New and Improved Model of Passing Sight Distance on Two-Lane Highways

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A mathematical model is derived for describing the critical nature of the passing maneuver on two-lane highways. This model is based on the hypothesis that a critical position exists during the passing maneuver where the passing sight distance requirements to either complete or abort the pass are equal. At this point, the decision to complete the pass will provide the same head-on clearance to an opposing vehicle as will the decision to abort the pass. Current highway practice in both designing and marking for passing sight distance uses a model that assumes that once a driver starts a pass, he must continue until the pass is completed. In other words, the model assumes that the driver has no opportunity to abort the pass. Because this hypothesis is unrealistic, the model derived here is recommended for determining new passing sight distance requirements for both designing and marking passing zones. Suggested values are given for these requirements. A brief analysis is also presented of the sensitivity of passing sight distance requirements to vehicle length. This analysis shows that the effect of truck length is not as dramatic as previously reported in the literature.

Although significant advances have been made since 1971 in understanding the critical aspects of the passing maneuver on two-lane highways, the highway community still clings to false and archaic principles. Actually in the current practice for both the design and the marking of passing zones, these zones are neither designed nor marked directly. Current marking practice in the 1978 *Manual of Uniform Traffic Control Devices* (MUTCD) (*1*), for example, is concerned with no-passing zones, and passing zones merely happen where no-passing zones are not warranted. In highway design, the current practice is stated in the 1984 *Policy on Geometric Design of Streets and Highways* (*2*) by the American Association of State Highway and Transportation Officials (AASHTO). In AASHTO policy, which has remained unchanged since 1954, the design of passing sight distance (PSD) only considers the percentage of highway that has PSD, regardless of whether that PSD forms passing zones of adequate length.

Another inconsistency exists in that, although the AASHTO design and MUTCD marking practices are based on the same hypothetical model, they use completely different criteria to exercise that model. Whereas the current AASHTO practice assumes a 10-mph speed differential between passing and impeding cars for all design speeds, the MUTCD practice comes from the 1940 AASHO policy (*3*), which used speed differentials ranging from 10 mph at a 30-mph design speed to 25 mph at a 70-mph design speed.

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Besides the inconsistencies already discussed, the basic hypothesis underlying both current PSD design and PSD marking practices is flawed. Although this hypothesis correctly considers the opposing vehicle and the final head-on separation distance as integral components of the critical passing maneuver, it determines overly long PSD requirements by assuming that the passing driver has no opportunity to abort the maneuver.

This paper first addresses the development of a more appropriate model for PSD requirements. With this model developed, the paper then focuses both on the application of the model to proper highway design and marking practices and also on the sensitivities of PSD requirements to vehicle length.

RESEARCH SINCE 1971

In 1971, Weaver and Glennon (*4*) and Van Valkenberg and Michael (*5*) independently recognized that the AASHTO model (*2–3, 6–7*) for PSD fails to address the critical nature of the passing maneuver. These studies also both recognized that a safe passing maneuver not only requires continuously varying amounts of PSD (depending on the lesser of the needs for completing or aborting the maneuver), but also has a relative position between the passing and impeding vehicles where the ability to complete the pass is equal to the ability to abort the pass. Weaver and Glennon called this the critical position, and Van Valkenberg and Michael called it the point of no return. Neither study, however, attempted to mathematically define this critical position.

In 1976, Harwood and Glennon (*8*) attempted to better explain the state-of-the-art concerning PSD requirements. This paper contributed further definition of the critical position as that point where the PSD needed to complete the pass is equal to the PSD needed to abort the pass. As shown in figure 1, the pass starts with a minimal PSD needed to abort, the PSD increases through the maneuver until the PSD needed for either completing or aborting the maneuver is equal, and then the PSD decreases through the remainder of the maneuver based on the temporal needs for pass completion.

