. Passing Sight Distance Criteria Used as Warrants for Marking No-Passing Zone Barrier Lines in Selected Countries**

<table>
<thead>
<tr>
<th>Country</th>
<th>Prevailing 85th Percentile Speed (km/h)</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>85</th>
<th>90</th>
<th>100</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td></td>
<td>150</td>
<td>180</td>
<td>210</td>
<td>240</td>
<td>–</td>
<td>270</td>
<td>300</td>
<td>–</td>
</tr>
<tr>
<td>Britain</td>
<td></td>
<td>90</td>
<td>105</td>
<td>125</td>
<td>–</td>
<td>155</td>
<td>–</td>
<td>185</td>
<td>–</td>
</tr>
<tr>
<td>Canada</td>
<td></td>
<td>160</td>
<td>200</td>
<td>240</td>
<td>275</td>
<td>–</td>
<td>330</td>
<td>400</td>
<td>–</td>
</tr>
<tr>
<td>South Africa</td>
<td></td>
<td>150</td>
<td>180</td>
<td>–</td>
<td>250</td>
<td>–</td>
<td>320</td>
<td>–</td>
<td>400</td>
</tr>
<tr>
<td>United States</td>
<td></td>
<td>155</td>
<td>175</td>
<td>210</td>
<td>240</td>
<td>–</td>
<td>280</td>
<td>315</td>
<td>–</td>
</tr>
</tbody>
</table>

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.

Proudlove (21) also points out that countries differ in the location at which the beginning of a no-passing zone barrier line marking begins relative to the point at which the minimum PSD for marking of a passing zone is lost. Two concepts have been generally 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 at which the no-passing zone barrier line begins. The “long zone” concept allows drivers who 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; i.e., the marked no-passing zone barrier line begins at the point at which 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 at which the no-passing zone warrant is first met. This practice recognizes that substantial sight distance is still available at the point at which 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.

![Figure 6. Passing Sight Distance Criteria Used as Warrants for Marking No-Passing Zone Barrier Lines in Selected Countries (20)](image)

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.

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 are also 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.

**Table 7. Australian Criteria for Minimum Lengths and Spacings Between No-Passing Zone Barrier Lines**

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

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)**

<table>
<thead>
<tr>
<th>Country</th>
<th>Driver eye height (ft)</th>
<th>Object height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(ft)</td>
<td>(m)</td>
</tr>
<tr>
<td><strong>Australia</strong></td>
<td>3.8</td>
<td>1.15</td>
</tr>
<tr>
<td><strong>Austria</strong></td>
<td>3.3</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Britain</strong></td>
<td>3.4</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>Canada</strong></td>
<td>3.4</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>Germany</strong></td>
<td>3.3</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Greece</strong></td>
<td>3.3</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>South Africa</strong></td>
<td>3.4</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>United States</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(geometric design criteria)</td>
<td>3.5</td>
<td>1.08</td>
</tr>
<tr>
<td>(marking of barrier lines)</td>
<td>3.5</td>
<td>1.07</td>
</tr>
<tr>
<td><strong>Note:</strong> All values in the table are based on passenger cars; none of the countries reviewed are known to consider trucks in their PSD criteria.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Section 3.
Review of Alternative Passing Sight Distance Models

This section of the report reviews a variety of alternative PSD models that have been formulated and published in the literature over the years 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 Project 15-26 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 that were reviewed in Section 2 of this interim report.

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 are presented in the latter part of the section.

Each model is presented with symbols and notation that are uniquely defined in this report and may differ from the symbols and notation used by the original author or developer of the model. Thus, 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<sub>1</sub> through d<sub>4</sub> 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 (e.g., d<sub>5</sub>, d<sub>6</sub> or d<sub>7</sub>). Time variables with the same numerical subscript as a distance variable refer to the time required for a vehicle to travel the corresponding distance (i.e., t<sub>1</sub> represents the time required to travel distance d<sub>1</sub>). All variables and models have been converted to use U.S. customary units, even for models that were presented in metric units by their original authors. Section 3.14 summarizes all of the nomenclature used in PSD models in this report.

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

\[
PSD = d_5 + d_6 + d_3
\]  

where:  
- PSD = passing sight distance (ft)
- \( d_5 \) = distance traveled by the passing vehicle from the critical position until it returns to its own lane (ft)
- \( d_6 \) = distance traveled by the opposing vehicle from the time the passing vehicle reaches the critical position until it returns to its own lane (ft)
- \( d_3 \) = 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 at which 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 as the opposing vehicle will be traveling at the design speed, the impeding vehicle traveling at a constant speed, the speed differential between the impeding and passing vehicles is a constant 10 mph and the minimum clearance between the passing and opposing vehicles is 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 $d_3$ and $d_6$ were both 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
- flying forced return

The passing distances and speeds measured in the field for these four types of passing maneuvers are presented in Section 4.3 of this report.

**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.

<table>
<thead>
<tr>
<th>Average off-peak speed (mph)</th>
<th>Minimum passing sight distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>750</td>
</tr>
<tr>
<td>35</td>
<td>900</td>
</tr>
<tr>
<td>40</td>
<td>1,050</td>
</tr>
<tr>
<td>45</td>
<td>1,200</td>
</tr>
<tr>
<td>50</td>
<td>1,300</td>
</tr>
<tr>
<td>55</td>
<td>1,450</td>
</tr>
<tr>
<td>60</td>
<td>1,600</td>
</tr>
<tr>
<td>65</td>
<td>1,750</td>
</tr>
<tr>
<td>70</td>
<td>1,900</td>
</tr>
</tbody>
</table>

**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 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 which 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 Section 4.2 of this report. In summary, 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.

![Figure 7. PSD Values as a Function of Average Speed From the Van Valkenburg and Michael Model (8)](image)

**3.2 Weaver and Glennon (1972)**

**Conceptual Approach**

Weaver and Glennon (9) developed a PSD model for two-lane rural highways as an alternative to the AASHO 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 (i.e., striping policies). The model proposed by Weaver and Glennon differed from the AASHO 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:

\[ \text{PSD} = d_1 + 2.33d_2 + d_3 \]  \hspace{1cm} (5)

Required PSD at the end of a passing zone

\[ \text{PSD} = \frac{4}{3}d_2 + d_3 \]  \hspace{1cm} (6)

\[ d_1 = 1.47t_1 \left( V_p - m + \frac{at_1}{2} \right) \]  \hspace{1cm} (7)

\[ d_2 = 1.47Vt_2 \]  \hspace{1cm} (8)

where:
- \( d_1 \) = distance traveled during perception and reaction time (ft)
- \( d_2 \) = distance traveled while the passing vehicle occupies the left lane (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\(^2\))
- \( t_2 \) = time passing vehicle occupies the opposing lane (sec)

**Assumed Values of Model Parameters**

As in the AASHO 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 all assumed to be equal. The authors recommended the speed differential between the passing and passed vehicles should vary from 8 to 12 mph as a function of passed vehicle speed rather than being a constant value of 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.

Table 10. PSD Values Determined With the
Weaver and Glennon Model (9)

<table>
<thead>
<tr>
<th>Design speed (mph)</th>
<th>Minimum sight distance throughout zone (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1,135</td>
</tr>
<tr>
<td>60</td>
<td>1,480</td>
</tr>
<tr>
<td>65</td>
<td>1,655</td>
</tr>
<tr>
<td>70</td>
<td>1,825</td>
</tr>
<tr>
<td>75</td>
<td>2,000</td>
</tr>
<tr>
<td>80</td>
<td>2,170</td>
</tr>
</tbody>
</table>

Figure 8. PSD Values as a Function of Design Speed
From the Weaver and Glennon Model (9)

Critique

Weaver and Glennon independently recognized the importance of the critical position in the passing maneuver in work that was 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 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.

### 3.3 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

\[
PSD = \frac{2}{3}d_2 + d_3 + d_4
\]  
(9)

where: \(d_4\) = distance traveled by an opposing vehicle for two-thirds of the time the passing vehicle occupies the left lane (or \(\frac{2}{3}\) of \(d_2\)) (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 impeding 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 are also 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.

**Table 11. PSD Values Determined With the Harwood and Glennon Model (10)**

<table>
<thead>
<tr>
<th>Design speed (mph)</th>
<th>Passing sight distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>628</td>
</tr>
<tr>
<td>35</td>
<td>769</td>
</tr>
<tr>
<td>40</td>
<td>918</td>
</tr>
<tr>
<td>45</td>
<td>1,074</td>
</tr>
<tr>
<td>50</td>
<td>1,238</td>
</tr>
<tr>
<td>55</td>
<td>1,408</td>
</tr>
<tr>
<td>60</td>
<td>1,586</td>
</tr>
<tr>
<td>65</td>
<td>1,772</td>
</tr>
<tr>
<td>70</td>
<td>1,964</td>
</tr>
<tr>
<td>75</td>
<td>2,164</td>
</tr>
<tr>
<td>80</td>
<td>2,371</td>
</tr>
</tbody>
</table>

### 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. (26). 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.

![Figure 9. PSD Values as a Function of Design Speed from the Harwood and Glennon Model (10)](image)

3.4 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.

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

$$PSD = d_7 + PSD_c$$ \hspace{1cm} (10)

$$d_7 = G_1' + 1.47V_i t_7 + \Delta_c$$ \hspace{1cm} (11)

$$PSD_c = 1.47(2V_i + m)t_5 + d_3$$ \hspace{1cm} (12)

$$t_5 = 0.68[(G_1 + \Delta_c)/m] + (1.47 m/2a)$$ \hspace{1cm} (13)

$$\Delta_c = G_1 - 1.47 m t_5$$ \hspace{1cm} (14)

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

where:

- $d_7$ = 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)
- $G_1'$ = 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)
- $t_7$ = travel time from the start of the passing maneuver to the attainment of the critical position (sec)
- $t_5$ = time required for the passing vehicle to return to its own lane from the critical position for a completed passing maneuver (sec)
- $\Delta_c$ = relative position of the front bumpers of the passing and passed vehicles at the critical position (negative $\Delta_c$ means that passing vehicle is behind passed vehicle; positive $\Delta_c$ means that passing vehicle is in front of passed vehicle) (ft)
- $a_{\text{max}}$ = maximum vehicle acceleration achievable at zero speed (ft/sec$^2$)
- $V_{\text{max}}$ = 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 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, $\Delta_c$ 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 (9) through (14) are presented in Table 12 and the PSD values plotted as a function of speed are shown in Figure 10.

Table 12. PSD Values Determined With the Lieberman Model (11)

<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>Passing sight distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>860</td>
</tr>
<tr>
<td>35</td>
<td>1,084</td>
</tr>
<tr>
<td>40</td>
<td>1,320</td>
</tr>
<tr>
<td>45</td>
<td>1,568</td>
</tr>
<tr>
<td>50</td>
<td>1,828</td>
</tr>
<tr>
<td>55</td>
<td>2,099</td>
</tr>
<tr>
<td>60</td>
<td>2,383</td>
</tr>
</tbody>
</table>

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 entitled “Assumed Values for Model Parameters” section.

