

THE PASSING MANEUVER AS IT RELATES TO
PASSING SIGHT DISTANCE STANDARDS

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ABSTRACT

Current AASHO design standards for passing sight distance are based upon mathematical formulas which employ several assumptions regarding driver-vehicle characteristics. Many of the values used in establishing these standards were determined from studies conducted approximately thirty years ago.

The subject of driver judgment and decision processes has been a popular research subject during the past decade. Studies conducted in this area suggest that the assumptions that form the basis of existing design standards may not be applicable to current vehicles and drivers.

The report is addressed to an examination of current state of knowledge concerning the passing maneuvers to ascertain the validity of existing passing sight distance standards. Examination of the state-of-the-art revealed:

- Many of the values used in establishing passing sight distance design standards are based solely on studies conducted between 1938 and 1941 and the criteria have remained virtually unchanged.
- Use of the 10-mph speed differential in extrapolating passing sight distance for the higher speed groups appears to be questionable.
- Use of assumed speeds somewhat lower than the highway design speed may not represent the critical passing situation under current operating conditions.
- Clearance distance under current AASHO standards appears to be somewhat short.
- Current striping specifications are identical to those outlined in the 1940 AASHO Policy for striping no-passing zones. Striping practices established for the 1940 assumptions are questionable for current highway operation.

FOREWORD

This report describes one phase of Research Study No. 2-8-68-134 entitled "An Evaluation of the Basic Design Criteria as They Relate to Safe Operation on Modern High Speed Highways." Other reports published under this research study include: No. 134-2, Re-evaluation of Truck Climbing Characteristics for Use in Geometric Design; No. 134-3, Evaluation of Stopping Sight Distance Design Criteria; and No. 134-4, State of the Art Related to Safety Criteria for Highway Curve Design. Separate reports and summary reports have been prepared for all phases of this research.

DISCLAIMER

The opinions, findings, and conclusions expressed or implied in this report are those of the research agency and not necessarily those of the Texas Highway Department or of the Bureau of Public Roads.

SUMMARY

This study was conducted in response to an increasing concern by highway design engineers regarding the validity of current passing sight distance standards. The report presents a review of the current AASHO design standards and an evaluation of these standards based on the existing state-of-the-art. The evaluation considered the criteria employed in developing the standards, including: 10 mph speed differential between passing and passed vehicle; assumed speeds for design; clearance distance; driver eye height and object height; and pavement striping for no-passing zones.

The following findings may be drawn from the evaluation presented in this report:

1. Many of the values used in establishing passing sight distance design standards are based solely on studies conducted between 1938 and 1941. Although studies were conducted in 1957 to validate certain aspects of the criteria, the criteria remained virtually unchanged. The test sites chosen for the 1957 studies were the same highways (geometrics unchanged) from which the 1938-41 data were collected. It is suggested that this choice may have been an inappropriate one with which to evaluate criteria under current conditions. Driving practice on these highways might not be indicative of that exercised on highways designed in recent years. That is, the geometrics of the chosen highways may have altered a driver's practice substantially from his normal operating characteristics.
2. As highway design speeds were raised, passing sight distance design standards were extrapolated linearly to establish standards for the

higher speed groups. Studies indicate that as speed increases, passing distance also increases, but at an increasing rate. Due to the trend toward higher speeds, it is suggested that there exists a definite need for objective documentation of high-speed passing maneuvers under current highway conditions to validate the passing sight distance standards for the higher speed groups.

3. Current AASHO Policy assumes a 10-mph speed differential between passing and passed vehicle for all speed ranges in passing sight distance design. The studies conducted in 1938-41 indicated that this was valid for approximately 51 percent of the drivers observed. However, these studies also indicated that as the speed of the passed vehicle was increased, the speed differential between the passing and passed vehicle was greatly reduced. In extrapolating passing sight distance for the higher speed groups, the 10-mph speed differential was maintained. Use of a constant speed differential for all speed ranges appears to be questionable.
4. Use of assumed speeds somewhat lower than the highway design speed can create dangerously short passing sight distances for certain speed combinations, especially for the higher speed passing maneuvers. Studies indicate that 85th percentile day operations speeds throughout Texas are equaling or exceeding posted speeds. Therefore, passing maneuvers are being performed at speeds in excess of posted speed. For a 70-mph design speed, current AASHO Policy assumes that a passed vehicle speed is traveling at 54 mph and that the passing vehicle is traveling 10 mph faster. This may not represent the critical combination under current operating conditions.

5. Clearance distance under current AASHO standards ranges from 100 feet for the 30-40 mph speed group to 300 feet for the 60-70 mph speed group. Travel time for the 300-foot clearance length is approximately 1.7 seconds under AASHO assumptions for closure speed. Since extensive research has indicated that the majority of drivers are unable to discriminate even grossly different opposing vehicle speeds, it is suggested that clearance lengths be extended to partially offset poor distance and speed judgment.
6. It appears that current striping specifications are identical to those outlined in the 1940 AASHO policy for striping no-passing zones. The 1940 minimum requirements were established according to assumptions relevant to design criteria in effect at that time. Striping practices established for the 1940 assumptions are questionable for current highway operation.

Recommendations For Further Research

The report indicates areas where further research would be appropriate.

These include:

1. Objective documentation of high-speed passing maneuvers under highway conditions. Specific attention should be directed toward acceleration rates, speed differential between passing and passed vehicle, and the relation of total passing distance to speed.
2. Detailed study of striping for no-passing zones from a safety and an economic (effect on highway capacity and throughput) aspect.

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INTRODUCTION

Despite the development of the Interstate Highway System and other divided highway networks, two-lane highways still comprise the largest road mileage. Almost all drivers pass other vehicles at some time on a two-lane road. In so doing, the passing vehicle must travel in the traffic lane normally reserved for opposing traffic, thus, creating a potentially dangerous situation.