Lieberman (*9*), in 1982, added further insight by developing a mathematical time-distance model that identified the critical position and the critical PSD as a function of design speed. however, he incorrectly concluded that AASHTO requirements for PSD were inadequate by calculating his PSD requirements as the sum of both the critical PSD and the distance needed for the passing vehicle to get from the initial trailing position to the critical position. His model also ignored the direct effects of vehicle length and the elapsed time for

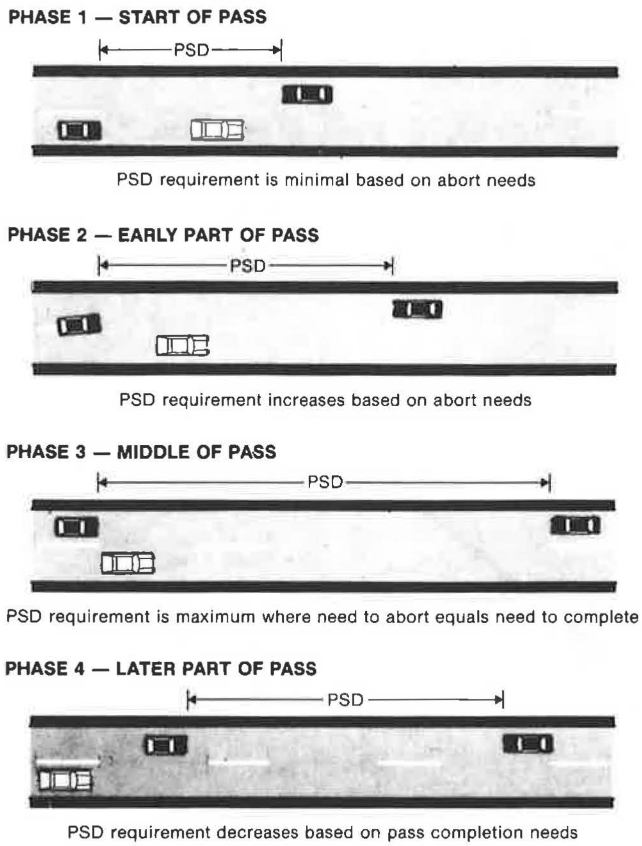

FIGURE 1 Four phases of a passing maneuver.

perception-reaction in the abort maneuver. Regardless of these shortcomings, the Lieberman formulation was conceptually correct and, as such, provided the inspiration for the model developed in this paper.

Saito (*10*), in 1983, re-emphasized the importance of the abort maneuver in determining PSD requirements. To that date, his modeling came closest to determining true PSD needs. However, he looked only at the needs of the abort maneuver and ignored the trade-offs between the completed and abort maneuvers. In other words, rather than calculating the critical position, he assumed that position was where the passing vehicle is immediately behind the impeding vehicle. As indicated later, this assumption gives PSD requirements that are not too different from those found by using a critical position calculated as a function of design speed.

DERIVATION OF A CRITICAL PASSING MODEL

Figure 2 shows time-space diagrams for both the completed passing maneuver and the aborted passing maneuver from the critical position where the PSD needed for safe completion equals the PSD needed for safe abortion. If an opposing vehicle appears before the passing vehicle reaches the critical position, the PSD needed to abort the pass is less than the PSD needed at the critical position. Likewise, if an opposing vehicle appears after the passing vehicle reaches the critical position, the PSD needed to complete the pass is less than the PSD needed at the critical position. Therefore, the maximum or critical PSD is that needed at the critical position.

The proposed model assumes that the opposing vehicle travels at the design speed, that the passing vehicle accelerates to the design speed at or before the critical position and continues at that speed unless the pass is aborted, and that the impeding vehicle travels at a constant speed at some increment less than the design speed.

Since the initial part of the pass is of no consequence in determining the critical sight distance, *Sc*, figure 2 starts the passing vehicle at the critical position and equates the two possible maneuvers in time and space. The sub-model for the completed pass assumes that each vehicle maintains a constant speed and that at the end of the pass there is an acceptable clearance, *C*, between passing and opposing vehicles and an acceptable gap, *G*, between passing and impeding vehicles. For the aborted pass, the impeding and opposing vehicles maintain their constant speeds, but the passing vehicle after a one-second driver perception-reaction time decelerates at rate, *d*, until it achieves an acceptable gap, *G*, behind the impeding vehicle and an acceptable head-on clearance, *C*. [Note that the one-second perception-reaction time is also a part of the completed pass time, but can be ignored in this part of the analysis because it does not affect any of the key time-distance parameters.]

To develop a usable model for the critical PSD requires simultaneous solutions of equations for both the completed and aborted passes, knowing by definition that their critical positions and critical sight distances are equal. The following sections illustrate the development of this model.