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 $\Delta_c$ 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 those recommended by Lieberman are often 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 should be considered for determining the desirable PSD at the beginning of a passing zone or in the early stages of a passing maneuver.

### 3.5 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 either 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**

\[
PSD = 2.93V_{85}t_d + d_3 - 0.73d_at_d^2
\]  \hspace{1cm} (16)

Passing maneuver aborted from head and tail position:

\[
t_d = \frac{2.93m + \sqrt{8.60m^2 + 11.73d_aG_2}}{2d_a}
\]  \hspace{1cm} (17)

Passing maneuver aborted from abreast position:

\[
t_a = \frac{2.93m + \sqrt{8.60m^2 + 11.73d_aG_3}}{2d_a}
\]  \hspace{1cm} (18)

where:  
- \(V_{85}\) = 85\textsuperscript{th} percentile speed (mph)
- \(t_d\) = deceleration time (sec)
- \(d_a\) = deceleration rate used in aborting a passing maneuver (ft/sec\(^2\))
- \(G_2\) = 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 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 9.7 ft/sec\(^2\)
- Length of impeding vehicle is accounted for in the value of \(G_3\)
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 10 mph for the speed difference between the passing and passed 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 (15) through (17) are presented in Table 13, and the PSD values plotted as a function of speed are shown in Figure 11.

Table 13. PSD Values Determined With the Saito Model (12)

<table>
<thead>
<tr>
<th>85th percentile speed (mph)</th>
<th>PSD(_{(\text{head-tail})})</th>
<th>PSD(_{(\text{abreast})})</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>410</td>
<td>284</td>
</tr>
<tr>
<td>35</td>
<td>524</td>
<td>372</td>
</tr>
<tr>
<td>40</td>
<td>646</td>
<td>463</td>
</tr>
<tr>
<td>45</td>
<td>773</td>
<td>559</td>
</tr>
<tr>
<td>50</td>
<td>905</td>
<td>659</td>
</tr>
<tr>
<td>55</td>
<td>1,043</td>
<td>763</td>
</tr>
<tr>
<td>60</td>
<td>1,186</td>
<td>870</td>
</tr>
<tr>
<td>65</td>
<td>1,334</td>
<td>980</td>
</tr>
<tr>
<td>70</td>
<td>1,486</td>
<td>1,093</td>
</tr>
</tbody>
</table>

Figure 11. PSD Values as a Function of 85th Percentile Speed From the Saito Model (12)
Critique

Saito documents the following aspects of PSD:

- sight distance required to abort a passing maneuver from the head-to-tail position
- 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 counterintuitive. 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.

3.6 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 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

\[
PSD = 1.47V_{close} \left[ - B + \sqrt{(B^2 - 4\alpha\gamma)} \right]/2a
\]

\[
B = -ap_c - d_a p_a - ad_3/1.47V_{close}
\]

where: \(V_{close}\) = closing rate between the passing and opposing vehicles (mph)
\(\alpha\) = not defined by author
\(\gamma\) = not defined by author
\(p_c\) = perception-reaction time to complete the passing maneuver (sec)
\(p_a\) = 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 10 mph is assumed; however, speed differentials ranging from 5 to 25 mph were also 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.

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.

Table 14. PSD Values Determined by Ohene and Ardekani (13)

<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>Passing sight distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>570</td>
</tr>
<tr>
<td>40</td>
<td>900</td>
</tr>
<tr>
<td>50</td>
<td>1,300</td>
</tr>
<tr>
<td>60</td>
<td>1,700</td>
</tr>
<tr>
<td>70</td>
<td>2,050</td>
</tr>
</tbody>
</table>

Figure 12. PSD Values as a Function of Speed Reported by Ohene and Ardekani (13)
Critique

There were no units given in report for the variables in the models and two variables were not defined. Therefore, the research team has not been able to reproduce the author’s computations, but has only been able to present the authors’ recommended PSD values. The Ohene and Ardekani model does not appear to be sufficiently developed for implementation.

3.7 Glennon (1988)

Conceptual Approach

A new PSD model by Glennon (14) evolved out of research that the author embarked upon to address what he 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

\[
PSD = 2V_d \left(2.93 + \frac{L_p - \Delta_c}{m}\right) \tag{21}
\]

\[
\Delta_c = L_p + 1.47m \left(\frac{2.93m + L_i + L_p}{1.47(2V_d - m)} - \left[\frac{4V_d(2.93m + L_i + L_p)}{1.47d(2V_d - m)}\right]^{1/2}\right) \tag{22}
\]

where:
- \(V_d\) = design speed (mph)
- \(L_p\) = length of passing vehicle (ft)
- \(L_i\) = length of passed vehicle (ft)
- \(\Delta_c\) = relative position of the front bumpers of the passing and passed vehicles at the critical position (negative \(\Delta_c\) means that passing vehicle is behind passed vehicle; positive \(\Delta_c\) 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 16 ft
• A reasonable deceleration rate in the aborting maneuver is 8 ft/sec$^2$
• The speed differential between the passing and passed vehicles will vary from 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 at which 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 impeding vehicles at the completion of the maneuver is 1 sec.
• For an aborted pass, the space headway between the passing and impeding vehicles at the completion of the maneuver is 1 sec.
• The minimum clearance between the passing and opposing vehicles at the point in which 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 55, 65, and 110 ft.

<table>
<thead>
<tr>
<th>Design speed (mph)</th>
<th>PSD based on vehicle being passed (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Passenger vehicle</td>
</tr>
<tr>
<td>40</td>
<td>670</td>
</tr>
<tr>
<td>50</td>
<td>830</td>
</tr>
<tr>
<td>60</td>
<td>990</td>
</tr>
<tr>
<td>70</td>
<td>1,140</td>
</tr>
</tbody>
</table>

Critique

The Glennon model appears to be the first model in published literature that is based analytically on the concept that the critical position is the point in the passing maneuver at which 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.

![Graph showing PSD values as a function of design speed from the Glennon Model](attachment:image.png)

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 Section 4 of this interim 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. (26) 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 Section 3.9.

- 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 Section 3.11.

- 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 addressed further in Section 3.11.

The Glennon model appears to be conceptually sound and should be considered as a candidate for implementation. The research team accepts the analysis by Good et al. (26) that the introduction of a minimum speed for the passing vehicle in a pass abort maneuver is not needed. However, the research team recommends that the two concerns about the Glennon model raised by Hassan et al. should be further investigated in the Phase II research.

### 3.8 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 first reported by Harwood et al. (25) 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 16 ft. In addition, Harwood and Glennon
used a truck length of 75 ft in examining PSD requirements with a truck as the passing vehicle, while Glennon conducted a sensitivity analysis with truck lengths of 55, 65, and 110 ft. Harwood and Glennon also recommended a deceleration rate for use by a truck in aborting a pass (5 ft/sec²), which is lower than the deceleration rate used by Glennon (14) for a passenger car in aborting a pass (8 ft/sec²).

**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.

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

![Figure 14. PSD Values Determined by Harwood and Glennon for Specific Passing Scenarios (15)](image-url)
Critique

Harwood and Glennon used the Glennon model \((14)\), discussed in Section 3.8 of this report. 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 be carried forward to Phase II for further evaluation.

3.9 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 in order 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.

Analytical Models

PSD to complete a passing maneuver:

\[
PSD_{\text{complete}} = 1.47V_{\text{cr}} t_7 + \frac{1.47at_7^2}{2} + 1.47V_d t_5 d_3 + 1.47V_o (t_7 + t_3) \quad (23)
\]
where: $V_{\text{crit}}$ = speed of passing vehicle at critical position (mph)
$V_o$ = speed of the opposing vehicle (mph)

PSD to abort a passing maneuver:

$$\text{PSD}_{\text{abort}} = 1.47V_{\text{crit}} p_a + 1.47V_{\text{crit}} t_{8} - \frac{1.47d_{\text{d}}^2}{2} + 1.47V_{\text{min}} t_{9} + d_{3} + 1.47V_{\text{o}} (p_a + t_{8} + t_{9})$$  (24)

where: $V_{\text{min}}$ = minimum speed of the passing vehicle which is equal to $V_{\text{d}} - 2m$ (mph)
$t_{8}$ = deceleration time needed for the passing vehicle to slow down to the minimum speed, $V_{\text{min}}$ (sec)
$t_{9}$ = an additional time during which the passing vehicle travels at $V_{\text{min}}$ (sec)

**Assumed Values of Model Parameters**

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

- the passed vehicle travels at a constant speed ($V_{\text{d}} - m$)
- the passing vehicle accelerates to the design speed at or before the critical position and continues at this speed unless the maneuver is aborted
- the perception-reaction time before a pass is aborted is 1 sec
- the opposing vehicle travels at the design speed of the roadway

In addition, the authors introduce the following additional assumptions:

- the 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, $V_{\text{min}}$, which is set equal to $V_{\text{d}} - 2m$
- for a completed pass, the passing vehicle is assumed to be traveling at a speed of $V_{\text{crit}}$ at the critical position; if this value is less than $V_{\text{d}}$, then the passer is assumed to be accelerating at a magnitude of the acceleration, a
- the speed differential is set at 10 mph so that the minimum speed constraint for an aborted pass is 20 mph less than the design speed

In producing an illustration of the Rilett et al. model, the research team assumed a 1-sec headway between the passing and impeding vehicles and also that the passed vehicle lengths for passenger cars and trucks were 16 and 66 ft.
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.

### Table 17. PSD Values for Rilett et al. Model (16)

<table>
<thead>
<tr>
<th>Design speed (mph)</th>
<th>16-ft passenger car</th>
<th>66-ft truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>722</td>
<td>1,027</td>
</tr>
<tr>
<td>44</td>
<td>984</td>
<td>1,312</td>
</tr>
<tr>
<td>50</td>
<td>1,296</td>
<td>1,640</td>
</tr>
<tr>
<td>56</td>
<td>1,624</td>
<td>1,952</td>
</tr>
<tr>
<td>62</td>
<td>1,952</td>
<td>2,257</td>
</tr>
<tr>
<td>68</td>
<td>2,297</td>
<td>2,575</td>
</tr>
</tbody>
</table>

**Figure 15. PSD Values From Rilett et al. Model (16)**

**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 (e.g., 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. (26) 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 research team accepts this critique by Good et al. of the critique by Rilett et al.

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 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.

### 3.10 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 at which a passing vehicle will determine that a pass is necessary. In other words, if a model suggests a speed differential of 10 mph, then Forbes appears to assume that passing drivers will only opt to pass if cars are traveling more than 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 based on his understanding. 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.

