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Model for Calculating Safe Passing Distances on Two-Lane Rural Roads

EDWARD B. LIEBERMAN

A model describing the kinematics of vehicle trajectories during the passing maneuver on two-lane rural roads is presented. This model is based on the hypothesis that there exists a point in the passing maneuver that can be identified as a critical position. At this point, the decision to complete the passing maneuver will provide the same factor of safety relative to an oncoming vehicle as will the decision to abort the maneuver. The model locates the critical position in terms of exogenous parameters. The results of a series of sensitivity studies conducted with the model are also presented. These results provide insight into those parameters that strongly influence the required sight distances. It is shown that the current sight-distance specifications of the American Association of State Highway and Transportation Officials may be inadequate from a safety standpoint, particularly for high-speed passing maneuvers and for passing vehicles that are low-powered subcompacts.

The calculation of passing sight distance as presented in the Blue Book of the American Association of State Highway and Transportation Officials (AASHTO) (1) is based on several simplifying assumptions. In this paper we examine the kinematics of the passing maneuver in greater detail and offer another point of view. The results obtained with this new model are compared with those detailed in the Blue Book (1); the implications of these comparisons are then discussed.

The benefits of an analytical model describing the passing maneuver on two-lane rural roads include the ability to identify those factors that play a role in determining safe passing sight distances. Furthermore, it is possible to conduct sensitivity studies to determine which of these factors are important relative to the others.

With the changing composition of the traffic stream--larger, faster, more powerful trucks mixing with smaller, lower, less powerful automobiles--such a model can be very useful in assessing the associated changes in safety margins provided by current sight-distance standards. It would also be possible to determine whether there is a need for changes in these standards or whether more positive forms of control are required to improve the safety characteristics of two-lane rural roads. Clearly, any change in these standards could also affect rural road capacity as well as operating speed.

OVERALL APPROACH

When a vehicle traveling on a rural road desires to pass an impeding vehicle, the driver must assess a large number of factors in deciding whether to attempt a passing maneuver. This assessment is a continuous one that extends, after the initial decision is made, throughout the passing maneuver.

This model is based on the hypothesis that there exists a point in the passing maneuver that can be identified as a critical position whenever an oncoming vehicle is in view. This critical position is defined as follows: At the critical position, the decision by the passing vehicle to complete the pass will afford it the same clearance relative to the oncoming vehicle as will the decision to abort the pass.

This implies that if a decision to abort the pass takes place downstream of the critical position (i.e., later in the passing maneuver), the clearance (and therefore the safety factor) relative to the oncoming vehicle will be less than if the passing vehicle completes the pass. The converse applies to a decision to complete the pass if made upstream of the critical position.

The determination of this critical position is a central issue in the development of the model. The critical position is defined in terms of the longitudinal separation between the passing vehicle in the passing lane and the impeder vehicle in the normal lane.

It should be noted that this hypothesis applies even in the absence of an oncoming vehicle. In this case, the oncoming vehicle is replaced by the need for the passing vehicle to return to its normal lane at the terminus of the passing zone or by the possibility of the sudden appearance of an oncoming vehicle if the sight distance is limited. This paper addresses only the condition where the oncoming vehicle is in view; these other cases can be easily represented by suitable modification of the model.

Given the definition of the critical position, the approach taken is to consider that the complete/abort decision is made at this point in the maneuver. (This implies that the decision processes of motorists are accurate--an optimistic assumption.) On this basis, it is possible to locate the critical position for any combination of vehicle operating conditions and to determine the required sight distances.