Equate Critical Positions

The critical position for the completed pass is shown on figure 2A as:

$$\Delta_c + vt_1 = L_p + G + (v - m)t_1$$

or

$$\Delta_c = L_p + G - mt_1 \tag{1}$$

The critical position for the aborted pass is shown on figure 2B as:

$$\Delta_c' + v + vt_2 - \frac{dt_2^2}{2} = (v - m) + (v - m)t_2 - G - L_i$$

or

$$\Delta_c' \frac{dt_2^2}{2} - m(t_2 + 1) - G - L_I \tag{2}$$

Since by definition $\Delta_c = \Delta_c$, Equations 1 and 2 can be solved simultaneously for t_1, as follows:

$$t_1 = t_2 + 1 - \frac{dt_2^2}{2m} + \frac{(2G + L_i + L_p)}{m} \tag{3}$$

Equate Critical Sight Distances

The critical PSD for each maneuver is taken directly from figure 2 as the total distance between passing and opposing vehicles when the passing vehicle is in the critical position.

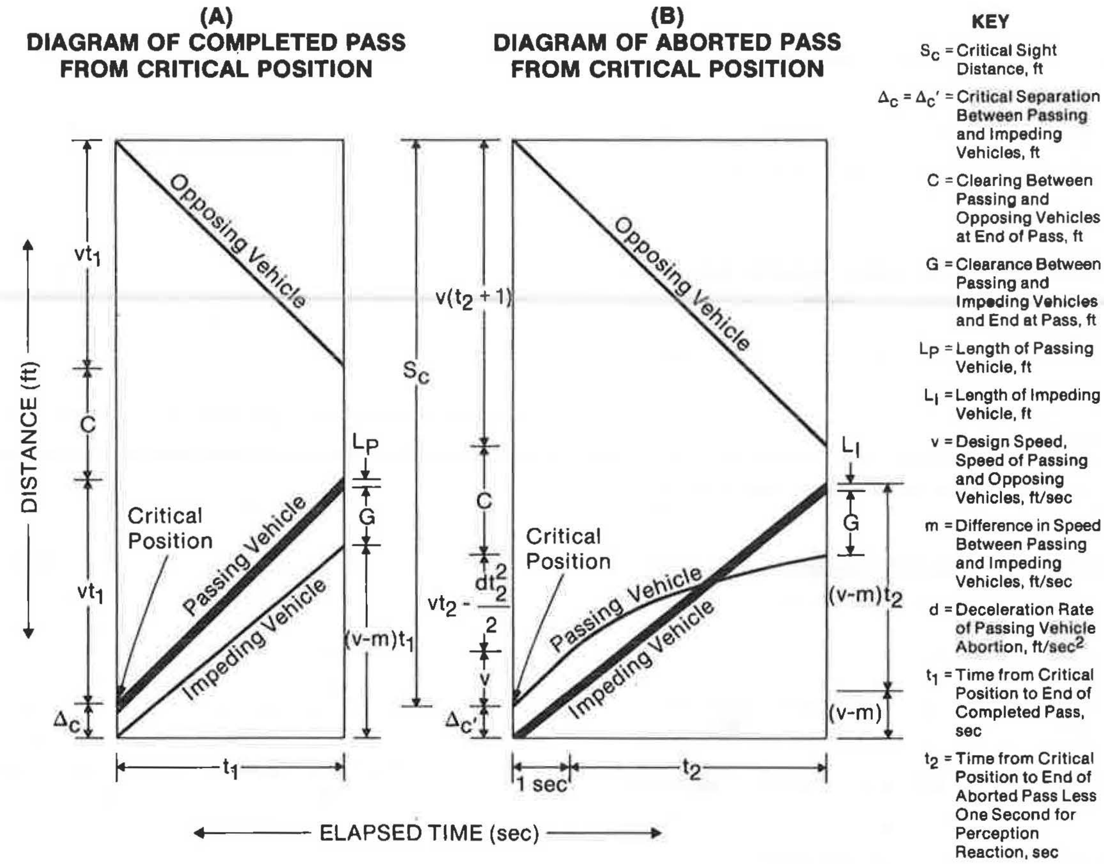

FIGURE 2 Time-space diagrams for the critical passing maneuver.