3.11 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 variable of the Glennon model and is represented in the following equations:

\[ \text{PSD}_c = 2.93 V_d (t_c + h) \]  

(25)
\[ t_c = p_a + t_a - \frac{d_a t_a}{5.88 V_d} (t_a + 2h) \quad (26) \]

\[ t_a = -h + \frac{\left[ h_2 + 5.88 V_d \left( L_p + L_i + 1.47h(2V_m - m)\right)\right]}{1.47d_a (2V_m - m)} \quad (27) \]

where: 

- \( t_c \) = time required to complete a passing maneuver from the critical position (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\(^2\))
- \( t_a \) = 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:

\[ \Delta_c = L_p + 1.47(V-m) h - 1.47mt_a \quad (28) \]

where: 

- \( \Delta_c \) = relative position of the front bumpers of the passing and passed vehicles at the critical position (negative \( \Delta_c \) means that passing vehicle is behind passed vehicle; positive \( \Delta_c \) 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 (\( \Delta_c > 0 \)). The authors 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:
\[
\text{PSD}_c = 2.93V_d \left( t^*_c + h \right)
\]  
(29)

\[
t^*_c = \frac{1.47(V_d - m)h + L_p}{m}
\]  
(30)

where: \( t^*_c \) = 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 \( \Delta_c \leq 0 \)
- use Equation (29) when \( \Delta_c > 0 \)

**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, \( P \), 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, \( d \), 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 was also assumed that the speed differential would vary according to speed by the following relationship:

\[
\begin{align*}
m &= 14.91-V_d/10 \text{ (mph) or } m = 24-V_d/10 \text{ (km/hr)}
\end{align*}
\]  

Hassan et al. assumed values of 16 ft for the passing and passed vehicles; the research team has used a 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 have used a tentative value of 1 sec. The critique section below discusses the applicability of this term.

The research team have assumed a deceleration rate of 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 8 ft/sec\(^2\) used by the research team in the Hassan et al. model is less than the 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)**

<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>Passing sight distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>470</td>
</tr>
<tr>
<td>35</td>
<td>590</td>
</tr>
<tr>
<td>40</td>
<td>710</td>
</tr>
<tr>
<td>45</td>
<td>840</td>
</tr>
<tr>
<td>50</td>
<td>980</td>
</tr>
<tr>
<td>55</td>
<td>1,160</td>
</tr>
<tr>
<td>60</td>
<td>1,440</td>
</tr>
<tr>
<td>65</td>
<td>1,770</td>
</tr>
<tr>
<td>70</td>
<td>2,150</td>
</tr>
<tr>
<td>75</td>
<td>2,610</td>
</tr>
<tr>
<td>80</td>
<td>3,160</td>
</tr>
</tbody>
</table>

**Figure 16. PSD Values From Hassan et al. Model (18)**
Critique

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

- the 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
- the 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 Section 4.2), 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 (i.e., 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 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 should be assessed in the Phase II research. 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 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 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 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.


Conceptual Approach

In this mathematical model the authors, Wang and Cartmell (1998) go to great lengths to include all parameters that influence a passing maneuver, a task that 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 at which 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 in which the passing vehicle occupies the left lane from the end of Stage 1 to the point at which 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

$$PSD = X_1 + X_2 + X_3 + C + 0.62V_o(T_1 + T_2 + T_3)$$  \hspace{1cm} (32)
where:  
\[ X_1 = \text{distance traveled by the passed vehicle in Stage 1 in the } x\text{-axis direction (ft)} \]
\[ X_2 = \text{distance traveled by the passed vehicle in Stage 2 in the } x\text{-axis direction (ft)} \]
\[ X_3 = \text{distance traveled by the passed vehicle in Stage 3 in the } x\text{-axis direction (ft)} \]
\[ T_1 = \text{time used during Stage 1 (sec)} \]
\[ T_2 = \text{time used during Stage 2 (sec)} \]
\[ T_3 = \text{time used during Stage 3 (sec)} \]
\[ C = \text{clearance between the front bumper of the passing and opposing vehicles at the end of the maneuver (ft)} \]

Case 1: Maximum Speed Reached at Stage 1

**Stage 1:**
\[ S_1 = d_{pmax} + 0.62V_{pmax}(T_1 - T_{pmax}) \]  \hspace{1cm} (33)
\[ X_1 = 0.62V_pT_1 + G_s \]  \hspace{1cm} (34)

**Stage 2:**
\[ S_2 = 0.62V_{pmax}T_2 \]  \hspace{1cm} (35)
\[ X_2 = 0.62V_pT_2 + L_p + L_i \]  \hspace{1cm} (36)

**Stage 3:**
\[ S_3 = 0.62V_{pmax}T_3 \]  \hspace{1cm} (37)
\[ X_3 = 0.62V_pT_3 + G_e \]  \hspace{1cm} (38)

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

Case 2: Maximum Speed Reached at Stage 2

**Stage 1:**
\[ S_1 = 0.62V_pT_1 + 0.46a_{pmax}(T_1)^2 \]  \hspace{1cm} (39)
\[ X_1 = 0.62V_pT_1 + G_s \]  \hspace{1cm} (40)

**Stage 2:**
\[ S_1 + S_2 = 0.91d_{pmax} + 0.62V_{pmax}(T_1 + T_2 - T_{pmax}) \]  \hspace{1cm} (41)
\[ X_2 = 0.62V_pT_2 + L_p + L_i \]  \hspace{1cm} (42)
Stage 3:

\[ S_3 = 0.62V_{p_{max}} T_3 \]  (43)

\[ X_3 = 0.62V_p T_3 + G_c \]  (44)

where: \( a_{p_{max}} \) = acceleration of the passing vehicle (ft/sec^2)

Case 3: Maximum Speed Reached at Stage 3

Stage 1:

\[ S_1 = 0.62V_i T_1 + 0.5a_{p_{max}}(T_1)^2 \]  (45)

\[ X_1 = 0.62V_p T_1 + G_s \]  (46)

Stage 2:

\[ S_1 + S_2 = 0.62V_i(T_1 + T_2) + 0.46a_{p_{max}}(T_1 + T_2)^2 \]  (47)

\[ X_2 = 0.62V_p T_2 + L_p + L_i \]  (48)

Stage 3:

\[ S_1 + S_2 + S_3 = 0.91d_{p_{max}} + 0.62V_{p_{max}}(T_1 + T_2 + T_3 - T_{p_{max}}) \]  (49)

\[ X_3 = 0.62V_p T_3 + G_c \]  (50)

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

Stage 1:

\[ S_1 = 0.62V_i T_1 + 0.46a_{p_{max}}(T_1)^2 \]  (51)

\[ X_1 = 0.62V_p T_1 + G_s \]  (52)

Stage 2:

\[ S_1 + S_2 = 0.62V_i(T_1 + T_2) + 0.46a_{p_{max}}(T_1 + T_2)^2 \]  (53)

\[ X_2 = 0.62V_p T_2 + L_p + L_i \]  (54)

Stage 3:

\[ S_1 + S_2 + S_3 = 0.62V_i(T_1 + T_2 + T_3) + 0.46a_{p_{max}}(T_1 + T_2 + T_3)^2 \]  (55)

\[ X_3 = 0.62V_p T_3 + G_c \]  (56)

Assumed Values of Model Parameters

- The impeding vehicle and the opposing vehicle move forward at constant speeds \( V_p \) and \( V_o \), respectively
- The passing vehicle accelerates from its initial speed, \( V_i \), at the start of the overtaking towards the maximum \( V_{p_{max}} \), achievable by it. According to the AASHTO 1994 suggestions, this value is normally 16-24 km/h higher than that of the overtaken vehicle. Once the \( V_{p_{max}} \) is reached, then it will keep moving at this 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>
<thead>
<tr>
<th>Design speed (mph)</th>
<th>Passing sight distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a_{pmax1}$</td>
</tr>
<tr>
<td>19</td>
<td>869</td>
</tr>
<tr>
<td>25</td>
<td>1,043</td>
</tr>
<tr>
<td>31</td>
<td>1,240</td>
</tr>
<tr>
<td>37</td>
<td>1,417</td>
</tr>
<tr>
<td>44</td>
<td>1,617</td>
</tr>
<tr>
<td>50</td>
<td>1,765</td>
</tr>
<tr>
<td>56</td>
<td>1,972</td>
</tr>
<tr>
<td>62</td>
<td>2,142</td>
</tr>
<tr>
<td>68</td>
<td>2,320</td>
</tr>
<tr>
<td>75</td>
<td>2,497</td>
</tr>
</tbody>
</table>

Figure 17. PSD Values From Wang and Cartmell Model (19)

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 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.

### 3.13 Comparison of Passing Sight Distance Models

The PSD values resulting from each of the PSD models reviewed in Section 2 and earlier in Section 3 of this report are compared in Figure 18 and in Table 20.

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.

Section 4 of this report summarizes the key issues concerning PSD models that need to be considered in the research. That section includes an explanation of the research team’s overall assessment of the models presented here. To summarize what will be presented in the next section, the research team considers that the PSD models developed by Glennon (14) and Hassan et al. (18) are the most appropriate to provide a rationale for making passing and no-passing zones on two-lane highways and that a broader range of models should be considered for potential use in geometric design.
Figure 18. Comparison of PSD Values From Various PSD Models
Table 20. Comparison of PSD Values From Various PSD Models