Performing a safe passing maneuver necessitates correct judgment of many variables. The speed of the passed vehicle, speed of an oncoming vehicle, distance required to pass, and a correct estimation of available passing distance must be assessed and evaluated. Unfortunately, passing requires speed increase, making judgment of the variables more difficult. Driving is considered to be a reflex action, conditioned by experience. Nonetheless, when one vehicle passes another on a two-lane road, the driver of the passing car must exercise correct judgment, even subconsciously, if he is to avoid being placed in a collision circumstance. Although the dynamic capabilities of the vehicle play an important role in the passing maneuver, the critical factor is the driver's judgment. Many drivers cannot judge if the available sight distance preceding a hill or curve is sufficient for safe passing. A greater number of drivers cannot accurately judge the speed of an oncoming vehicle (1).*

Usually, the driver can see far enough ahead and must judge for himself if the passing distance is sufficient. However, in cases where visibility is limited by road alignment or obscured by roadside objects, correct driver

* Denotes reference listed in the Bibliography.

judgment is difficult. Where insufficient sight distance exists, traffic engineers have generally marked no passing zones to inform drivers that passing is prohibited.

It is evident that a passing maneuver depends on the interplay of physical and psychological elements. Mathematics and testing can reduce the physical elements to a degree of intimate knowledge. It is a simple problem to determine vehicular characteristics such as height, weight, horsepower, accelerative capabilities and other physical aspects which enter into the design of highways. Designing to accommodate the human element is more complicated. When the designer leaves the field of mathematics and testing and enters the human factors field to establish values, there is a certain indefiniteness in his answers. Safe design cannot, however, ignore the human factors aspect. This is especially true in design of passing sight distance because the passing maneuver is equally or more dependent on driver judgment than on the physical capabilities of the vehicle or the roadway.

Current AASHO design standards (2) for passing sight distance are based upon mathematical formulas which employ several assumptions regarding driver-vehicle characteristics. Many of the values used in establishing passing sight distance standards were determined from studies conducted approximately thirty years ago. Other values were based on studies conducted within the last ten or fifteen years.

In the past three decades, vehicles have undergone extensive changes in design and performance characteristics: horsepower has increased, silhouettes have been lowered, lengthened, and widened thus lowering center of gravity; increased window area has improved driver visibility. Addition of power steer-

ing and brakes, and improved suspension systems also assist the driver in operating a vehicle. Although these changes produce streamlined vehicles capable of attaining higher speeds with a minimum of driving effort, their inception has created new problems with which highway designers must contend. Increased horsepower has contributed to higher operating speeds on the highway. The Texas annual speed survey conducted in 1968 indicated that 85th percentile day operations speeds either approached or exceeded posted speeds (3). Light-colored vehicles of low silhouette with large transparent glass areas are difficult to discern at long distances. Increased height and width of commercial vehicles adversely affects a trailing driver's sight distance. An examination of these changing vehicular characteristics suggests that an evaluation of current passing distance criteria is required.

In the past ten years, the subject of driver judgment and decision processes has become an important topic of research. How does a driver react in a passing situation? Can he accurately judge distance, time and speed in order to perform a safe passing maneuver? What aids can be incorporated into vehicles to assist the driver in evaluating the many variables which interact when one vehicle passes another on a two-lane road? Have improved vehicles changed drivers' passing practices? Research conducted in this area suggests that the assumptions upon which the current design standards are based may not be entirely applicable to current vehicles and drivers. In view of the emphasis being placed on highway safety, these assumptions at least require examination.

This report is addressed to an examination of the current state of knowledge concerning the passing maneuver for the purpose of ascertaining the validity of current passing sight distance design standards. The report includes presentation of current passing sight distance design criteria and

documentation of research concerning the passing maneuver. Evaluation of design criteria is presented in the third section.

CURRENT AASHO PASSING SIGHT DISTANCE DESIGN CRITERIA

The current AASHO design criteria for computing minimum passing sight distance on two-lane highways are based on certain assumptions for traffic behavior. It is apparent that design distances should be determined on the basis of the length required to complete a single passing maneuver, that is, one in which one vehicle passes a single vehicle. Multiple passings occur but minimum design criteria for these cases create unnecessarily long passing distances. Similarly, design should not be based upon maneuvers where a driver takes unnecessary risks by passing without seeing a safe passing zone ahead.

Criteria for Design

The assumptions used in establishing minimum passing sight distance criteria as set forth in A Policy on Geometric Design of Rural Highways, 1965, (2) are:

1. The overtaken vehicle travels at uniform speed.
2. The passing vehicle has reduced speed and trails the overtaken vehicle as it enters a passing section.
3. When the passing section is reached, the driver requires a short period of time to perceive the clear passing section and to react to start his maneuver.
4. 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 10 mph higher than that of the overtaken vehicle.

5. When the passing vehicle returns to its lane there is a suitable clearance length between it and an oncoming vehicle in the other lane.

Drivers perform passing maneuvers in various ways. Some accelerate in the initial phase to an appreciably higher speed than that of the passed vehicle and then continue at a uniform speed throughout the passing maneuver. Many drivers accelerate at a fairly high rate until just beyond the passed vehicle and then complete the maneuver without further acceleration or at a reduced speed. Still others accelerate throughout the entire maneuver. Extraordinary passing characteristics are ignored in the current design criteria assumptions and passing distances are developed using speeds and times observed which fit the practices of a high percentage of drivers.

The AASHO Policy's minimum passing sight distances for two-lane highways are described as the sum of four distances, defined below and shown graphically in Figure 1.

- d_1 - Distance traversed during perception and reaction time and during the 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 the passing vehicle at the end of its maneuver and the opposing vehicle.
- d_4 - Distance traversed by an opposing vehicle for two-thirds of the time the passing vehicle occupies the left lane, or $2/3$ of d_2 above.