Figure 1 is a schematic of the passing maneuver from the instant the critical position is attained (a) until the pass is completed (b) or aborted (c). A glossary of all terms used in Figure 1 and in the model formulation is given below:

$\bar{A}$ = average acceleration by passer vehicle to increase its speed from V to V + m (m/s^2),
A_{max} = maximum acceleration achievable at zero speed (m/s^2),
a = design value of abort maneuver deceleration [m/(s•s)],
C = clearance between passing and oncoming vehicles at completion of successful passing maneuver (m),
$\hat{C}$ = clearance between passing and oncoming vehicles at completion of aborted passing maneuver (m),
D_1 = distance traveled by passer from start of passing maneuver to critical position (m),
$\hat{D}_1$ = distance traveled by impeder vehicle while passer is moving to critical position (m),
D_2 = distance traveled by impeder vehicle during successful passing maneuver from time critical position established (m),
$\hat{D}_2$ = distance traveled by impeder vehicle during aborted passing maneuver from time critical position established (m),
D_3 = distance traveled by passing vehicle from critical position to its return to original lane during its successful passing maneuver (m),
$\hat{D}_3$ = distance traveled by passing vehicle from critical position to its return to original lane during its aborted passing maneuver (m),
$d_{\bar{A}}$ = distance traversed by passer vehicle while accelerating (m),
G' = space headway between impeder and passing vehicles at start of passing maneuver (m),
G = space headway between passer and impeder vehicles at instant passer returns to normal lane (m) (in general, G ≠ G'),
m = V_p - V = speed difference, passing versus impeder vehicles, at critical position (m/s),
S_c = sight distance (to oncoming vehicle) when passing vehicle is at critical position (m),
S_o = distance traveled by oncoming vehicle from time critical position is attained to end of passing maneuver (m),
T_1 = travel time from start of passing maneuver to attainment of critical position (s),
t = time for passing vehicle to return to its own lane from its critical position for completed passing maneuver (s),

Figure 1. Passing scenarios.

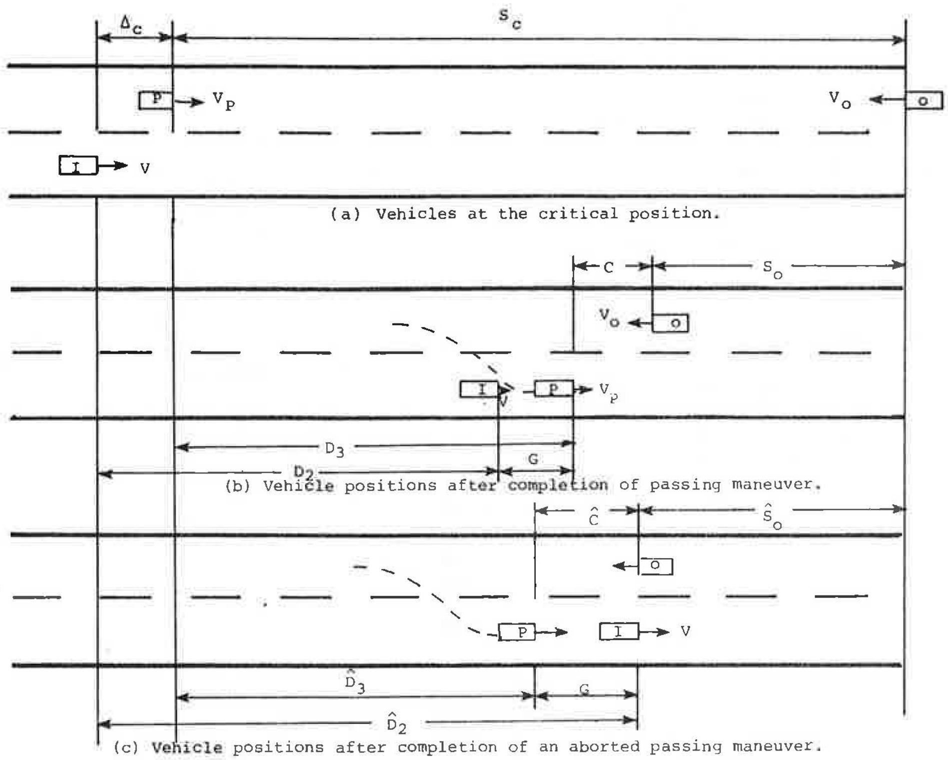
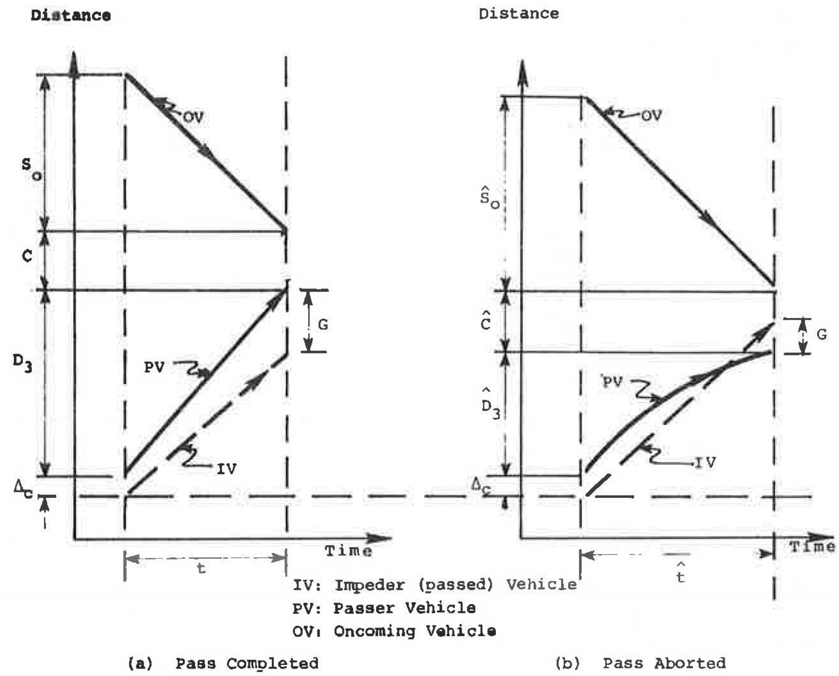