Equating these distances and solving for t_1 gives:

$$2vt_1 + C = v + vt_2 - \frac{dt_2^2}{2} + C + v(t_2 + 1)$$

$$t_1 = t_2 + 1 - \frac{dt_2^2}{4v} \tag{4}$$

Solve Time Relationships

By simultaneous solution of Equations 3 and 4, t_2 can be isolated as a function of definable parameters as follows:

$$t_2 + 1 - \frac{dt_2^2}{4v} = t_2 + 1 - \frac{dt_2^2}{2m} + \frac{(2G + L_I + L_p)}{m}$$

or

$$t_2 = \sqrt{\frac{4v(2G + L_I + L_p)}{d(2v - m)}} \tag{5}$$

since

$$t_1 = t_2 + 1 - \frac{dt_2^2}{4v}$$

then

$$t_1 = 1 + \sqrt{\frac{4v(2G + L_I + L_p)}{d(2v - m)}} - \frac{(2G + L_I + L_p)}{2v - m} \tag{6}$$

Solve the Critical Position

Equations 1 and 6 can be solved simultaneously to derive an expression for the critical position as a function of design speed, v, speed difference, m, desired gap, G, deceleration rate, d, and lengths of vehicles, L_I and L_p, as follows:

$$\Delta_c = L_p + G - mt_1$$

or

$$\Delta_c = L_p + G - m + m\left[\frac{(2G + L_I + L_p)}{2v - m} - \sqrt{\frac{4v(2G + L_I + L_p)}{d(2v - m)}}\right] \tag{7}$$

Assuming a minimum acceptable headway of one second for G, then $G = m$ and Equation 7 is revised as follows:

$$\Delta_c = L_p + m\left[\frac{(2m + L_I + L_p)}{2v - m} - \sqrt{\frac{4v(2m + L_I + L_p)}{d(2v - m)}}\right] \tag{8}$$

[Note that the same relationship is found if, in Figure 2, the passing vehicle is assumed to be behind the impeding vehicle at the critical position.]

Solve the Critical Passing Sight Distance

Using Figure 2 and Equation 1, the passing sight distance, S_c, can be solved for any design speed as a function of the critical position, Δ_c, speed differential, m, and length of passing vehicle, Lp, as follows:

$$S_c = 2vt_1 + C$$

and

$$t_1 = \frac{L_p + G - \Delta_c}{m}$$

therefore

$$S_c = \frac{C + 2v(L_p + G - \Delta_c)}{m}$$

Having already assumed $G = m$ and also assuming a minimum acceptable head-on clearance of one second, then $C = 2v$. Therefore:

$$S_c = 2v + \frac{2v(L_p + m - \Delta_c)}{m}$$

or

$$S_c = 2v\left[2 + \frac{L_p - \Delta_c}{m}\right] \qquad (9)$$

PASSING SIGHT DISTANCE REQUIREMENTS

Now that a usable model has been developed for the critical PSD, the question remains how to apply it to the design and marking of a passing zone. Obviously, S_c defines the minimum PSD required for any part of the passing zone where a passing vehicle can reach the critical position. As a worst-case scenario, it seems appropriate to provide S_c at the end of a passing zone, assuming that it is reasonable to expect the critical situation at this point. It is not reasonable, however, to expect that the passing vehicle will be in the critical position at the beginning of a passing zone. Actually the PSD requirement at the beginning of the zone is something less than S_c; however, because passing operations vary widely by speed differentials, opposing vehicle speeds, and vehicle lengths, an added safety factor would be incorporated by starting the passing zone where S_c first becomes available.

Recognizing that the assumptions used to develop the critical passing model may be subject to some interpretation and adjustment, this section provides recommendations for PSD requirements based on the following additional assumptions:

1. The AASHTO use of passenger cars for the passing and impeding vehicles are appropriate criteria.
2. The length of the average passenger car is 16 feet.
3. A reasonably safe deceleration rate in the abort maneuver is 8 ft/sec^2.
4. Based on the Weaver and Glennon study (*4*), the following table of critical (15th percentile) speed differentials is appropriate:

Design Speed (mph)	*Speed Differential (mph)*
30	12
40	11
50	10
60	9
70	8

Substituting Assumptions 1 through 3 into Equations 8 and 9, the critical passing model is reduced to relationships that are a function of the design speed and the speed differential as follows:

$$S_c = 2v\left[2 + \frac{16 - \Delta_c}{m}\right]$$

where

$$\Delta_c = 16 + m\left[\frac{(2m + 32)}{2v - m} - \sqrt{\frac{v(2m + 32)}{2(2v - m)}}\right]$$

Using these equations and solving for the design relationships found under Assumption 4 above, table 1 shows the derived PSD requirements. In comparing these recommendations with current AASHTO and MUTCD requirements, they are found to be considerably less than the AASHTO requirements, but very close to the MUTCD requirements (even though the MUTCD requirements were derived with a completely different set of models and criteria.)