The initial maneuver distance (d_1) contains two components: distance traveled during perception and reaction time, and a distance in which the driver brings his vehicle from the trailing speed to the point of encroachment on the passing lane. The two components overlap. The acceleration

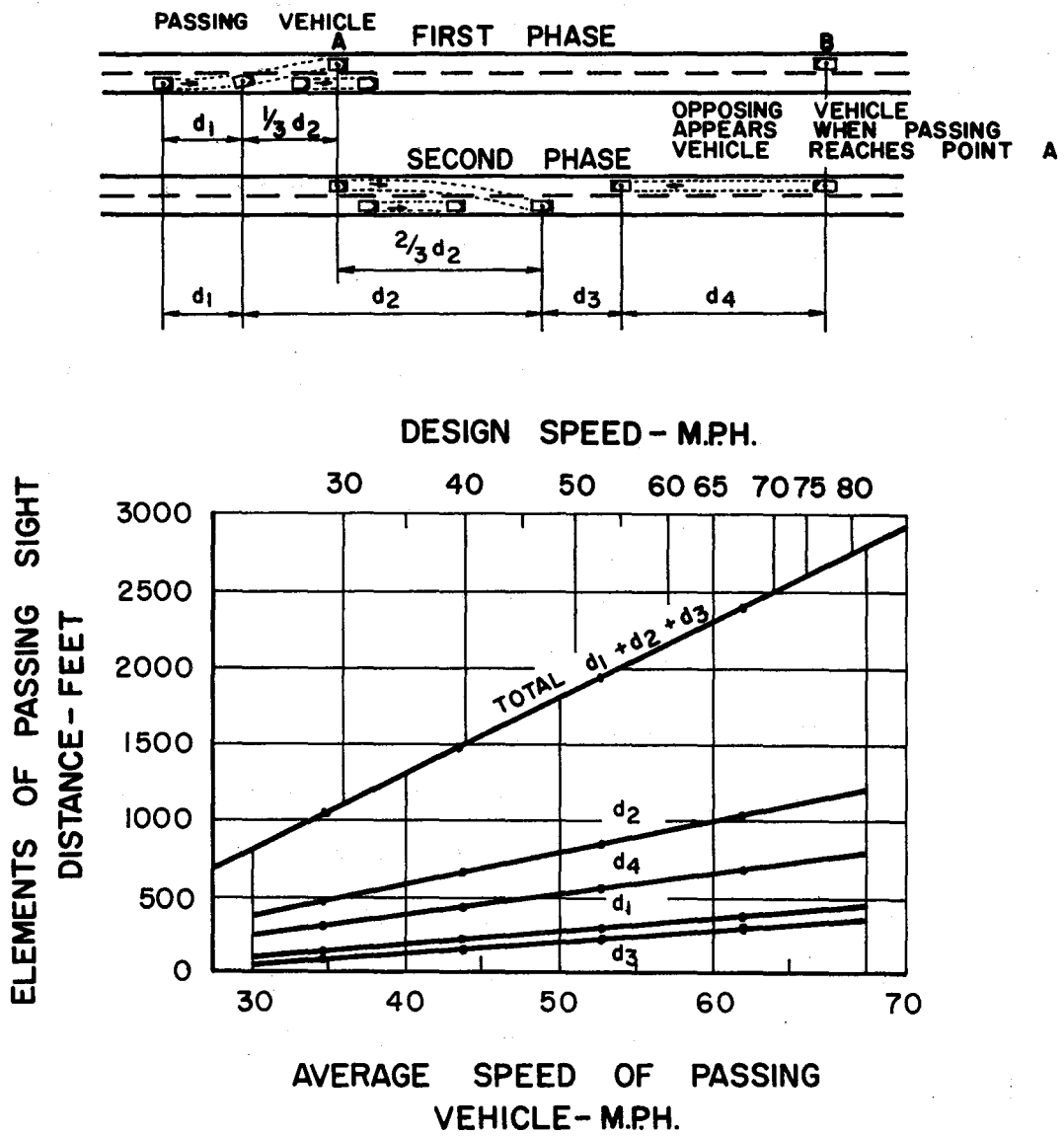


Figure 1. AASHO Passing Sight Distance Criterion Curves (2).

rates obtained from the passing study data in the three speed groups during the initial maneuver ranged from 1.41 to 1.47 mphps; the average time varied from 3.7 to 4.3 seconds, and the average passing speeds were 34.9, 43.8, and 52.6 mph. For the 60 and 70 mph group based on extrapolated data, the average acceleration was assumed to be 1.50 mphps, the maneuver time 4.5 seconds, and the average speed 62 mph.

The distance traveled during the initial maneuver period, d_1 , is computed from the following formula:

$$d_1 = 1.47 t_1 \left(v - m + \frac{at_1}{2} \right)$$

where t_1 = time of initial maneuver (seconds),

a = average acceleration (mphps),

v = average speed of passing vehicle (mph),

m = difference in speed of passed vehicle and passing vehicle (mph).

The d_1 line in Figure 1 represents distance plotted against the average passing speed for the assumptions previously mentioned.

Passing vehicles were found in the study to occupy the left lane from 9.3 to 10.4 seconds. The distance traveled by the vehicle in the left lane, d_2 , is computed by:

$$d_2 = 1.47 vt_2$$

where t_2 = time passing vehicle occupies the left lane (seconds),

v = average speed of passing vehicle (mph).

Distances are plotted against average passing speeds as curve d_2 in Figure 1.

Clearance lengths, d_3 , between the opposing and passing vehicles at the end of the maneuvers found in the study varied from 110 to 300 feet. These lengths, adjusted somewhat for practical consistency, are shown as the clearance length, d_3 , in Figure 1.

Passing sight distance includes the distance traversed by an opposing vehicle during the passing maneuver. During the first phase of the passing maneuver, the passing vehicle has not yet pulled abreast of the vehicle being passed and its driver can still return to the right lane if he sees an opposing vehicle. Therefore, this time element which can be computed from the relative position of passing and passed vehicles to be about one third the time the passing vehicle occupies the left lane, is not included in computing the distance traveled by the opposing vehicle. The opposing vehicle is assumed to be traveling at the same speed as the passing vehicle, and $d_4 = 2d_2/3$.

Extensive field observations of driver behavior during passing maneuvers were made during 1938 to 1941. Three locations studied were restudied in 1957 with very little change noted in the passing practices despite increased vehicle performance capabilities (4). Data were grouped into three passing speed groups, 30 to 40, 40 to 50, and 50 to 60 miles per hour. A fourth speed group, 60 to 70 mph, based on extrapolated data obtained from the summary report (5), has been added to the 1965 AASHO policy. Time and distance values were determined in relation to the average speed of the passing vehicle. Speeds of overtaken vehicles were approximately 10 mph less than speeds of passing vehicles. Values from the 1938-41 study, with minor adjustments for consistency, are shown in Table 1. These values form the basis for the current AASHO passing sight distance criterion curves shown in Figure 1.