<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>65</th>
<th>70</th>
<th>75</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passing Sight Distance (ft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AASHTO (2001)</td>
<td>1,090</td>
<td>1,280</td>
<td>1,470</td>
<td>1,625</td>
<td>1,835</td>
<td>1,985</td>
<td>2,135</td>
<td>2,285</td>
<td>2,480</td>
<td>2,580</td>
<td>2,680</td>
</tr>
<tr>
<td>MUTCD (2003)</td>
<td>500</td>
<td>550</td>
<td>600</td>
<td>700</td>
<td>800</td>
<td>900</td>
<td>1,000</td>
<td>1,100</td>
<td>1,200</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>British FOSD (1998)</td>
<td>918</td>
<td>1,071</td>
<td>1,224</td>
<td>1,377</td>
<td>1,530</td>
<td>1,683</td>
<td>1,836</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>British ASD (1998)</td>
<td>456</td>
<td>533</td>
<td>610</td>
<td>687</td>
<td>764</td>
<td>841</td>
<td>918</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Australian ESD (1998)</td>
<td>1,056</td>
<td>1,260</td>
<td>1,504</td>
<td>1,785</td>
<td>2,106</td>
<td>2,465</td>
<td>2,862</td>
<td>3,299</td>
<td>3,773</td>
<td>4,287</td>
<td>4,839</td>
</tr>
<tr>
<td>Australian CSD (1998)</td>
<td>537</td>
<td>619</td>
<td>721</td>
<td>842</td>
<td>984</td>
<td>1,145</td>
<td>1,325</td>
<td>1,526</td>
<td>1,746</td>
<td>1,986</td>
<td>2,245</td>
</tr>
<tr>
<td>Van Valkenburg and Michael (1971)</td>
<td>750</td>
<td>900</td>
<td>1,050</td>
<td>1,200</td>
<td>1,300</td>
<td>1,450</td>
<td>1,600</td>
<td>1,750</td>
<td>1,900</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Weafer and Glennon (1972)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1,135</td>
<td>–</td>
<td>1,480</td>
<td>1,655</td>
<td>1,825</td>
<td>2,000</td>
<td>2,170</td>
<td>–</td>
</tr>
<tr>
<td>Harwood and Glennon (1976)</td>
<td>628</td>
<td>769</td>
<td>918</td>
<td>1,074</td>
<td>1,238</td>
<td>1,408</td>
<td>1,586</td>
<td>1,772</td>
<td>1,964</td>
<td>2,164</td>
<td>2,371</td>
</tr>
<tr>
<td>Lieberman (1982)</td>
<td>860</td>
<td>1,084</td>
<td>1,320</td>
<td>1,568</td>
<td>1,828</td>
<td>2,099</td>
<td>2,383</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Saito head-tail (1984)</td>
<td>409</td>
<td>524</td>
<td>646</td>
<td>773</td>
<td>905</td>
<td>1,043</td>
<td>1,186</td>
<td>1,334</td>
<td>1,486</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Saito abreast (1984)</td>
<td>284</td>
<td>372</td>
<td>463</td>
<td>559</td>
<td>659</td>
<td>763</td>
<td>870</td>
<td>980</td>
<td>1,093</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Ohene and Ardekani (1988)</td>
<td>570</td>
<td>–</td>
<td>900</td>
<td>–</td>
<td>1,300</td>
<td>–</td>
<td>1,700</td>
<td>–</td>
<td>2,050</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Glennon 55-ft truck (1988)</td>
<td>–</td>
<td>–</td>
<td>760</td>
<td>–</td>
<td>960</td>
<td>–</td>
<td>1,150</td>
<td>–</td>
<td>1,320</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Glennon 110-ft truck (1988)</td>
<td>–</td>
<td>–</td>
<td>850</td>
<td>–</td>
<td>1,080</td>
<td>–</td>
<td>1,320</td>
<td>–</td>
<td>1,550</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Harwood and Glennon pc-truck (1989)</td>
<td>575</td>
<td>–</td>
<td>800</td>
<td>–</td>
<td>1,025</td>
<td>–</td>
<td>1,250</td>
<td>–</td>
<td>1,450</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Harwood and Glennon truck-pc (1989)</td>
<td>600</td>
<td>–</td>
<td>875</td>
<td>–</td>
<td>1,125</td>
<td>–</td>
<td>1,375</td>
<td>–</td>
<td>1,625</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Harwood and Glennon truck-truck (1989)</td>
<td>675</td>
<td>–</td>
<td>975</td>
<td>–</td>
<td>1,275</td>
<td>–</td>
<td>1,575</td>
<td>–</td>
<td>1,875</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Rilett et al. 16-ft passenger car (1989)</td>
<td>–</td>
<td>–</td>
<td>836</td>
<td>1,069</td>
<td>1,312</td>
<td>1,567</td>
<td>1,832</td>
<td>2,109</td>
<td>2,397</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Rilett et al. 66-ft truck (1989)</td>
<td>–</td>
<td>–</td>
<td>1,152</td>
<td>1,403</td>
<td>1,653</td>
<td>1,903</td>
<td>2,154</td>
<td>2,404</td>
<td>2,654</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Hassan et al. (1996)</td>
<td>472</td>
<td>588</td>
<td>710</td>
<td>840</td>
<td>976</td>
<td>1,165</td>
<td>1,441</td>
<td>1,767</td>
<td>2,153</td>
<td>2,610</td>
<td>3,155</td>
</tr>
<tr>
<td>Wang and Cartmell Apmax1 (1998)</td>
<td>1,204</td>
<td>1,350</td>
<td>1,496</td>
<td>1,642</td>
<td>1,787</td>
<td>1,933</td>
<td>2,079</td>
<td>2,225</td>
<td>2,371</td>
<td>2,517</td>
<td>–</td>
</tr>
<tr>
<td>Wang and Cartmell Apmax2 (1998)</td>
<td>921</td>
<td>1,035</td>
<td>1,149</td>
<td>1,262</td>
<td>1,376</td>
<td>1,490</td>
<td>1,604</td>
<td>1,717</td>
<td>1,831</td>
<td>1,945</td>
<td>–</td>
</tr>
</tbody>
</table>
3.14 Summary of Nomenclature

The following list defines all of the nomenclature used in PSD models in Sections 2 and 3 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.

\( a \) = acceleration rate of the passing vehicle to increase its speed from \( V_i \) to \( V_i + m \) (ft/sec\(^2\))

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

\( d_1 \) = distance traveled during perception and reaction time and during initial acceleration to the point of encroachment on the left lane (ft)

\( d_2 \) = distance traveled while the passing vehicle 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 2/3 of \( d_2 \) (ft)

\( d_5 \) = distance traveled by the passing vehicle from the critical position until it returns to its own lane (ft)

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

\( d_7 \) = distance traveled by the passing vehicle from the start of the passing maneuver to the critical position (ft)

\( d_a \) = deceleration rate used in aborting a passing maneuver (ft/sec\(^2\))

\( G_1 \) = space headway between passing and passed vehicles at the instant the passing vehicle returns to the normal lane (ft)

\( G_1' \) = 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)

\( \text{PSD} \) = 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)

\( t_5 \) = time required for the passing vehicle to return to its own lane from the critical position for a completed passing maneuver (sec)

\( t_7 \) = travel time from the start of the passing maneuver to the attainment of the critical position (sec)

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

\( t_9 \) = additional time at which the passing vehicle travels at \( V_{\text{min}} \) (sec)

\( t_a \) = time required to abort a passing maneuver from the critical position (after perception-reaction time) (sec)

\( t_c \) = time required to complete a passing maneuver from the critical position (sec)

\( t_{c^*} \) = time required to complete a passing maneuver from the position where the front bumpers of the passing and passed vehicles are abreast (sec)

\( t_d \) = deceleration time (sec)

\( V_{85} \) = 85th percentile speed (mph)

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

\( V_{\text{crit}} \) = speed of passing vehicle at the critical position (mph)

\( V_d \) = design speed (mph)

\( V_i \) = speed of passed vehicle (mph)

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

\( V_{\text{min}} \) = 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)

\( \Delta_c \) = relative position of the front bumpers of the passing and passed vehicles at the critical position (negative \( \Delta_c \) means that the passing vehicle is behind the passed vehicle; positive \( \Delta_c \) means that the passing vehicle is in front of the passed vehicle) (ft)
Section 4.
Key Passing Sight Distance Issues

This section reviews the current state of knowledge about a number of key PSD-related issues. Research needed to address these issues is addressed in Section 5 of this report.

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?
- What is the current level of driver understanding of passing and no-passing zone markings?
- What driver judgments are involved in passing maneuvers and how good are drivers at making those judgments?
- What is the current level of driver compliance with passing and no-passing zone markings? How frequent are passing maneuvers in no-passing zones? How frequent are jumping (starting a passing maneuver in a no-passing zone before the beginning of a passing zone) and clipping (completing a passing maneuver in a no-passing zone after the end of a passing zone)?
- Is the current MUTCD minimum passing zone length appropriate?
- If the current AASHTO and/or MUTCD models were to be replaced, what alternative model(s) are most appropriate?

Each of these issues is addressed below.

4.1 Safety Concerns Related to Passing Maneuvers and Passing Sight Distance

The first and most basic issue in reconsidering 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. (28) 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) (29). 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 (30); 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 22 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 21 contradict the common belief that passing-related accidents on two-lane roads are primarily head-on accidents. Furthermore, it should be recognized that 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.
Table 21. Distribution of Collision Types for Passing-Related Accidents (28)

<table>
<thead>
<tr>
<th>Collision type</th>
<th>State A</th>
<th>State B</th>
<th>State C</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-vehicle run-off-road</td>
<td>25.5(^a)</td>
<td>34.1</td>
<td>30.7</td>
<td>30.1</td>
</tr>
<tr>
<td>Sideswipe passing</td>
<td>31.9</td>
<td>12.1(^b)</td>
<td>31.7(^c)</td>
<td>25.3</td>
</tr>
<tr>
<td>Sideswipe meeting</td>
<td>8.2</td>
<td>3.1(^b)</td>
<td>8.7(^c)</td>
<td>6.5</td>
</tr>
<tr>
<td>Rear end</td>
<td>12.2</td>
<td>25.2</td>
<td>12.2(^c)</td>
<td>16.5</td>
</tr>
<tr>
<td>Head-on</td>
<td>6.4</td>
<td>6.7</td>
<td>6.4(^c)</td>
<td>6.5</td>
</tr>
<tr>
<td>Other/unknown</td>
<td>15.8</td>
<td>18.8</td>
<td>10.8</td>
<td>15.1</td>
</tr>
</tbody>
</table>

- 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.
- Sideswipe accidents for State B have been split between sideswipe passing and sideswipe meeting in proportion to State A data.
- Sideswipe, rear-end, and head-on accidents for State C have been split in proportion to State A data.

FARS data for 2003 indicate that 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 (29) 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. Similar estimates could be made of the frequency of injury and property-damage-only (PDO) accidents related to PSD.

These data do not suggest that 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.

4.2 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 is 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.

The concern has been raised in Section 2.2 of this report 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 19 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 at which 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 19 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
- 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 of the above items (PSD for the driver at the critical position) is most critical.
Figure 19. Conceptual Representation of the Changes in Sight Distance Needed to Complete or Abort a Passing Maneuver as the Passing Maneuver Progresses

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.

Thus, 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 which 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. This potential approach to marking criteria will be addressed further in Sections 4.4 and 4.10.
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” 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 (i.e., approximately abreast 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 20 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 $d_5$) downstream of the beginning of the no-passing zone. Thus, the distance $d_5$ in Figure 20 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.

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
- 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” 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 (31) found that 44 states used the “short zone” concept and 6 states used the “long zone” concept for passing and no-passing zone enforcement. A review of state laws and driver license manuals for those six states as part of the current research found that today only one state (Illinois) formally uses the “long zone” concept for enforcement. There appears to be one additional 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 48 of the 50 states. It is not clear to what extent drivers in Illinois and Vermont behave differently than drivers in other states or are even aware that their state laws differ from the norm. The “long zone” concept does not appear to be in sufficiently wide use today to constitute a factor that should affect national policy concerning PSD criteria.
Figure 20. Buffer Area Downstream of a Passing Zone Where It Is Safe, But Not Legal, to Complete a Pass
Some past researchers \((31, 32)\) have recommended introducing a third level of passing and no-passing pavement markings for the buffer area shown in Figure 20. 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” 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*. This model is presented in Equation (1) of this report 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. (Needless to say, 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. In fact, published alternative models such as those developed by Glennon \((14)\) and Hassan et al. \((18)\) show that PSD needs 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 is also very conservative in that portions 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 buffer zone 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.

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 by some 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 below in Section 4.4. Specific alternatives to the current AASHTO PSD models are identified in Section 4.10.

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 1938 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. By contrast, today’s drivers are probably less experienced in making passing maneuvers than the drivers of that older era. In the 1950s and before, most rural travel was on two-lane highways; today, freeway travel predominates. Drivers today are much less exposed to the need to make passing maneuvers and may have less finely honed decision skills concerning passing. On the other hand, it is possible that the drivers experienced in traveling on two-lane highways and in making passing maneuvers (perhaps because they travel on two-lane highways every day) may be most likely to make passing maneuvers. Drivers without much two-lane highway experience may be reluctant to pass, at least at first, and may wait for longer passing zones than more familiar drivers.