Although this paper does not analyze the requirements for passing zone length, previous studies (*4, 11*) have shown that very short zones, such as the 400-ft default length allowed by the MUTCD, are not appropriate for safe highway operations. Therefore, the recommendations of Weaver and Glennon (*4*) for minimum passing zone length, based on 85th percentile passing vehicle distances, should be implemented unless another rationale is shown to be more appropriate. These passing zone lengths are also shown in table 1.

TRUCK LENGTH CONSIDERATIONS

Several authors (*9, 12–14*) have expressed alarm at the supposed inadequacy of PSD requirements (most particular AASHTO requirements) for passes involving trucks in general and longer trucks, in particular. These studies were dramatized by Donaldson (*15*) as follows:

> The recent research of Lieberman demonstrates the thorough inadequacy of the AASHTO sight distance formulae for the successful execution of the passing maneuver . . . . Lieberman has shown that significantly longer sight distances are needed when the impeding vehicle is a truck . . . . The research of Gericke and Walton demonstrates that the AASHTO sight distance formulae for geometric design are inadequate for any vehicle and especially inadequate for cars passing trucks . . . . Saito shows that successful aborts are impossible under most high-speed conditions on the basis of current MUTCD standards . . . . If one extrapolates his kinematic model, it shows substantial increases in the lengths of time and distances for successful aborts of cars attempting to pass longer trucks . . . . The passenger car/truck relationship in the passing maneuver is highly dangerous on many thousands of our rural arterial and collector routes that have inadequate sight distance but which are marked to permit passing maneuvers that cannot be accomplished by most of the vehicles making the attempts.

The flaw in the remarks quoted above is that none of the studies cited by Donaldson were based on a correct analysis of passing sight distance requirements. Of the sources cited, Lieberman (*9*) failed to correctly apply his own insights on the definition of the critical sight distance, Saito (*10*) ignored the trade-offs between completed and aborted passes, and Gericke and Walton (*12*) used the [incorrect] AASHTO model to derive their results, as did Fancher (*13*) and Khasnabis (*14*).

Table 2 shows the sensitivity of the derived PSD requirements to vehicle length. As can be seen, the PSD requirements increase as a function of vehicle length but not as dramatically as previously stated in the literature.

Whether a truck should be considered as a design vehicle

TABLE 1 DERIVED PASSING SIGHT DISTANCE REQUIREMENTS

Design Speed (mph)	Critical Position Front of passing vehicle relative to front of impeding vehicle (ft)	Maximum Abort Position Front of passing vehicle relative to front of impeding vehicle (ft)	Minimum Length of Passing Zone (Ref. 4)	PSD Requirement (ft)
40	-43	-10	600	670
50	-38	-10	900	830
60	-32	-8	1200	990
70	-25	-5	1500	1140

TABLE 2 DERIVED PASSING SIGHT DISTANCE REQUIREMENTS AS A FUNCTION OF PASSED VEHICLE LENGTH

Design Speed (mph)	Rounded PSD Requirements for Various Passed Vehicle Lengths (ft)*			
	Passenger Car	55-ft. Truck	65-ft. Truck	110-ft. Truck
40	670	760	780	850
50	830	960	980	1080
60	990	1150	1180	1320
70	1140	1320	1380	1550

* Uses passenger car for passing vehicle

for PSD is a moot point, considering, first, that the vehicle length is really only critical for an end-zone pass and, second, that passing drivers have adaptive behavior that considers not only their position in the zone but the vehicle length to be passed.

CONCLUSIONS

The current AASHTO (*2*) model for passing sight distance requirements ignores the possibility of an aborted maneuver and thereby determines overly long distances. This paper derives a more appropriate model that considers the trade-offs between aborted and completed passes. The passing sight distance requirements derived with this model are considerably less than the AASHTO requirements but are surprisingly close to those presented in the MUTCD (*1*). Application of the derived model also shows that the effect of truck length is not as dramatic as previously reported in the literature.

The derived model should be used to revise both the AASHTO and MUTCD practices so that a correct and consistent basis is used for both the design and marking of passing zones. In doing so, the assumption of a one-second, head-on clearance; a one-second gap; an 8-ft/sec^2 deceleration; and a 15th-percentile speed differential should all be questioned. However, because the critical condition addresses only the infrequent pass at the end of a zone, care should be exercised in being overly conservative in selecting these values. For example, the one-second, head-on clearance and one-second gap seem short but may be reasonable considering the rarity of a [small] 15th-percentile speed differential and a [relatively low] 8-ft/sec^2 abort deceleration.

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