Figure 2. Vehicle trajectories.



t_1 = time passer vehicle moves at speed V_p to reach the critical position (s),
$\hat{t}$ = time for passing vehicle to return to its own lane from its critical position for aborted passing maneuver (s),
$t_{\bar{A}}$ = time passer vehicle spends accelerating to speed V + m (s),
S.D. = required sight distance (m),
V = speed of impeder vehicle (m/s),
V_o = speed of oncoming vehicle (m/s),
V_p = speed of passing vehicle at its critical position (m/s),
V_{max} = maximum speed achievable at zero acceleration (m/s), and
Δ_c = distance that passing vehicle is downstream of impeder vehicle at critical position (m).

The formulation of the model proceeds in two parts, which are subsequently joined together:

1. Description of the passing and abort maneuvers from the critical position to the completion of these maneuvers and
2. Description of the passing maneuver from its inception until the critical position has been attained.

DEVELOPMENT OF MODEL

The trajectories of the vehicles of interest--passer, impeder, and oncomer--from the critical position to the completion of the maneuver are shown in Figure 2. In Figure 2a, the passer completes the maneuver; in Figure 2b, the passing maneuver is aborted. It is assumed that the passer has attained passing speed (V_p) by the time the critical position is reached and that the impeder and oncoming vehicles travel at constant speeds, V and V_o, respectively.

From Figure 2a it is seen that $D_3 + \Delta_c = Vt + G$. Here,

$$D_3 = (V + m)t$$

$$m = V_p - V \text{(speed difference)}$$

Substituting, we obtain

$$(V + m)t + \Delta_c = Vt + G$$

or

$$\Delta_c = G - mt \quad (1)$$

From Figure 2b, it is seen that $\hat{D}_3 = \hat{V}t - G - \Delta_c$. Here,

$$\hat{D}_3 = (V + m)\hat{t} - (1/2)a\hat{t}^2$$

Substituting, we obtain

$$(V + m)\hat{t} - (1/2)a\hat{t}^2 = V\hat{t} - G - \Delta_c$$

or

$$1/2a\hat{t}^2 = m\hat{t} + G + \Delta_c \quad (2)$$

The sight distance from the passer vehicle to the oncoming vehicle when the former is at the critical position is

$$S_c = D_3 + C + S_o = \hat{D}_3 + \hat{C} + \hat{S}_o \quad (3)$$

By definition of critical position, $C = \hat{C}$. Then, $D_3 + S_o = \hat{D}_3 + \hat{S}_o$. Substituting and assuming the oncoming vehicle speed to be V_o = V yields