### 4.3 Parameter Values Used in PSD Models

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

- distance traveled by the passing vehicle from the beginning of the passing maneuver to the critical position \(d_6\)
- assumed speeds for passing and passed vehicles \((V_p\) and \(V_i\)) in relation to design speed \((V_d)\)
• speed differential between the passing and passed vehicles (m)
• 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 maneuver
• clearance time between passing and oncoming vehicles
• perception-reaction time required for the passing driver to decide to abort the passing maneuver (p_a)

The research team has made tentative choices for some of these parameters for use in comparing the PSD models in Section 3 of this report. These choices will need to be confirmed or modified in Phase II for whatever models are recommended for implementation. Selection of values for some parameters may require field studies. Other parameters may not require field studies but may be based on further literature review and analysis.

Recommended values of d_a may need to be developed from field data. The value of m has been suggested by Glennon (14) and others to range from 8 to 12 mph, with lower speed differentials at higher speeds. The deceleration rate (d_a) for aborting a passing maneuver has been recommended by Glennon (14) to be 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. The lengths of the passing and passed vehicles (L_p and L_i) have been tentatively recommended by the research team as 19 ft for passenger cars, and longer for trucks of various sizes. The 19-ft passenger car was selected for consistency with the AASHTO PC design vehicle, but others have suggested passenger-car lengths as short as 16 ft. The roadway between the passing and passed vehicles before and after the maneuver and the clearance time between the passing and passed vehicles are both recommended to have values of 1 sec. The perception-reaction time for the passing driver to decide to abort a passing maneuver (p_a) did not have a value recommended by Hassan et al. (18), despite its inclusion in their model. The research team currently recommends a value of 1 sec or less for p_a where an opposing vehicle could appear within a distance equal to PSD_c from the passing vehicle and a value of 0 sec for p_a if the opposing vehicle is in sight of the passing driver at a distance substantially greater than PSD_c.

There are several sets of existing field data that are potentially useful in quantifying the values of parameters in PSD models. However, most of these field data are older; it would be desirable to replace such data with more recent measurements.

Data collected by Gordon and Mast (44) on overtaking and passing distances from their study and from other studies are in Section 4.8. Gordon and Mast established the following regression equation for estimating passing distance:
\[ D = 112.2 + 15.2V + 0.93 V^2 \]  \hspace{1cm} (57)

where:  
\( D \) = passing distance (ft)  
\( V \) = passing vehicle speed (mph)

Table 22 summarizes the observations of Van Valkenburg and Michael (8) on the mean length and speed of passing maneuvers for specific types of the return maneuvers. A voluntary return was a pass completion when there was nothing facing the driver of the passing vehicle to return to the normal lane. A forced return indicated that the passing driver was forced to return to the normal lane by the presence of an approaching vehicle or the beginning of a no-passing zone. It should be noted that Van Valkenburg and Michael visually identified the location of the critical position, but did not measure it.

### 4.4 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. A preliminary assessment has been made of whether this practice is warranted.

Section 4.1 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 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 potential economic justification (or lack of economic justification) for such a change should be addressed in the Phase II research.

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.
### Table 22. Mean Lengths and Speeds of Passing Maneuvers Observed in the Field (8)

<table>
<thead>
<tr>
<th>Type of passing maneuver</th>
<th>Speed of passed vehicle (mph)</th>
<th>Distance (ft)</th>
<th>Speed (mph)</th>
<th>Distance (ft)</th>
<th>Speed (mph)</th>
<th>Distance (ft)</th>
<th>Speed (mph)</th>
<th>Distance (ft)</th>
<th>Speed (mph)</th>
</tr>
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<tbody>
<tr>
<td>Accelerative voluntary return</td>
<td>38</td>
<td>496</td>
<td>49.6</td>
<td>531</td>
<td>48.1</td>
<td>666</td>
<td>48.2</td>
<td>906</td>
<td>42.7</td>
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<td></td>
<td>47</td>
<td>618</td>
<td>56.9</td>
<td>693</td>
<td>54.6</td>
<td>642</td>
<td>52.0</td>
<td>965</td>
<td>52.2</td>
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<td></td>
<td>61</td>
<td>808</td>
<td>71.2</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<td>–</td>
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<tr>
<td>Flying voluntary return</td>
<td>38</td>
<td>449</td>
<td>55.4</td>
<td>496</td>
<td>50.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td></td>
<td>47</td>
<td>567</td>
<td>63.3</td>
<td>573</td>
<td>58.8</td>
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<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td></td>
<td>61</td>
<td>619</td>
<td>79.4</td>
<td>–</td>
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<td>Accelerative forced return</td>
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<tr>
<td></td>
<td>47</td>
<td>430</td>
<td>61.3</td>
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<tr>
<td></td>
<td>61</td>
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<td></td>
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</tr>
</tbody>
</table>

**NOTE:** Distance to pass is the distance from the critical position to the point at which the pass was completed. Average passing speed was computed from distance to pass and the corresponding time to pass.
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. A potential research approach to this issue is to compare the sight distance profiles and the frequency and length of marked passing and no-passing zones that result from design in accordance with the current AASHTO criteria, the current MUTCD criteria, and/or other PSD criteria between those values.

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. The research team has heard (years ago) of at least one example in which a highway agency constructed a project to increase passing opportunities on a two-lane road, but found that the completed highway had less total length in marked passing zones than the original highway. Whatever the design and marking criteria for PSD, automated technology (CAD systems and/or IHSDM) should provide an opportunity to ensure that such mistakes are not made in the future, but it appears to the research team that would be desirable (even if the AASHTO PSD criteria were not changed) to have the likely passing and no-passing zone markings on the completed road be considered as part of the design process.

4.5 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 (8), 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 60 mph, it takes 1,025 ft of sight distance for a passenger car to pass another passenger car and 1,250 ft of sight distance for a passenger car to pass a 75-ft truck. Comparable values for a truck to pass a passenger car and a truck to pass another truck are 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 needs 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 has not been documented, but could be examined in the Phase II research.

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. These ideas are addressed further in Sections 4.9 and 4.10 of this report.

4.6 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 (33-38), 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 (33) 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. (39) 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.
4.7 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 (40) have stated that, when forced to follow a slow-moving vehicle for up to 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. (41) 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 (31, 42).

4.8 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 as to whether to initiate a passing maneuver in any particular road and traffic situation
- Judgment 2—the decision as to 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

These two types of judgments/decisions occur in the real world and they have been studied and modeled within TWOPAS (43) and TRARR (44), the two most commonly used computer simulation models of traffic operations on two-lane highways.

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 (45) 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 21 compared with previous results by Matson and Forbes (46), Prisk (4), and Crawford (47).

Jones and Heimstra (48) 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.

Farber and Silver (49, 50, 51, 52) 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.

![Figure 21. Passing Distance in Relation to Speed (4, 10, 45, 46, 47)](image)

Research was conducted by Hostetter and Seguin (40) 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 (53) 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.

The research findings described here present something of a conundrum. Drivers in older research 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 that current level of safety.

4.9 Minimum Length of Passing Zones

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 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 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 (1,600 to 2,200 ft). In addition, two longer zones having lengths of 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 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 in which a vehicle entered one of the study areas trailing another vehicle within four car-lengths (approximately 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 22 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 1,640-ft zone had 22.8 percent use, and the 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.

![Graph showing the relationship between pass occurrence and length of passing section.](image)

**Figure 22. Driver Acceptance of Passing Opportunities (7, 10)**

Additional data were collected at the three short zones about each passing opportunity that resulted in a passing maneuver. 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:

<table>
<thead>
<tr>
<th>Rating</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Smooth return from passing lane to normal operating lane</td>
</tr>
<tr>
<td>1</td>
<td>Forced return in which the passing driver apparently realized that the remaining sight distance was less than adequate</td>
</tr>
<tr>
<td>2</td>
<td>Violent return in which the passed vehicle or an opposing vehicle was forced to brake or move to the shoulder</td>
</tr>
</tbody>
</table>

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

Figure 23 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 400-ft zone, 45 percent of the passes for the 640-ft zone, and 10 percent of the passes for the 880-ft zone. Only the results for the 880-ft zone appear tolerable under any reasonable safety standard.
The point of return of passing vehicles to the right lane was also recorded as an indication of safety and legality. The standards established by the MUTCD and the laws governing highway operation in many 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 400-ft section were illegal. On five of these 11 passes, the passing vehicle did not return to the right lane until more than 400 ft after the beginning of the no-passing stripe. Only one pass out of nine on the 640-ft section and two of the 10 passes observed on the 880-ft section were legal. For all three study sites, the drivers who penetrated the no-passing zone entered an area of extremely restricted sight distance.

The results of the Jones study indicate that most drivers are reluctant to use passing zones shorter than 880 ft long. The overwhelming majority of drivers who did use such zones did so illegally or unsafely.

Given that the Jones findings are 35 years old and were obtained on rural two-lane highways with 70-mph speed limits (higher than most, but not all, states today), there is need for current data to resolve this issue. If specifying a longer minimum passing zone length in marking criteria (and instituting a minimum length with adequate PSD in design) would improve safety at little cost in level of service, an increase in minimum zone length should be considered. A longer minimum passing zone length may also be desirable on roads with substantial truck volumes. The cost to highway agencies of striping out short zones would be substantially less than the cost of changing PSD criteria, because passing zone length is much more easily measured than PSD. On the other hand, if the Jones observations result from the higher speeds and more aggressive
two-lane highway driving of another era, there may be little benefit from a change. This issue should be addressed further in the Phase II research.

4.10 Appropriate Alternative PSD Models

The choice of appropriate PSD models for design and marking involves all of the considerations discussed in Sections 1 through 3 of this report and in the preceding portions of Section 4. While the final decision to retain the current MUTCD and AASHTO models, or to replace them with alternative models, can be made only after completion of the Phase II research, some key perspectives on that decision can be drawn from the material already available.

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 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. Thus, an analysis should be undertaken to determine whether the potential benefits of changing PSD criteria for marking could conceivably exceed the costs.

The review of alternative PSD models in Section 3 of this report found two credible models based on the critical position concept that provide PSD values very close to the current MUTCD criteria. These models are those developed by Glennon (14) and Hassan et al. (18). Based on these alternative models, it seems possible that a more credible rationale for PSD marking criteria could be developed without changing the actual PSD values presented in the MUTCD or, possibly, changing those values only slightly. The research team recommends that the use of these alternative models be fully investigated in the Phase II research. This will require resolution of the differences between the Glennon and Hassan et al. models, particularly at higher speeds.