Passing Sight Distance Design Values

Upon determination of a likely and logical relation between average passing speed and highway design speed, the distances represented by the "Total"

TABLE 1

ELEMENTS OF PASSING SIGHT DISTANCE ON TWO-LANE HIGHWAYS (2)

Speed Group, mph	30-40	40-50	50-60	60-70
Average Passing Speed, mph	34.9	43.8	52.6	62.0
Initial Maneuver:				
a = average acceleration, mphps*	1.40	1.43	1.47	1.50
t ₁ = time, seconds*	3.6	4.0	4.3	4.5
d ₁ = distance traveled, feet	145	215	290	370
Occupation of left Lane:				
t ₂ = time, seconds *	9.3	10.0	10.7	11.3
d ₂ = distance traveled, feet	475	640	825	1030
Clearance length:				
d ₃ = distance traveled, feet	100	180	250	300
Opposing vehicle:				
d ₄ = distance traveled, feet	315	425	550	680
Total Distance,				
d ₁ +d ₂ +d ₃ +d ₄ , feet	1035	1460	1915	2380

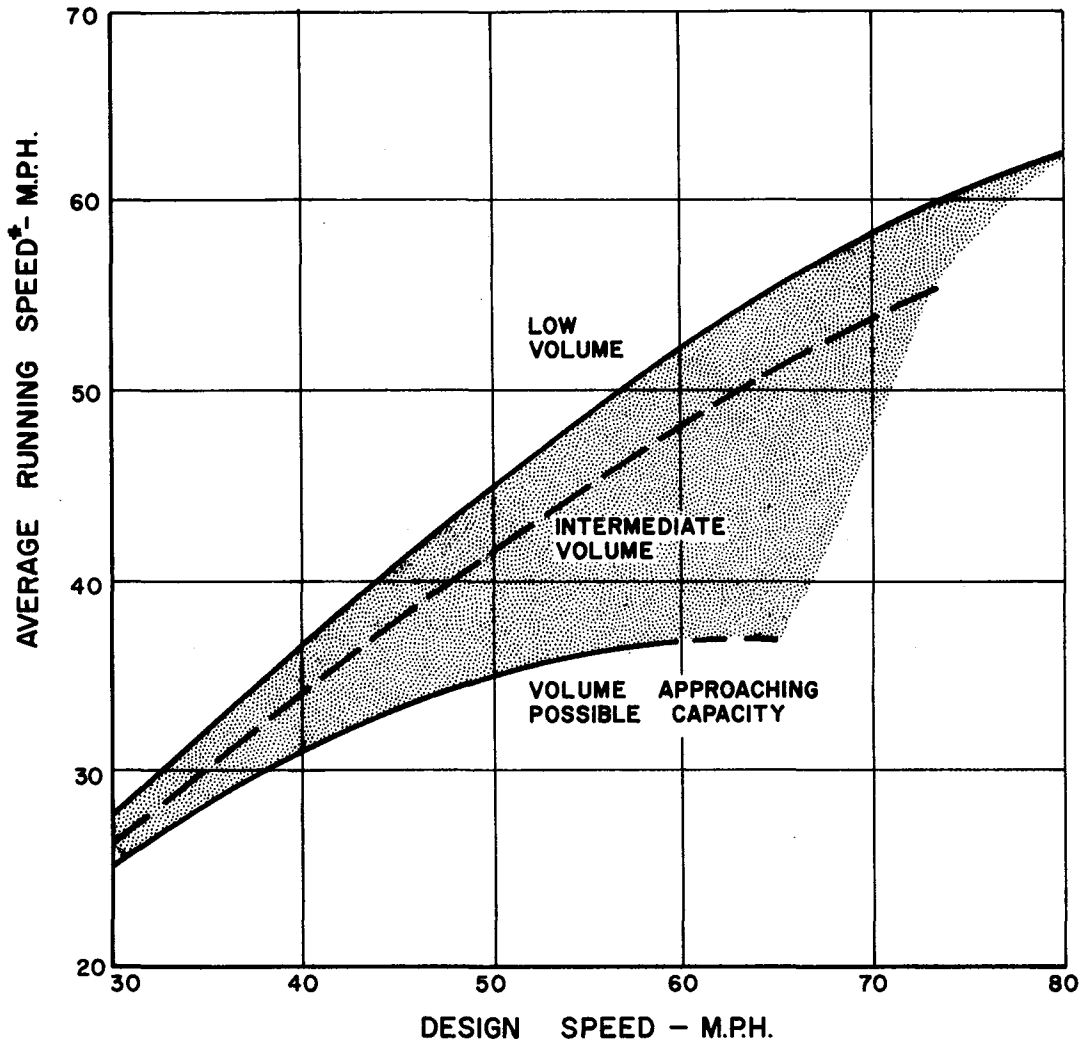
* For consistent speed relation, observed values adjusted slightly.

curve in Figure 1 can be used to express the minimum distance needed for design purposes. The speed of the passed vehicle has been assumed to be the average running speed at a traffic volume near design capacity as represented by the curve for "intermediate" volumes in Figure 2. The speed of the passing vehicle is assumed 10 mph greater. The assumed speeds for passing vehicles in Table 2 represent the likely passing speeds on two-lane highways; they correspond to the "Total" curve in Figure 1. The rounded values in the last column of Table 2 are design values for minimum passing sight distance.

Criteria for Measuring Passing Sight Distance

Sight distance along a highway is measured from the driver's eye to some object on the roadway when it first comes into view. Current AASHO Policy defines driver eye height to be 3.75 feet above the road surface. Since vehicles are the objects to be seen when passing, it is assumed that the height of object for passing sight distance is 4.5 feet (the approximate height from roadway to the top of a passenger vehicle body). Headlights of a vehicle are about two feet above the pavement, but use of this value for the assumed object height is not realistic. Headlight beams are generally seen at night even before the top of the vehicle could be seen at the same location in the daytime. Thus, passing sight distance both on profile crests and on horizontal curves is measured between the driver eye height of 3.75 feet and object height of 4.5 feet.