$$(V + m)t + Vt = (V + m)\hat{t} - 1/2a\hat{t}^2 + V\hat{t}$$

or

$$(2V + m)(\hat{t} - t) = (1/2)a\hat{t}^2 \quad (4)$$

Equating Equations 2 and 4 yields

$$(2V + m)(\hat{t} - t) = m\hat{t} + G + \Delta_c \quad (5)$$

Substituting Equation 1 into Equation 5 yields

$$t = \hat{t} - (G/V) \quad (6)$$

Substituting Equation 6 into Equation 4 and solving for $\hat{t}$ yields

$$\hat{t} = [2G(2V + m)/aV]^{1/2} \tag{7}$$

Solving Equations 7, 6, and 1 in that sequence yields the values of $\hat{t}$, t, and Δ_c, respectively. The calculation for the required sight distance from the critical position (S_c) follows immediately from Equation 3:

$$S_c = (2V + m)t + C \tag{8}$$

It is seen that, subject to reasonable assumptions, the critical position (Δ_c) is independent of the sight distance (S_c) but is dependent on the value of deceleration (a) that is acceptable to the motorist during any abort maneuver.

Figure 3 depicts the vehicle deployments from the start of the passing maneuver to the attainment of the critical position. During this period, the passer vehicle accelerates from its initial speed, assumed to be that of the impeder ("flying" passes are not considered here), until it attains its passing speed (V_p) before or at the critical position.

This acceleration is a function of the vehicle speed, as shown in Figure 4. This function, in turn, depends on the type of vehicle, its weight-to-horsepower ratio, and other factors. To simplify the formulation yet retain the dependence of acceleration on vehicle speed, we will use an average acceleration ($\bar{A}$), calculated as follows:

$$\bar{A} = A_{max}\{1 - [(V + m/2)/V_{max}]\} \tag{9}$$

It follows that the time to attain passing speed (V + m) is

$$t_{\bar{A}} = m/\bar{A}$$

and

$$d_{\bar{A}} = Vt_{\bar{A}} + 1/2\bar{A}t_{\bar{A}}^2 = (m/\bar{A})\,[V + (m/2)] \tag{10}$$

After attaining its passing speed, $V_p = V + m$, the passer vehicle travels for t_1 s until it

Figure 3. Start of passing maneuver.