It also appears to be appropriate to reexamine the minimum 400-ft passing zone length implied by the MUTCD criteria. It is clear that delayed passes involving high speeds cannot be safely completed within a 400-ft passing zone. It may also be likely that such passes are rarely attempted. It needs to be established whether passing zones as short as 400 ft are used in other ways, such as for flying pass maneuvers or for passing vehicles, such as farm tractors, traveling at very low speeds. The research team recommends that Phase II research address the current use of and the need for short passing zones to assess whether any change in the current minimum passing zone length of 400 ft is needed.
PSD Criteria for Design

Further work on PSD criteria for design should focus on developing a clear rationale as to the benefits of having PSD criteria for designs that exceed those used for marking. The following five alternatives should be assessed:

- Alternative 1—Retain the current AASHTO Green Book criteria
- Alternative 2—Use the same PSD criteria for geometric design that are used for marking passing and no-passing zones, modified in whatever manner is recommended in the Phase II research
- Alternative 3—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:
  \[
  \text{PSD} = X + \text{PSD}_c
  \]
  where:  \( \text{PSD}_c = \) sight distance required to complete or abort the passing maneuver when the passing vehicle is at the critical position

  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 \( (d_f) \), 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 4—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) either for all passing zones or for passing zones on roads with substantial truck volumes. In most terrain, this should result in passing zones with more PSD at the beginning of the zone.

- Alternative 5—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.

The research team’s current assessment is that Alternative 1, the use of the current AASHTO design criteria, is extremely conservative and that the consideration of alternatives is appropriate. It is also recognized, however, that the AASHTO criteria may serve to ensure that there are more and better passing opportunities on the completed road than the minimum necessary. A major concern with current practice is that, since separate PSD criteria are used for design and markings, the design process never explicitly considers the passing and no-passing zones that will be marked on the completed roadway and the traffic operational effects of those markings. However,
recommendation of changes to current criteria will be considered only with a strong rationale for one of the other alternatives.

The consideration of Alternative 2 is appropriate because there is every indication that two-lane highways operate safely under current PSD marking criteria, so there may be no good rationale for a requirement to consider longer sight distances in design. Adoption of Alternative 2 has an advantage in that it would force the design process to look directly at how the completed highway will be marked and will operate. However, Alternative 2 would remove any “cushion” provided by the design process in ensuring that the completed highway has more PSD than the minimum necessary. This “cushion” may contribute to current safety performance and could be important to traffic operations in future years if, for example, new intersections providing access to new development shorten or eliminate some passing zones.

Alternative 3 is intriguing, in comparison to Alternative 2, in that increased sight distance is supplied to make it more likely that the passing driver can get to the critical position without having to abort the passing maneuver in its early stages. This approach maintains a consistent relationship between design and marking criteria in that the PSDc value in Equation (58) is the PSD value used in marking passing and no-passing zones. It should be noted, however, that the same concern could be addressed by requiring a minimum passing zone length rather than requiring increased sight distance, as suggested in Alternative 4.

Alternative 4 might accomplish the same objective as Alternative 3 while tying the minimum length of passing zone issues discussed in Section 4.9 directly to the issue of PSD criteria. Appropriate PSD criteria together with an appropriate minimum length of passing zone could be a conceptually simple approach to accomplish the same objective as Alternatives 3 and 5.

Alternative 5 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. On the other hand, in typical rolling terrain, where, whenever a driver surmounts one crest, there is often a view all the way to the next crest, it is possible that this approach results in regions of adequate PSD for passing at about the same places where the marking criteria in Alternative 2 or the other alternatives would. Trial applications to real terrain in the Phase II research could establish how the overall percentage of highway length with adequate PSD would compare between the alternatives discussed.
Section 5.
Potential Work Plans for Phase II Research

This section presents work plans for potential Phase II research to assess the need for potential changes to the PSD criteria used for design and marking.

Overall, the key considerations in whether existing PSD criteria should be changed are:

- safety considerations (effect on accident frequency and/or severity)
- traffic operational considerations (effect on level of service)
- economic considerations (safety or traffic-operational benefits to compensate for any costs incurred by highway agencies)
- rationality and consistency of PSD criteria (assuring that PSD criteria have a sound scientific basis whose rationale is understood and accepted by the engineers who apply them)

Potential Phase II data collection and analysis activities to address the key issues identified in Section 4 of this report include:

- analysis of accident data related to passing maneuvers on two-lane roads
- identification of alternative PSD models for consideration in planning subsequent data collection
- traffic operational simulation of various design and marking scenarios to determine their effects on level of service which depends on the frequency of passing opportunities
- field observation of passing frequencies, passing-related conflict rates, and driver compliance with traffic control devices in passing and no-passing zones with various dimensions and sight distances
- field measurement of vehicle speeds, speed differentials, and accelerations used in passing maneuvers
- review of actual road markings and alignments from computerized records and as-built plans
- compare SSD and PSD criteria and the implications of those criteria for vertical curve length
- provide guidance or recommendations on the average frequency or percentage of passing opportunities that should be provided on two-lane highways
In formulating research plans to address these issues, the research team has considered factors potentially related to passing accidents including vehicle performance, driver behavior, terrain, road conditions, and weather conditions. Research results in NCHRP Report 505 (34) have documented regional variations in truck weight/power ratios, which would certainly influence the performance of trucks as the passing vehicle and the speed of trucks on grade as the passed vehicle. It is uncertain whether there are meaningful regional variations in the performance of passenger cars, SUVs, RVs, and buses, but there are definite regional variations in the mix of these vehicle types that may influence the demand for and characteristics of passing maneuvers. Regional differences in driver behavior in passing maneuvers are not well understood; this makes it important that any accident or field studies be conducted for a geographically diverse set of sites; at least two regions of the United States, and possibly three, will be considered. Any review of actual road markings and alignments for a number of selected sites will be specifically intended to include a variety of geographic locations and terrain types. The extent to which specific road and weather conditions will be addressed will need to be determined in the research; for example, accident data could be used to identify conditions which occur with sufficient frequency to be of interest.

5.1 Analysis of Accident Data Related to Passing Maneuvers on Two-Lane Roads

The analysis of accidents related to passing maneuvers on two-lane highways performed in a 1994 study as part of FHWA’s HSIS program (29) (see Section 4.1 of this report) provides strong evidence that the frequency of passing-related accidents on two-lane highways is low. The HSIS study found that only about 2 percent of accidents on rural two-lane highways involve passing maneuvers. Passing-related accidents were found to be more severe than other accidents, so fatal passing-related accidents may constitute about 3 percent of all fatal accidents. These data suggest that there may be as few as 390 fatal accidents per year related to passing maneuvers on two-lane highways in the United States. Only a portion of these passing-related accidents are likely to be related to lack of sufficient PSD. With this small number of accidents spread over the extensive rural two-lane highway network, it appears unlikely that changes in PSD criteria are likely to have a large effect on safety on two-lane highways in the United States.

Three alternative work plans have been formulated by the research team concerning potential safety research in Phase II of the project:

- **Work Plan A—Benefit-Cost Analysis of the Potential Safety Effects of Remeasuring PSD and Remarking Passing and No-Passing Zones With Revised PSD Criteria**

Modification of the PSD criteria for marking of passing and no-passing zones would eventually require remeasurement of PSD on every two-lane highway in the United States with a marked centerline. The cost of restriping could be
avoided by waiting to implement the modified PSD criteria until restriping is needed, but the cost of remeasuring PSD would not be avoidable. Weaver and Woods (31) estimated in 1978 that there are between 500,000 and 1,100,000 no-passing zones in the United States, all of which would eventually need to be remarked. A benefit-cost analysis should be performed to determine what percentage reduction in passing-related accidents would be needed for remeasuring of PSD to be cost-effective as a safety countermeasure on two-lane highways. The cost of remeasuring PSD would be estimated through contacts with highway agencies. PSD measurement has typically been accomplished with a two-vehicle system, but North Carolina has tried a one-vehicle system that holds promise as a less expensive measurement method (55).

The “breakeven” level of benefits resulting from this analysis would be converted to the number (and percentage) of passing-related accidents that would need to be reduced in order for revised PSD criteria for marking to be cost-effective. FHWA is soon expected to publish accident cost estimates for different collision types, including head-on and same-direction sideswipe collisions on roadways with speed limits above and below 45 mph. The “breakeven” number of accidents would then be compared to the results of the previous HSIS research (29). The results of the benefit-cost analysis would be used to judge whether a change in PSD criteria for marking is feasible and whether further safety research such as that described in Work Plan B should be undertaken.

- **Work Plan B—Identification and Analysis of Passing-Related Accidents**

An analysis of accident data would be undertaken if found to be desirable in light of the results of Work Plan A. The objective of this analysis would be to identify a set of passing-related accidents using criteria from the previous HSIS research (29) and to use that set of passing-related accidents to investigate issues that were not addressed in the previous research. Potential research questions to be addressed are identified below.

Using data from two or three selected states, passing-related accidents would be identified using procedures similar to those used in the previous HSIS study (29). Recent data from HSIS states would probably be used for this purpose. Further analyses of passing-related accidents would be conducted, including:

- obtain more complete data on the severity of passing-related accidents in comparison to all accidents on the same roads.
- determine how much PSD was available at the sites where passing accidents occurred, for accidents within both passing and no-passing zones. This would require a site review on videolog, from construction plans, or in the field.
determine the percentage of passing-related accidents that occur at the beginning, the middle, and the end of passing zones. Available data already suggest that 90 percent of passing-related accidents occur in passing zones and 10 percent occur in no-passing zones. In particular, it should be determined whether there is any concentration of passing-related accidents just downstream of passing zones. This may require review of hard-copy police accident reports or review of videologs of accident sites.

- investigate the involvement of trucks and other heavy vehicles in passing maneuvers, as passing and passed vehicles, relative to their percentage in the traffic stream.

- determine the percentage of older drivers involved in passing-related accidents as drivers of the passing vehicle and as drivers of the passed or oncoming vehicle, in relation to the percentage of older drivers in the driving population and in veh-mi of travel on rural roads.

- determine the weather and pavement conditions under which passing-related accidents occur, with a focus on the extent to which such accidents are related to limited visibility or wet or ice-and-snow covered road surfaces.

As addressed in Section 6, execution of Work Plan B is likely to be costly and will be considered only if there appears to be a strong need. A potential benefit of Work Plan B is that, together with the results of the HSIS study (29), it could be used to set priorities for the later work plans.

- **Work Plan C—Review of Accident Data for Field Study Sites**

In this work plan, the research team will review the accident history data for all field sites studied in Work Plans D, E, F, G, and H, described below. The purpose of this review will be to determine whether the sites used in these studies have experienced passing-related accidents and, if so, what types of passing-related accidents. The research team would like to be able to provide assurance that none of the sites used in field studies have adverse passing-related accident experience. Five years of accident history data will be considered. All field data will be evaluated in light of any passing-related accident patterns that may be present at the site.

### 5.2 Field Observation of Passing Frequencies, Passing-Related Conflict Rates, and Driver Compliance With Traffic Control Devices

Two issues merit consideration for investigation in observational field studies in the Phase II research. The first issue deals with the potential for safety problems created by passing maneuvers that are completed in areas with no-passing barrier stripes beyond the
end of the passing zone. The second issue deals with short passing zones created by the MUTCD’s implied minimum passing zone length of 400 ft. Work plans to address these two issues are described below.