Figure 3 shows the length of vertical crest curve required to provide the passing sight distance for various algebraic differences in grade (6). Vertical curve lengths were determined from the following formulas:



RUNNING SPEED IS THE SPEED (OF AN INDIVIDUAL VEHICLE) OVER A SPECIFIED SECTION OF HIGHWAY, BEING DIVIDED BY RUNNING TIME.

* AVERAGE RUNNING SPEED IS THE AVERAGE FOR ALL TRAFFIC OR COMPONENT OF TRAFFIC, BEING THE SUMMATION OF DISTANCES DIVIDED BY THE SUMMATION OF RUNNING TIMES. IT IS APPROXIMATELY EQUAL TO THE AVERAGE OF THE RUNNING SPEEDS OF ALL VEHICLES BEING CONSIDERED.

Figure 2. Relation of Average Running Speed to Volume Conditions (2).

TABLE 2

AASHO MINIMUM PASSING SIGHT DISTANCE FOR DESIGN OF TWO-LANE HIGHWAYS (2)

Design speed, mph	Assumed Speeds		Minimum passing sight distance, feet	
	Passed vehicle, mph	Passing vehicle, mph	Fig. III -2	Rounded
30	26	36	1090	1100
40	34	44	1480	1500
50	41	51	1840	1800
60	47	57	2140	2100
65	50	60	2310	2300
70	54	64	2490	2500
75*	56	66	2600	2600
80*	59	69	2740	2700

* Design speeds of 75 and 80 mphs are applicable only to highways with full control of access or where such control is planned in the future.

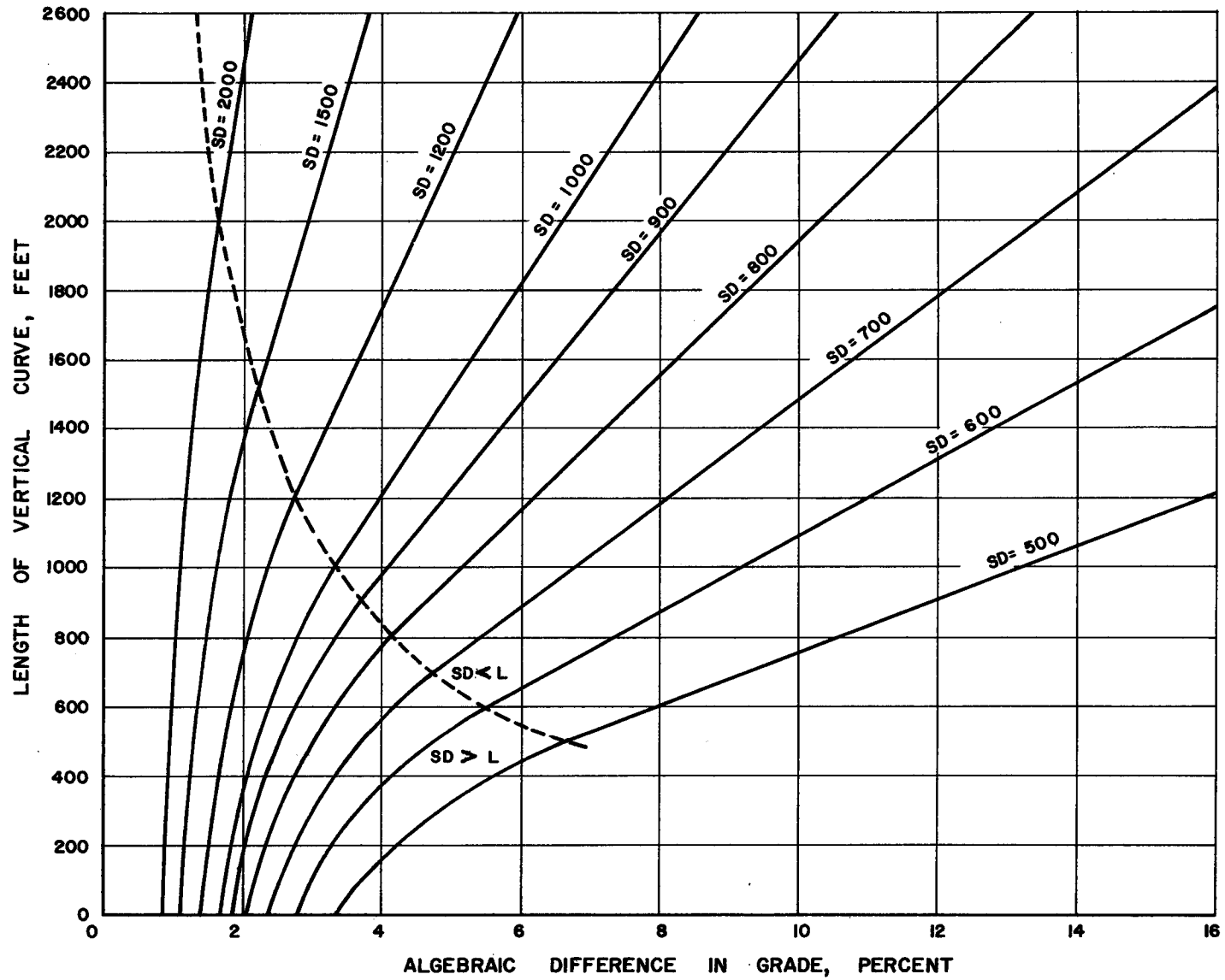


Figure 3. Passing Sight Distance Chart Based on Eye Height of 3.75 Feet
And Vehicle Height of 4.5 Feet (6).

$$L = 2S - \frac{32.95}{A} \quad \text{Valid only where } L < S$$

and

$$L = \frac{AS^2}{32.95} \quad \text{Valid only where } L > S$$

where L = Length of vertical curve, stations

S = Sight distance, stations

A = algebraic difference in grades, percent

STATE-OF-THE-ART

Highway design standards involving sight distance appear to have been prepared assuming that a driver has a high degree of visual acuity, and without accounting for changes that may occur in human vision and perception in high-speed circumstances. Minimum passing sight distances range up to 2,500 feet for 70-mph design speeds. The capacity of a driver to perceive a vehicle 2,500 feet away approaching over a crest is open to doubt even if the observer is at rest (7). How far away can a driver see an object? Will he perceive the object? What time will elapse after it comes into view before he brakes, changes course, or makes a decision to perform some other driving maneuver?