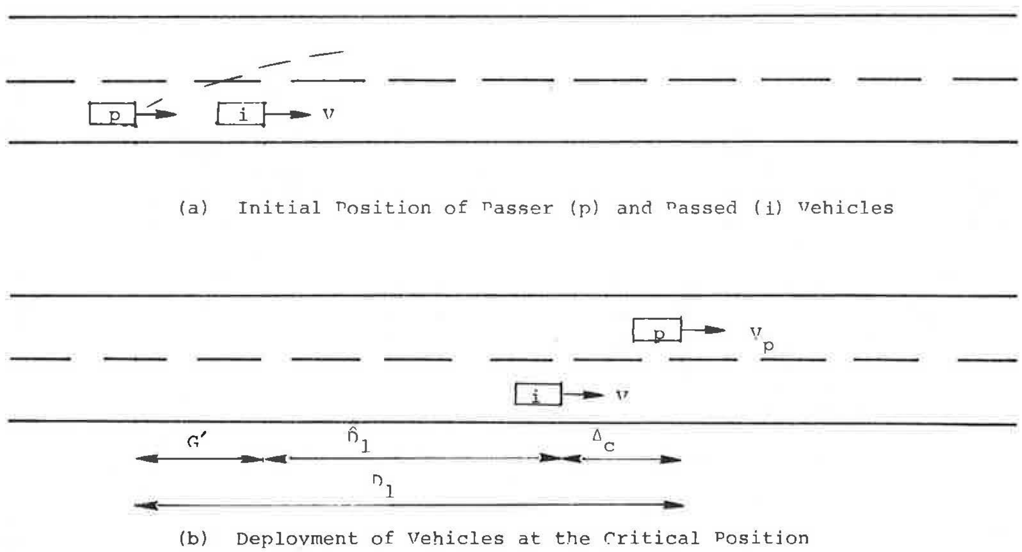
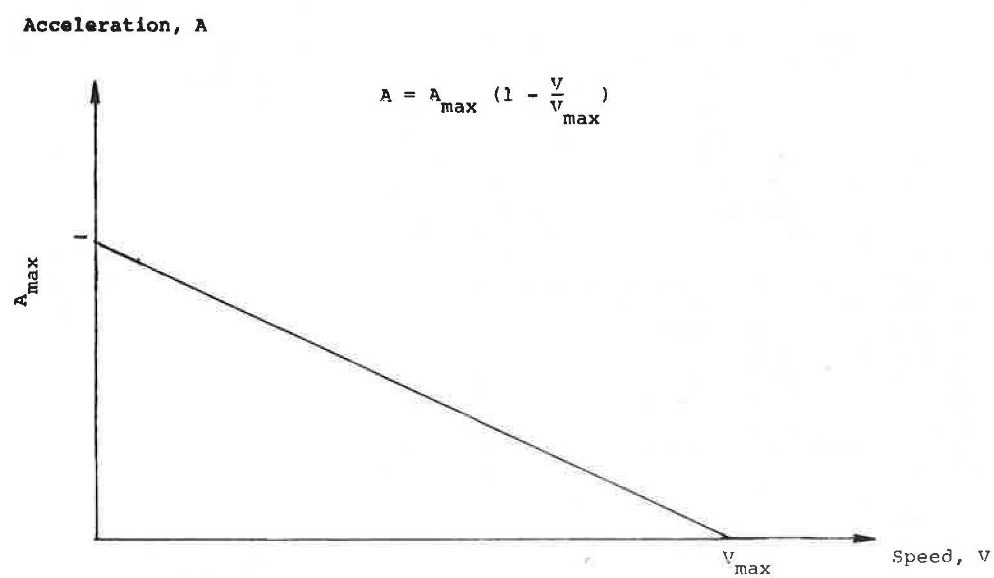


Figure 4. Dependence of vehicle acceleration on vehicle speed for specified vehicle type (level tangent).



reaches the critical position. Since the total travel time is T_1, then

$$t_1 = T_1 - t_{\bar{A}} = T_1 - (m/\bar{A}) \quad (11)$$

Thus,

$$D_1 = d_{\bar{A}} + (V + m)t_1$$

From Figure 3 it is seen that

$$D_1 = G' + \hat{D}_1 + \Delta_c$$

Equating these two expressions for D_1 and recognizing that $\hat{D}_1 = VT_1$ yields the following:

$$d_{\bar{A}} + (V + m)[T_1 - (m/\bar{A})] = G' + VT_1 + \Delta_c$$

Substituting Equation 10 and solving for T_1 yields

$$T_1 = [(G' + \Delta_c)/m] + (m/2\bar{A}) \quad (12)$$

Then

$$D_1 = G' + VT_1 + \Delta_c \quad (13)$$

and the required sight distance is

$$S.D. = D_1 + S_c \quad (14)$$

To solve this system, the passer vehicle type must be specified in order to obtain A_{max} and V_{max}, its operating characteristics. With these values ascertained, $\bar{A}$ may be found from Equation 9, then T_1 from Equation 12, where Δ_c is provided from Equation 1; the values of D_1 and of S.D. follow immediately by using Equations 13 and 14, where S_c is provided by Equation 8. Note that the critical position (Δ_c) is not dependent on the passer vehicle type and that the values of G and of G' depend on the vehicle speeds and lengths.

It should be emphasized that a major difference between this model and the approach used to develop the AASHTO specifications is that both the aborted and the completed passing maneuvers are considered here. (The analysis indicates that the abort time $\hat{t}$ always exceeds the passing time as measured from the critical position--see Equation 6.) The need to provide safe sight distances for both passing options is self-evident.

REPRESENTATIVE RESULTS

This formulation was programmed on a TI-59 calculator and a parameter study was undertaken.