- **Work Plan D—Safety of Passing Maneuvers Completed Beyond the End of a Passing Zone**

An issue that can be investigated through field observation is whether passing vehicles that “clip” the beginning of a no-passing zone actually extend their pass into a region of limited PSD where there is a substantial potential for a collision. Section 4 of this report has demonstrated that, although such maneuvers are illegal, there is, in many cases, adequate PSD for passes begun in a passing zone to be safely completed in a no-passing zone. However, if a passing maneuver extends too far into a no-passing zone, the passing vehicle may reach a region of limited sight distance where oncoming vehicles cannot be seen sufficiently in advance for safe operations. The existence of this region downstream of a passing zone where PSD is adequate for completing a pass, but passing is not permitted, provides a key margin of safety for passing maneuvers on two-lane highways. The purpose of Work Plan D is to determine whether drivers are abusing this margin of safety.

Field observations to address this issue will be made at approximately 10 passing zones located in level and rolling terrain in at least two distinct geographical areas of the United States. The passing zones selected will be screened to assure that they have relatively frequent passing activity and will have passing zone lengths of 1,000 to 2,500 ft, so that there is a good expectation that passing maneuvers should occur throughout the length of the passing zone. Field observations will determine:

- the percentage of passing maneuvers that are completed within the marked passing zone and within the marked no-passing zone
- the relative positions of the passing and passed vehicles at the end of the marked passing zone (passing vehicle ahead/passing vehicle abreast/passing vehicle behind)
- location of passing vehicle’s return to normal lane (distance upstream or downstream of end of marked passing zone)
- sight distance at location of passing vehicle’s return to normal lane (The sight distance profile will have been determined in advance of the field study, so the available PSD at any point on the road is known.)
- any conflicts between passing, passed, and/or oncoming vehicles that result from the observed maneuvers. The severity of the return maneuvers at the end of pass completions and pass aborts will be classified using the categories from either the Jones (7) or the Van Valkenburg and Michael (8) studies.
The data will be collected with a combination of video recording and manual observation. A manual observer will be stationed at an inconspicuous location near the end of the marked passing zone. One to three video cameras will be used also along the roadway upstream and downstream of the end of the marked passing zone. The video cameras will be placed in inconspicuous locations and, where feasible, an elevated vantage point will be used. The video cameras will have an elapsed time superimposed on the video image and this elapsed time will be tied to a master stopwatch so that all video data are on a common time base.

The data collected will be used to assess whether there are safety concerns created by current PSD marking criteria, particularly in the portion of the no-passing zone immediately downstream of the passing zone and whether passing operations are generally conducted as represented in PSD models.

- **Work Plan E—Safety and Operations of Short Passing Zones**

This work plan will involve collection of observational field data to verify whether short passing zones permitted under MUTCD criteria (i.e., passing zones 400 to 800 ft in length) have the potential to create safety problems on two-lane highways. It is expected that such short passing zones are used very infrequently for passing, at least for delayed passes involving vehicles traveling at high speeds, but this needs to be verified. It also needs to be determined whether such short passing zones are used for passing maneuvers that can be completed safely, even given the short length of the passing zone. If, for example, such short passing zones are used primarily for passes of low-speed vehicles (e.g., a flying pass of a slow-moving tractor on the road), then the potential for safety concerns created by short passing zones may not be real. Approximately 10 short passing zones will be studied.

The field data collected will be similar to the data collected for Work Plan D, except that the passing zones studied will be shorter. Key data will include the frequency of passes in short zones, the types and species of vehicles passed, the resulting intervehicle conflicts, and the severity of the return maneuver. The data gathered will be used to make recommendations as to whether current marking practices for short passing zones should be retained unchanged or whether the minimum passing zone length specified in the MUTCD should be increased. The data will also be considered in determining whether a minimum length of adequate PSD should be added to the PSD criteria used in geometric design.
5.3 Field Measurement of Vehicle Speeds, Speed Differentials, and Accelerations Used in Passing Maneuvers

The review of PSD models in Section 3 of this report and the review of key issues related to PSD in Section 4 of this report has led to some tentative directions for potential modification of the PSD models used for roadway design and for marking of passing and no-passing zones. The research team has tentatively recommended that the current PSD marking model be replaced with a model based on the work of either Glennon (14) or Hassan et al. (18) that is likely to provide about the same PSD criteria as the current MUTCD. The research team has recommended investigation of five alternative models or approaches to the PSD design.

Since the field data that have been used to calibrate the existing PSD models, and most of the PSD models in the literature, are dated, new field data will be collected to calibrate whichever PSD models are finally recommended. Work Plan F addresses this data collection need:

- Work Plan F—Field Data Collection to Quantify the Parameters of Revised PSD Models

The parameters of potential PSD models that most need to be quantified with field data are as follows:

- speed differential between passing and passed vehicles (m)
- distance traveled by the passing vehicle from beginning of passing maneuver to the critical position (d_7)
- deceleration rate used in aborting a passing maneuver (d)

The parameters are listed above in descending priority order for evaluation. The speed differential between the passing and passed vehicles (m) is assigned the highest priority because the Green Book considers this parameter to have a constant value of 10 mph, but the literature suggests that it actually varies with the speeds of the involved vehicles. The next highest priority is assigned to the distance traveled to reach the critical position (d_7) which, to the best of our knowledge has never been measured in a field study. The lowest priority is assigned to the deceleration rate used in aborting a passing maneuver, because this can be readily estimated from other sources of braking rate information, if necessary.

While we have assigned priorities to the parameters to be measured, as stated above, the research team believes that data on all of these parameters can and should be collected. As part of these field studies, we expect to obtain other data that should help in calibrating and explaining PSD models, such as the
percentage of passing maneuvers that are completed and aborted and the
distribution of locations at which pass abort decisions take place.

Previous studies reported in the literature have gathered data on driver passing
behavior by using slow-moving vehicles operated by research team members in
the traffic stream and recording data on the resulting passing maneuvers (40); we
do not recommend such an approach, but rather we recommend data
collection from roadside locations and/or from temporary sensors on the
pavement surface. Other studies have gathered data on passing behavior by
filming from helicopters or fixed-wing aircraft (56). This approach would
require substantially more resources than available in the project; therefore, we
do not believe it will be feasible in this study.

The field observations will be accomplished by video recording of traffic
maneuvers with one or more video cameras in elevated vantage points. Prior to
the beginning of data collection, an “establishing shot” will be taken with a
research team vehicle stopped in several pre-measured locations along the
shoulder of the highway to establish a line on the video image from which the
position of moving vehicles can be measured. The video cameras will have an
elapsed time superimposed on the video image and this elapsed time will be tied
to a master stopwatch so that all video data are on a common time base.

Average speeds for each observed vehicle over distances between the
established points can be determined by the elapsed time from the video and the
known distance. MRI also has traffic classifiers with pavement sensors that can
be placed along the road to measure vehicle speeds and accelerations at fixed
locations to supplement the speed and volume data from the video, if needed.
Laser speed measurement devices are also available for use if needed to
document vehicle speed profiles; if the lidar beam is aimed at a good reflective
spot on a vehicle, such as the license plate, and the beam is kept activated, the
distance vs. speed profile of the vehicle can be continuously recorded. The laser
speed measurement devices will be used only if needed because it needs to be
used from a position near the road, where the operator is likely to be more
conspicuous than for the other types of data collection anticipated for this study.

Figure 24 illustrates a potential data collection set-up for this study. We
recommend the use of approximately 10 sites for data collection under Work
Plan F. The sites used for Work Plan F may be the same sites used for Work
Plan D, unless we see a specific need to use sites in longer passing zones for
Work Plan F. The data needed for Work Plans D and F may be collected
simultaneously at a given site, if this proves to be practical.

The data collected in Work Plan F will be used to quantify the parameters of the
PSD models that will be recommended in Task 7.
Figure 24. Example of Data Collection Layout for a Passing Zone in Work Plan F
5.4 Effect of Alignment and Alternative PSD Criteria on Actual Road Markings and Roadway Lengths With Sufficient PSD for Passing

To investigate the appropriateness of using different PSD criteria for design and marking, it will be desirable to assess the marked passing and no-passing zones (or the extent of regions of adequate PSD) that potentially result from the adoption of alternative PSD criteria. This issue is addressed in the following work plan.

- Work Plan G—Application of Revised PSD Criteria to Actual Terrain: Effect of Alternative PSD Criteria on Road Markings and Extent of Roadway Length with Sufficient PSD for Passing

The objective of Work Plan G is to better understand the effects of changing the PSD criteria used in design and making.

A key issue in understanding the potential effects of changes in PSD criteria is their effect on the frequencies of passing and no-passing zones, the sight distances available in those zones, and the lengths of those zones. Data that can be used to make such an assessment include: highway agency records of passing and no-passing zone markings, highway agency records of horizontal and vertical alignment (available from the FHWA Highway Safety Information System for the state of Washington), and as-built plans showing horizontal and vertical profiles. As noted below, an algorithm in the TWOPAS model can be used to estimate the sight distance profile of a roadway for which the horizontal and vertical alignment are known. These data can be used to estimate the effect of changes in PSD marking criteria on the dimensions of marked passing and no-passing zones and the availability of passing opportunities.

As part of this work plan, the research team will obtain data on the actual horizontal and vertical profiles of approximately 10 sections of rural two-lane highway, including sections in both level and rolling terrain. These data will be entered into TWOPAS and the tools within TWOPAS will be used to generate the sight distance profile for the roadway section. This sight distance profile will be used, in turn, as a baseline, to generate the locations of passing and no-passing zones marked in accordance with the current MUTCD criteria and the locations of adequate PSD for passing determined in accordance the current AASHTO criteria. Then, as alternative PSD criteria for either design or marking are generated, they will be applied to the established sight distance profile and the effects of marked passing and no-passing zones and/or areas of adequate PSD for passing will be noted. The results of this effort will be included in the final consideration of PSD models for design and marking. The traffic operational effects of the changes in design and marking criteria will be considered below in Work Plan H.
To supplement the evaluation of road profiles discussed above, the research team also plans to interview approximately five experienced designers about the manner in which PSD design is conducted. These interviews, which will be conducted in person or by telephone, will address practical issues of the extent to which horizontal and vertical alignment is dictated by terrain and the extent to which the designer has flexibility (and budget) to modify the alignment to increase the percentage of roadway length that meets the PSD criteria for design.

5.5 Traffic Operational Evaluation of Various Design and Marking Scenarios

Another potential work activity in Phase II is the use of a traffic operational simulation model to determine the effect of any proposed changes in PSD criteria on level of service. Clearly, safety should take priority over traffic operational level of service if a clear need to enhance safety by changing PSD criteria is identified. However, there is also a need to assure that level of service is not degraded by requiring greater PSD, especially for marking passing and non-passing zones, unless there is a clear safety-based need to do so. The traffic operational effects of proposed changes in PSD criteria are addressed in the following work plan.