Performing a safe passing maneuver necessitates correct judgment of many variables. This judgment becomes more difficult with increased speed. Considerable research has been conducted to obtain an understanding of passing maneuvers. Several studies concern the driver's ability to estimate variables such as: available sight distance, closure speed between a passing vehicle and the passed or approaching vehicle, required passing distance or time under impedance conditions (either by an approaching vehicle or by available sight distance), and other judgment aspects of the passing maneuver. One study (8) was conducted to determine how drivers understood and acted at no-passing zones on highways. Another study (9) reviewed the trends of dimension and performance characteristics of passenger cars which were relevant to highway and traffic engineers. Although most studies concerning the passing maneuver were supported by field studies, one study (10) involving mathematical simulation

of a two-lane rural road is discussed in this section.

Although it is evident that a considerable number of studies have been conducted to accumulate knowledge of various aspects of the passing maneuver, the fact remains that the current AASHO Policy is based primarily on two studies: one performed during 1938-41 (4,5) and the other conducted in 1957 (11). Since these two studies were so instrumental in establishing the current design policy, they represent the logical choice with which to introduce this section. Discussion of each research program which comprises the state-of-the-art pertaining to passing maneuvers is presented separately within this section, each containing objectives, methodology (where applicable for clarity) and results obtained.

1938-1941 U. S. Public Roads Administration Passing Studies (4,5)

During 1938 to 1941, the U. S. Public Roads Administration (presently called the U. S. Bureau of Public Roads) conducted field studies of vehicle passing practices on selected sections of two-lane highways as part of its traffic research program. In this study, records were made of over 20,000 passing maneuvers in the States of Maryland, Virginia, Massachusetts, Illinois, Texas, California and Oregon.

Normann (4) reported the results of analysis of 1,635 passing maneuvers in 1938 from the studies in Maryland and Virginia. Passing maneuvers were classified in single and multiple passing types. In the single passing maneuvers, one vehicle passed one other vehicle, while in the multiple passing maneuvers, two or more vehicles either passed or were passed by one or more vehicles. The types of passing maneuvers observed are shown in Table 3. Data revealed that 33 percent of the maneuvers were multiple passings involving a total of

TABLE 3

TYPES OF PASSING MANEUVERS OBSERVED IN 1938 USPRA (4)

Type of maneuver	Maneuvers made		Passings accomplished	
	Number	Percent	Number	Percent
Single	1, 096	67.0	1,096	42.7
Multiple				
1 vehicle passing 2 vehicles	181	11.1	362	14.1
2 vehicles passing 1 vehicle	161	9.8	322	12.6
1 vehicle passing 3 vehicles	63	3.9	189	7.4
2 vehicles passing 2 vehicles	42	2.6	168	6.5
3 vehicles passing 1 vehicle	30	1.8	90	3.5
1 vehicle passing 4-6 vehicles	31	1.9	136	5.3
2 vehicles passing 3-5 vehicles	13	0.8	102	4.0
All other multiple passings	18	1.1	99	3.9
Total Multiple	539	33.0	1,468	57.3
Grand Total	1,635	100.0	2,564	100.0

57.3 percent of the passings that occurred (average hourly volume of 375 vehicles). This fact indicates the importance of studying multiple passing maneuvers as well as maneuvers in which one vehicle passes only one vehicle. In nearly 85 percent of the single passing maneuvers that occurred, the passing vehicle slowed down to some extent before attempting to pass, and in 53.7 percent, the passing vehicle slowed down to the same speed as the vehicle to be passed.

Speeds that the passing driver desired to travel were determined by noting his speed either before slowing down prior to making the passing maneuver or after the maneuver was completed. Speed data for single passing maneuvers are shown in Table 4.

Table 4 shows that in 55 percent of the passings, the passed vehicle was travelling from 31 to 40 mph, and that 51.4 percent of the drivers that passed desired to travel less than 11 miles per hour faster than the passed vehicle.

Prisk (5) presented analysis of data from 3,521 single-type passings. The single passings were classified according to the manner in which the passing vehicle was affected by opposing traffic, as follows: (A) delayed start, (B) hurried return, (C) delayed start and hurried return, and (D) free moving passings with no opposing traffic.

The passing maneuver was assumed to be a composite of three separate elements, each of which represented a certain amount of road space: preliminary delay, occupation of left lane, and interval for oncoming vehicles. Measurements were made of acceleration rates of passing vehicles, passing times

TABLE 4

SINGLE PASSINGS CLASSIFIED BY SPEED OF PASSED VEHICLE
AND DESIRED SPEED OF PASSING VEHICLE, 1938 USPRA STUDY (4)

Desired speed of passing vehicle in miles per hour fas- ter than speed of passed vehicle	Speed of passed vehicle in miles per hour					Total
	20 and under	21-30	31-40	41-50	Over 50	
	Percent	Percent	Percent	Percent	Percent	Percent
5 and under	---	1.9	11.2	7.8	0.3	21.2
.	---	4.0	18.8	7.1	0.3	30.2
11-15	0.4	6.7	17.6	5.5	0.3	30.5
16-20	0.7	5.0	5.7	0.8	---	12.2
21-30	0.3	2.9	1.6	0.3	0.1	5.2
Over 30	0.3	0.2	0.1	0.1	---	0.7
TOTAL	1.7	20.7	55.0	21.6	1.0	100.0
Average difference is speed between passed and passing vehicle (mph)						
	20.6	14.2	10.5	8.6	11.1	10.9

and distances, and spacing between vehicles before and after maneuvers. Analysis was performed on the 2,649 passings which were begun and completed within the limits of the test section. Table 5 shows the distance traveled in the left lane by the passing vehicle under three different conditions of pavement and visibility. It was found that the average distances used in the left lane by the passing vehicle for the four types were: (A) 601 feet; (B), 601 feet; (C), 521 feet; and (D), 703 feet. Time spent in the left lane for the various speed groups is shown in Table 6.

Prisk concluded that most passing drivers desired to travel about 10 mph faster than the vehicles they passed but seldom made a passing before slowing to a speed within 5 mph of that of the vehicle ahead. Passing distance was found to increase as the speed of the passed vehicle increased.