Figure 5 displays the sensitivity of the critical position (Δ_c) with respect to the acceptable abort deceleration (a) for three values. It is seen that this sensitivity increases with speed (V) for any speed difference (m). Note that the critical position of the passing vehicle moves upstream of the impeder (i.e., Δ_c negative) as the speed difference (m) increases. To state it another way, the passer must decide earlier whether to abort, since the speed difference of the passer increases relative to that of the impeder.

Of particular interest is the great sensitivity of Δ_c with respect to the acceptable abort deceleration (a). The more this rate of deceleration decreases (which implies increased safety by virtue of easier vehicle handling and lower driver work load), the earlier the passer motorist must decide to abort. These relationships are intuitively satisfying.

Figure 6 displays the sensitivity of the critical sight distance (S_c) as measured from the critical position with respect to impeder speed (V), speed difference (m), and acceptable deceleration (a). These values correspond to standard automobiles and the assumption of a 1.5-s headway for the calculation of the space headway (G).

As expected, the required critical sight distance (S_c) increases with speed (V). S_c is relatively insensitive to the speed difference (m), other factors being equal. This reflects the impact of two opposing factors: Higher value of m implies lower time to complete the pass, but the passer is farther upstream of the impeder at the critical position (as shown in Figure 5); thus, a longer distance is required to complete the pass.

Of particular interest is the sensitivity of S_c with acceptable abort deceleration (a). It is seen that the passing motorist must accept higher rates of deceleration in order to accept more passing opportunities when the available sight distance is limited. This sensitivity again demonstrates the need to consider the abort option when computing required sight distances.

The total sight distance (S.D.) is used as a basis for designing rural-road passing zones. To produce representative values of required passing sight distance by applying the model, a speed difference, m = 10 mph (16.1 km/h), is employed. (This value of m is used for the AASHTO specifications.) With this value of m, it is possible to estimate a reasonable value of abort deceleration (a), which provides computed passing sight distances that approximate the AASHTO sight-distance specifications. As shown in Figure 7, this value of acceptable abort deceleration is approximately 12 ft/s² (3.66 m/s² or 0.37 g) over the range of speeds considered.

Examination of Figure 7 reveals that the AASHTO specifications for required passing sight distances are reasonable and conservative for impeder speeds up to 45 mph (72 km/h) for the case of a standard automobile passing an automobile. These results reflect the lower speeds of impeder vehicles in the 1940s when the empirical data supporting these specifications were gathered relative to speeds characteristic of today's traffic.

Recent observations of traffic on rural roads confirm that trucks (which often act as impeders) frequently travel at speeds well in excess of 50 mph (80 km/h). As shown in Figure 7, the model predicts that the required passing sight distances at these higher speeds are substantially greater than those specified currently by AASHTO.

It is necessary to consider the impact of the changing fleet composition characterized by smaller, low-powered automobiles and longer, high-powered trucks on the calculation of required passing sight distances. The model presented here permits the determination of required sight distances for different passing scenarios involving different types of vehicles. Specifically, the following passing scenarios are examined:

Scenario	Passing Vehicle	Impeder Vehicle
1	Standard automobile	Automobile
2	Standard automobile	Trailer truck [65 ft long (19.5 km)]
3	Subcompact automobile	Automobile
4	Subcompact automobile	Trailer truck

It is instructive to normalize all results with respect to the AASHTO specifications. In Figure 8, the horizontal axis represents the AASHTO specifications. Where the curves representing the results of this model extend above the axis, the AASHTO passing sight-distance specifications are inadequate; where

Figure 5. Sensitivity of critical position to impeder speed, speed difference, and acceptable abort deceleration (standard-sized automobile).