- Work Plan H—Traffic Operational Effects of Alternative PSD Criteria

Traffic operational analyses for the proposed research will be performed with the TWOPAS model, which was originally developed by MRI and has been used extensively in two-lane highway research and operational analysis. The TWOPAS model was used in the development of the HCM2000 chapter on two-lane highways and its predecessor, TWOWAF, was used in the development of the previous HCM1985 chapter on two-lane highways. The TWOPAS capabilities that are most important to the proposed work include:

- capability to determine appropriate locations for marked passing and no-passing zones for any user-specified alignment and sight distance profile
- capability to run identical traffic streams (the same sequence of drivers and vehicles) over varying alignments or over the same alignment with varying passing and no-passing zone markings
- capability to estimate the traffic operational measures that define level of service for two-lane highways in the HCM2000: percent time spent following and average travel speed

Given these capabilities, TWOPAS can be used to quantify the traffic operational effects of any changes in PSD criteria proposed in the research. Such analyses can be readily performed because the geometrics of a number of typical sites will be set up in TWOPAS for the review of the effects of alternative PSD criteria on the extent of marked passing and no-passing zones in
Work Plan G. It will be a very simple extension of that analysis to make a series of runs with TWOPAS to assess the traffic operational effects of the alternative PSD criteria.

5.6 Comparison of Stopping Sight Distance and Passing Sight Distance Criteria

Understanding of the effects of alternative PSD criteria will require a comparison between those alternative criteria and the \textit{Green Book} stopping sight distance (SSD) criteria. This comparison is addressed in the following work plan.

- \textit{Work Plan I—Comparison of PSD and SSD Criteria}

The research team will make a formal comparison of SSD and PSD criteria, including both current PSD criteria for design and marking and any revised PSD criteria that may be recommended in the research. This comparison will address not only the sight distance values used in design and marking, but also the vertical curve lengths required to provide these sight distance values. In particular, the impact of the recent change in SSD object height from 6 in to 2 ft will be considered. This work plan will determine, for specific values of algebraic difference in grade, what levels of SSD provide vertical curves that also provide the minimum required PSD under proposed PSD models for design and marking. Specifically, this study will focus on the K-values for vertical curves needed to provide:

- SSD for a 6-in object (past AASHTO policy)
- SSD for a 2-ft object (current AASHTO policy)
- PSD for current MUTCD marking criteria
- PSD for current AASHTO design criteria
- PSD for any recommended alternative criteria developed in the research

5.7 Frequency of Passing Opportunities Needed on Two-Lane Highways

Current PSD design policies do not address the frequency of passing opportunities or the percentage of roadway length with adequate PSD needed on two-lane highways. The percentage of roadway length with adequate PSD for particular projects is a decision that is left to the designer or the highway agency. The following work plan would develop more specific guidance on this issue for use by designers.
Work Plan J—Develop Guidance for Designers on Determination of the Percentage of Roadway Length with PSD Adequate for Passing

The research team will develop guidance or recommendations on the average frequency or percentage of passing opportunities that should be provided on two-lane highways. The need for passing opportunities is clearly dependent on traffic volumes, with greater percentages of passing zones being needed as volumes increase (and as the percentage of heavy vehicles increases). Either Highway Capacity Manual procedures or the TWOPAS traffic operational simulation model could be used to explore the percentage of passing zones needed to attain a specified level of service (e.g., see Green Book Table 2-32) appropriate for the functional class and terrain of a roadway section that serves specified values of traffic volume and traffic mix. Another issue that might be considered is the effect of added passing lanes on PSD requirements for the roadway between passing lanes; where passing lanes are provided at regular intervals on a roadway, the percentage of passing zones needed between passing lanes may be much less than on comparable facilities without passing lanes.
Section 6.
Priorities and Budget Allocations for Phase II Work

This section of the interim report describes the work to be performed in Phase II of the work, including execution of the work plans presented in Section 5 of the report. The research team expects to discuss the recommendations with the NCHRP project panel at the upcoming meeting.

6.1 Phase II Tasks

The Phase II work will be performed in four tasks, as follows:

Task 6—Execute Approved Work Plans
Task 7—Prepare new or modified PSD criteria
Task 8—Prepare Final Report
Task 9—Prepare and Deliver Final Presentations

Each of these tasks is discussed below.

Task 6—Execute Approved Work Plan

In Task 6, the research team will execute the work plans presented in Section 5 of this report, as approved by the NCHRP project panel. These plans will be discussed with the NCHRP project panel at the upcoming meeting. The work plans will be revised, as needed, in response to panel comments. The research team will not begin work on Task 6 without NCHRP approval.

Task 7—Prepare New or Modified PSD Criteria

In Task 7, the research team will develop new or modified PSD criteria for inclusion in the Green Book and the MUTCD. These new or modified PSD criteria may involve revised PSD models and may involve new input parameters or revised values of current input parameters. The revised PSD criteria will be based on the results of the data collection and analysis performed in Task 6. Revised Green Book text for consideration by the AASHTO Technical Committee on Geometric Design and revised MUTCD text for consideration by FHWA and the National Committee on Uniform Traffic Control Devices will be prepared.
A specific recommendation will be made in Task 7 about whether the *Green Book* and MUTCD PSD models and criteria should be the same or should differ, and the reasons for this recommendation will be presented and explained. If revised PSD criteria are recommended, the safety and traffic operational effects of implementing such criteria will be estimated for presentation in the final report.

If new PSD criteria are proposed in Task 7, the final report prepared in Task 8 will recommend how the adoption of the new criteria can be recommended and encouraged. In preparing these recommendations, we will address methods for encouraging implementation in addition to their eventual inclusion in the *Green Book* and MUTCD.

**Task 8—Prepare Final Report**

In Task 8, MRI will prepare and submit a final report documenting the entire research effort. The final report will describe how the research was conducted and how any new or revised PSD criteria were developed. Recommended revisions to the *Green Book* and the MUTCD will be presented as appendices to the final report. MRI has prepared numerous NCHRP reports and we are very familiar with the desired organization and format of such reports.

The final report will first be submitted in draft form no later than 90 days prior to the project completion date. NCHRP and the project panel will have 60 days to review the report and provide written comments to MRI. MRI will then revise the draft report in response to the panel comments and then submit the revised report to NCHRP on or before the contract completion date.

As part of Task 8, MRI will prepare, and submit to NCHRP, a PowerPoint presentation on the background, methodology, and results of the study.

**Task 9—Prepare and Deliver Final Presentations**

In Task 9, the MRI principal investigator will prepare and deliver presentations on the research results to both the AASHTO Technical Committee on Geometric Design and the National Committee on Uniform Traffic Control Devices.

**6.2 Recommended Allocation of Phase II Budget**

The contract has a planned total funding level of $300,000. Within the planned funding level of $300,000, $64,066 was budgeted for Phase I (Tasks 1 through 5) and $235,934 was budgeted for Phase II (Tasks 6 through 9). The research team estimates that Phase I will be completed for a cost of approximately $61,000, or approximately $3,066 below the Phase I budget of $64,066. The research team recommends that the unexpended amount of $3,066 be added to the available budget for Task 6. With this
addition, the research team recommends that the Phase II budget should be reallocated as follows:

<table>
<thead>
<tr>
<th>Task</th>
<th>Original budget</th>
<th>Revised budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 6</td>
<td>$177,873</td>
<td>$180,939</td>
</tr>
<tr>
<td>Task 7</td>
<td>23,968</td>
<td>23,968</td>
</tr>
<tr>
<td>Task 8</td>
<td>25,890</td>
<td>25,890</td>
</tr>
<tr>
<td>Task 9</td>
<td>8,203</td>
<td>8,203</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$235,934</td>
<td>$239,000</td>
</tr>
</tbody>
</table>

The estimated funds required for the ten specific work plans presented in Section 5 of this interim report are as follows:

<table>
<thead>
<tr>
<th>Work plan</th>
<th>Estimated budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Benefit-cost analysis of PSD marking revisions</td>
<td>$10,000</td>
</tr>
<tr>
<td>B Identification and analysis of passing-related accidents</td>
<td>100,000</td>
</tr>
<tr>
<td>C Review of accident data for field study sites</td>
<td>5,000</td>
</tr>
<tr>
<td>D Safety of passing maneuvers completed beyond the end of a passing zone</td>
<td>30,000</td>
</tr>
<tr>
<td>E Safety and operations of short passing zones</td>
<td>30,000</td>
</tr>
<tr>
<td>F Field data collection to quantify parameters of revised PSD models</td>
<td>50,000</td>
</tr>
<tr>
<td>G Application of revised PSD criteria to actual terrain</td>
<td>10,000</td>
</tr>
<tr>
<td>H Traffic operational effects of alternative PSD criteria</td>
<td>15,000</td>
</tr>
<tr>
<td>I Comparison of PSD and SSD criteria</td>
<td>5,000</td>
</tr>
<tr>
<td>J Guidance on determining the percentage of roadway length with adequate PSD</td>
<td>10,000</td>
</tr>
</tbody>
</table>

These budget values presented above are estimates that may vary in the actual performance of the work. The research team is confident that, while some portions of the work may cost more than expected, other parts of the work will cost less than expected, so that the work plans as a whole can be completed within the estimated amount.

The research team estimates that all of the work plans recommended in Section 5 for performance in Task 6 can be completed for a cost of $265,000. However, as shown above, the funding expected to be available for Task 6 is $180,939, a shortfall of approximately $84,000. Thus, it appears that some portion of the recommended work plans will need to be dropped or scaled back. Among the work plans proposed, the research team considers that Work Plan B may have the lowest priority because it is a relatively costly activity and because the results of the previous HSIS study (29) can be relied upon for at least a partial answer to the issues addressed in Work Plan B. Based on this assessment, the research team sees two alternative courses of action that should be considered for completion of the work within the project budget:
- Eliminate Work Plan B entirely. This would eliminate the funding shortfall and free up $16,000 for allocation to other work plans. The research team considers that the additional $16,000 could most productively be used for field work in Work Plans D, E, and F.
- Scale back Work Plan B to an effort that can be completed for $16,000, rather than $100,000. A scaled-back effort would focus on a limited analysis of existing HSIS accident databases and would not include review of videologs or hard-copy police accident reports.

The research team plans to discuss these alternative approaches to realignment of the Phase II budget and other possibilities with the NCHRP project panel, at the upcoming meeting.

### 6.3 Period of Performance

The Phase II work will start when authorized by NCHRP. This can happen as soon as mid-April, but will depend on the extent of needed revisions to the work plans requested by the NCHRP project panel.

The Phase I work has required approximately two months of additional calendar time beyond that originally planned. The original project schedule anticipated that Phase II work would begin on February 1, 2005, but it now appears that the earliest the Phase II work can begin is mid-April.

The scheduled submission date for the preliminary draft final report is February 28, 2006, and the scheduled project completion date is May 31, 2006. This schedule allows, at most, 10.5 months for completion of the work in Tasks 6 and 7 and completion of the preliminary draft final report in Task 8. The research team will do everything possible to make up the time lost in Phase I, but we are not sure whether it will be possible to meet this schedule while completing all aspects of Phase II. Our immediate goal is to make sure that the field data are collected during the 2005 summer season. We will monitor progress carefully and inform NCHRP in the fall of 2005 whether we will need to request an extension of the project period of performance.
Section 7.
References