Measurements of vehicle acceleration rates during the passing maneuver indicated that few vehicles accelerated at the maximum rates of which they were capable, even when passing in the face of oncoming traffic. Approximately 40 percent of all passing vehicles were found to be decelerating during the return to the right lane.

Prisk defined the critical interval for the oncoming vehicle to be the distance traveled by an opposing vehicle while the passing vehicle was in the left lane, plus an allowance for clearance at the end of the passing maneuver. Clearance distances were found to be 110, 160, and 300 feet respectively, for passing speed groups of 30-39 mph, 40-49 mph, and 50-59 mph in the "C" classification.

Table 7 shows the elements of the passing maneuver based on characteristic operating data obtained from the studies, for three speed group combinations

TABLE 5

FREQUENCY OF VARIOUS TYPES OF SIMPLE PASSINGS AND AVERAGE PASSING DISTANCE FOR EACH (PRISK STUDY)

Type of Passing	Visibility and pavement condition									All Passings*		
	Day-dry			Day-wet			Night-dry					
	No. of passings	% of total passings	Average passing distance	No. of passings	% of total passings	Average passing distance	No. of passings	% of total passings	Average passing distance	No. of passings	% of total passings	Average passing distance
A (delayed start)	956	38.4	605	27	35.5	618	33	39.3	427	1,016	38.3	601
B (hurried return)	328	13.2	607	14	18.4	564	7	8.3	418	349	13.2	601
C (delayed start and hurried return)	681	27.4	522	16	21.1	550	18	21.4	472	715	27.0	521
D (free moving)	524	21.0	706	19	25.0	653	26	31.0	669	569	21.5	703
All Types	2,489	100.0	604	76	100.0	603	84	100.0	529	2,649	100.0	601

*Begun and completed within the test section.

TABLE 6

TIME PASSING VEHICLE SPENT IN LEFT LANE FOR VARIOUS TYPES OF SIMPLE PASSINGS
(DAYLIGHT-DRY PAVEMENT), PRISK STUDY (5)

Average speed of passed vehicle	Type A (Delayed start)				Type B (Hurried return)				Type C (Delayed start and hurried return)				Type D (Free moving)				Types A, B, C, and D combined			
	All passings		Passing veh. 10 mph faster than passed veh.		All passings		Passing veh. 10 mph faster than passed veh.		All passings		Passing veh. 10 mph faster than passed veh.		All passings		Passing veh. 10 mph faster than passed veh.		All passings		Passing veh. 10 mph faster than passed veh.	
MPH	No.	Av. time	No.	Av. time	No.	Av. time	No.	Av. time	No.	Av. time	No.	Av. time	No.	Av. time	No.	Av. time	No.	Av. time	No.	Av. time
0-19	24	8.7	15	9.3	13	8.1	4	6.7	11	7.7	3	7.1	9	10.0	2	7.6	57	8.6	24	8.4
20-29	260	8.8	209	8.7	88	8.9	65	8.7	241	8.0	194	8.0	143	9.9	91	10.0	732	8.8	559	8.7
30-39	531	9.8	425	9.5	165	9.8	119	9.4	343	8.8	278	8.7	246	11.0	172	11.1	1,285	9.8	994	9.5
40-49	132	10.9	86	10.4	50	11.8	31	10.8	80	9.4	60	9.2	105	11.8	74	11.4	367	10.9	251	10.4
50-59	8	10.5	5	11.0	2	9.3	2	9.3	1	8.4	1	8.4	7	9.6	7	9.6	18	9.9	15	9.9
All speeds combined	955	9.7	740	9.4	318	9.8	221	9.3	676	8.6	536	8.5	510	10.8	346	10.8	2,459 ^a	9.6	1,843	9.4

^aDoes not include 30 passings in the "day-dry" group for which data were not available.

TABLE 7

ELEMENTS OF THE PASSING MANEUVER, PRISK (5)

Speed of passing vehicle	30-39 miles per hour	40-49 miles per hour	50-59 miles per hour
Speed of passed vehicle	20-29 miles per hour	30-39 miles per hour	40-49 miles per hour
1. Preliminary delay	$\frac{(3.7 \times 1.41 + 25)}{2} \times 3.7 \times 1.47 = 150 \text{ ft.}$	$\frac{(3.7 \times 1.43 + 35)}{2} \times 3.7 \times 1.47 = 205 \text{ ft.}$	$\frac{(4.3 \times 1.47 + 45)}{2} \times 4.3 \times 1.47 = 305 \text{ ft.}$
2. Occupation of left lane	$9.3 \times 34.9 \times 1.47 = 477 \text{ ft.}$	$10.4 \times 43.8 \times 1.47 = 670 \text{ ft.}$	$10.2 \times 52.6 \times 1.47 = 789 \text{ ft.}$
3. Interval for oncoming vehicle	$(9.3 \times 36 \times 1.47) + 110 = 602 \text{ ft.}$	$(10.4 \times 39 \times 1.47) + 160 = 756 \text{ ft.}$	$(10.2 \times 40 \times 1.47) + 300 = 900 \text{ ft.}$
Total distance for passing maneuver	1229 ft.	1631 ft.	1994 ft.
Rounded value	1200 ft.	1600 ft.	2000 ft.

in the "C" classification. Preliminary delay distances of 150, 205, and 305 feet, respectively, were based on 3.7 to 4.3 seconds of delay and observed acceleration rates of 1.41 to 1.47 mphps. The distances for left lane occupancy were the least distances that included 80 percent of the "C" group drivers. These values are 477, 670, and 789 feet, respectively. Clearance distances of 110, 160, and 300 feet included 90 percent of drivers studied. Prisk emphasized that the total distances shown did not necessarily represent the minimum sight distance requirements because a passing driver did not need to see the entire passing distance before initiating the maneuver. The essential point was that the driver needs sufficient clear distance to maneuver his vehicle to the right lane when an opposing vehicle appears.

1957 Study of Passing Practices - Normann (11)

After World War II, substantial increases in horsepower of passenger cars and the decrease in height of driver's eye in the newer cars created concern to many highway design engineers. One of the advantages cited for increased horsepower was the improved ability to complete passing maneuvers in less time, thus reducing the possibility of being caught in the left lane of a two-lane road with an oncoming vehicle rapidly approaching. On the other hand, lowered eye height reduced the distance that a driver could see a clear road ahead. It was recommended that the effect of these changes as related to the current practice of marking no-passing zones on two-lane highways be investigated.