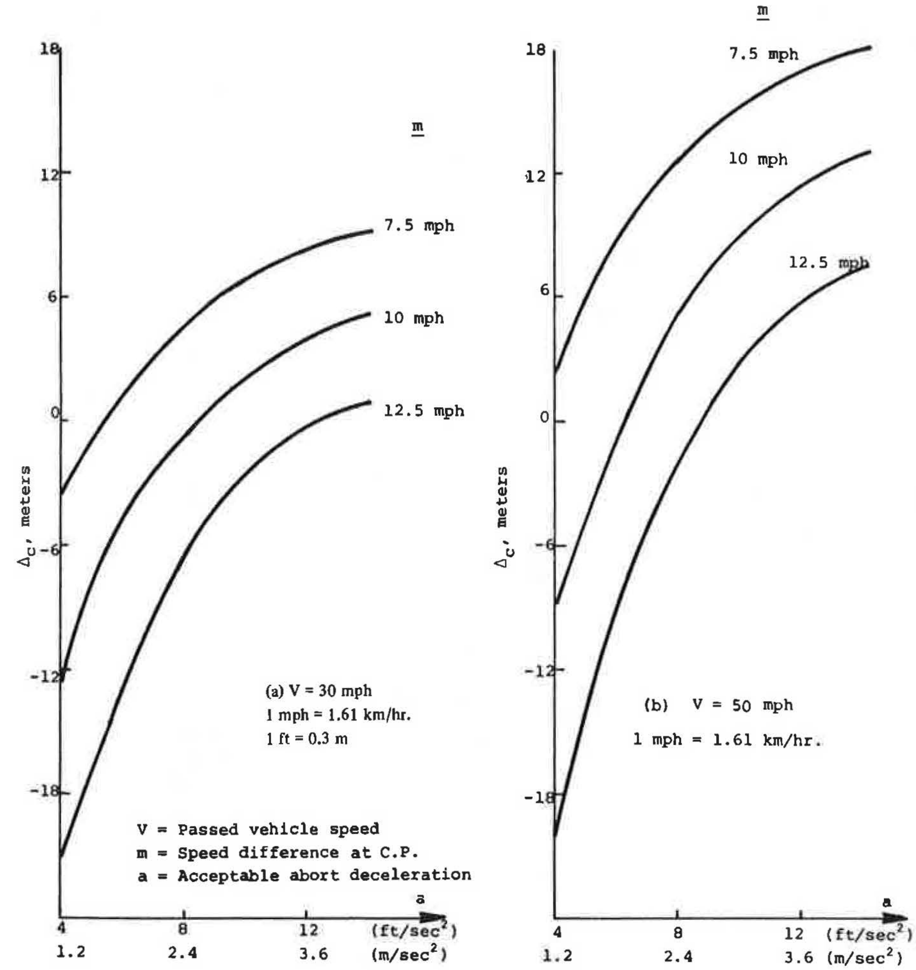
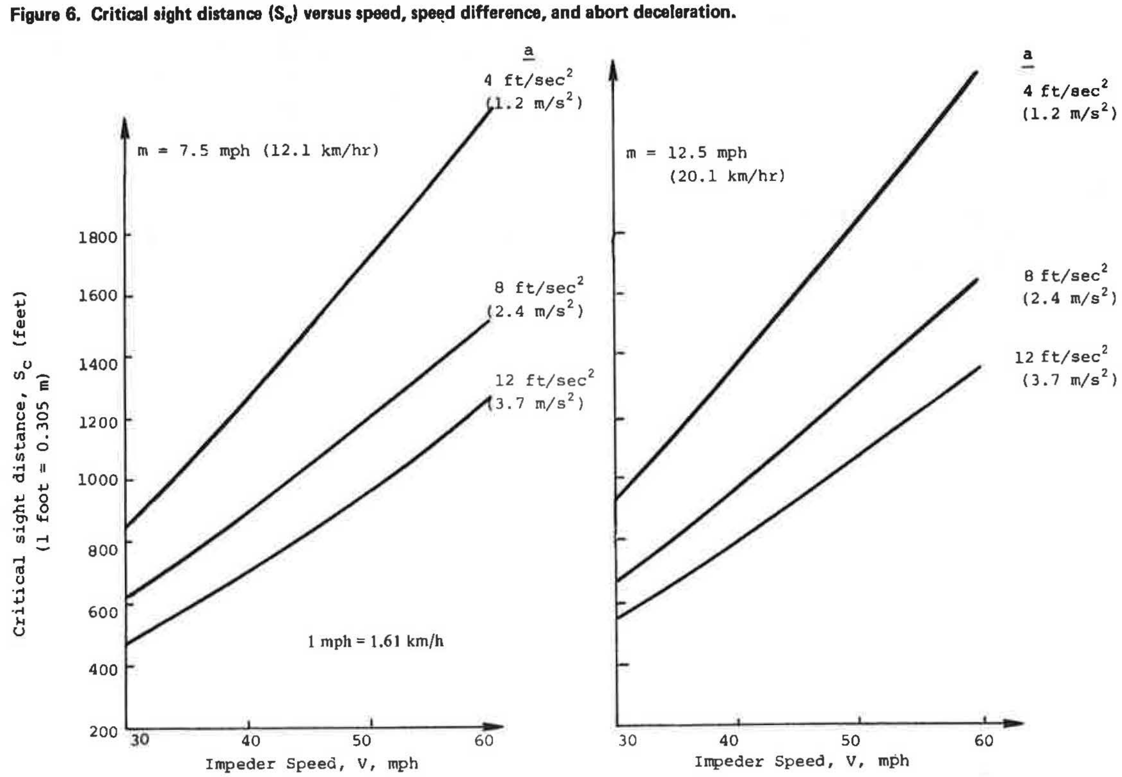


Figure 6. Critical sight distance (S_c) versus speed, speed difference, and abort deceleration.



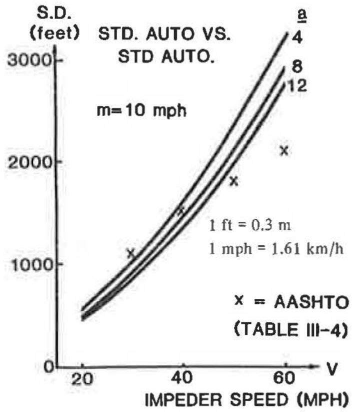


Figure 7. Required sight distance.

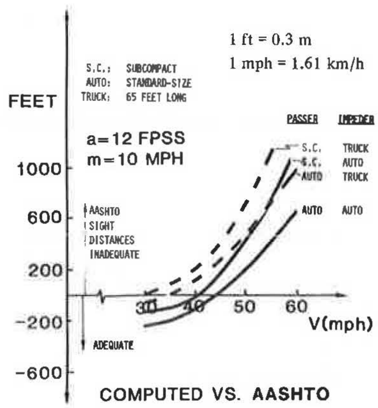


Figure 8. Assessment of AASHTO passing sight distance.

the curves are below this axis, the AASHTO specifications are satisfactory.

Figure 8 compares the required sight distances estimated by this model for m = 10 mph and a = 12 ft/s² with those specified by AASHTO for the four scenarios defined above. As indicated, subcompact automobiles require a longer sight distance than do standard automobiles. Also, longer sight distances are required when the impeder is a truck than when the impeder is an automobile, which reflects the longer distance the passer must travel when the impeder is a truck.

The AASHTO specifications for passing sight distance are reasonable for speeds well below 44 mph (70 km/h) but appear to be increasingly inadequate (i.e., unsafe) at higher speeds. This inadequacy is more pronounced when the impeder is a truck or the passer is a subcompact automobile. As indicated in Figure 8, up to 1000 additional ft (300 km) of passing sight distance may be required relative to the current AASHTO specifications when the impeder vehicle is traveling at 55 mph (88 km/h). These results have been confirmed by empirical observation (2-4).

SUMMARY AND CONCLUSIONS

A formulation is presented that describes the passing maneuver on two-lane rural roads. A parameter study was undertaken that generated results describing the sensitivity of required passing sight distance with respect to the specified conditions. These results were compared with current AASHTO specifications for required passing sight distance. This comparison raises some questions concerning the adequacy of these AASHTO specifications when impeder speeds exceed 40 mph (64 km/h), particularly when subcompact automobiles and trucks are involved.

Based on these results, a review of the AASHTO specifications appears to be justified, particularly since the size of automobiles is projected to be reduced over the next decade. More conservative sight-distance requirements should enhance the safety of traffic roads. The impact of more restrictive passing zone delineation on roadway capacity may well increase the need to upgrade roadway geometrics or to improve control of passing operations. This is a problem area that deserves further study.

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