In 1957 Normann conducted a study to investigate passing practices. In choosing test sites, it was found that at three of the sites where the 1938 studies (4) were conducted, there had been no change in the geometric highway features. Surface width and condition, shoulder width, and sight distance conditions had remained unchanged for nearly twenty years. Thus, the 1957 observations of passing practices were conducted at these three study areas and data were compared to the 1938 data in which cars of much lower horsepower ratings had been observed.

A comparison of the results of the 1938 and 1957 studies is shown in Table 8. Detailed data were obtained for 608 passing maneuvers in 1938 and 476 passing maneuvers in 1957. The 1957 data were separated into two groups, one including passing maneuvers performed by 1954 or older model vehicles, the other including 1955 to 1957 models because the greatest increase in horsepower occurred between 1954 and 1955 model vehicles.

Normann found that the speeds of both the passed and passing vehicles were higher in 1957 than in 1938 (Table 8). The passed vehicles in 1957 were moving three or four miles-per-hour faster than in 1938, and the speeds of the passing vehicles were six to seven miles-per-hour higher. He also observed that the average speed of free-flowing vehicles was five miles-per-hour higher in 1957. The average difference between the speed of the passed vehicle and the speed of the passing vehicle had increased from 10 mph in 1938 to 13 mph in 1957. The time spent in the left lane by the newer model vehicles in 1957 was 0.5 seconds less than the time in 1938. The distance traveled in the left lane, however, increased by 100 feet in 1957. Thus, it would appear that increasing the average horsepower (from 1938 to 1957) by

TABLE 8

COMPARISON OF PASSING PRACTICES IN 1938 AND 1957, NORMANN (11)

Study Section	1938 Study		1957 Study	
	All Models	1954 and Older models	1955-57 models	
Number of Passings Studied				
1	130	46	90	
2	245	69	139	
3	<u>233</u>	<u>45</u>	<u>87</u>	
Total	608	160	316	
Average Speed of Passed Vehicles, mph				
1	34	34	36	
2	35	38	39	
3	<u>36</u>	<u>42</u>	<u>42</u>	
Average	35	38	39	
Average Speed of Passing Vehicles While in Left-hand Lane, mph				
1	44	48	50	
2	45	51	50	
3	<u>46</u>	<u>54</u>	<u>56</u>	
Average				
Average Time Passing Vehicles Were in Left-hand Lane, sec.				
1	11.4	9.0	9.0	
2	9.0	9.3	9.0	
3	<u>10.1</u>	<u>11.9</u>	<u>11.1</u>	
Average	10.2	10.1	9.7	
Average Distance Passing Vehicles were in Left-hand Lane, ft.				
1	740	630	650	
2	540	700	650	
3	<u>640</u>	<u>950</u>	<u>910</u>	
Average	640	760	740	
Average Speed of Free Moving Vehicles, mph				
1	42	44		
2	41	42		
3	<u>40</u>	<u>49</u>		
Average	41	45		

ent had decreased the time needed to perform passing maneuvers about 5 percent but resulted in an increase of the distance traveled in the left lane by about 19 percent. This is not in accordance with what may be expected, and illustrates the importance of research concerning the manner in which drivers operate their vehicles.

Normann stressed that average values may be misleading. Although the new vehicles occupied the left lane for a slightly shorter time in 1957, the times for the fastest maneuvers were not significantly different from those measured in 1938.

Two and one-half percent of the passings studied in 1938 were completed with oncoming vehicles less than 200 feet away. Only 0.5 percent of the passings studied in 1957 involving the newer cars were completed with oncoming cars less than 200 feet away. When two vehicles approach each other at 50 mph a clearance distance of 200 feet is reduced to zero in approximately 1.4 seconds.

Normann concluded that there was little evidence to indicate that 1957 practices of marking no-passing zones should be changed due to changes that had occurred in vehicle design and driver performance.

Distance Judgment Studies - Gordon and Mast (12)

Gordon and Mast analyzed the passing maneuver in terms of four basic quantities:

- α - gap time or distance separating the overtaken and opposing vehicles,
- α' - driver's estimate of gap available,

β - time or distance required by the driver-car combination to perform the maneuver,

β' - driver's estimate of time or distance required to perform the maneuver.

The driver's judgment in overtaking and passing involves a comparison of α' and β' . If the outcome is favorable, (i.e., the gap available, α , is judged to be longer than the distance, β , with adequate safety margin), the driver will accept the gap. If not, he will reject it, and wait for a longer gap. Both α and β are measured in physical units of time and distance; α' and β' are also measured in physical units, but these quantities must be obtained in psychological experimentation.

In presenting their results, Gordon and Mast compared their data to those of Matson and Forbes, (13) Prisk, (14) and Crawford, (15) authors of previous studies on overtaking and passing maneuvers. In their literature search, Gordon and Mast reported that Matson and Forbes, and Prisk gave figures on overtaking distance when the pass was started at the same speed as the car ahead (accelerative pass) and when the following car had an initial speed advantage (flying pass). A distinction was also made between voluntary (unhurried) returns to the right lane and those where the overtaking car was forced to return by an opposing car. The first human factors study of overtaking and passing was made by Crawford who regarded overtaking and passing judgments as psychological. He conducted controlled experiments in which measurements were made of accepted gap distance, overtaking, and clearance distances. Validating highway studies were then made.

Research conducted by Gordon and Mast was concerned with the ability of drivers to judge the distance required to overtake and pass. The decision was

simplified by terminating the maneuver at a fixed point on the road, rather than by the impedance of an oncoming car. In this way, errors in the driver's assessment of the situation (α errors) were minimized. Estimations were made by twenty drivers in their own cars, and for another phase of the research, in a government vehicle. The studies were carried out on a runway as shown in Figure 4. Positions on the runway where overtaking and passing occurred were indicated by a marking pistol (American Automobile Association detonator) attached to the rear bumper of each car. When a button was pressed, a solenoid release mechanism fired a shell containing yellow chalk at the runway.

In the first phase, drivers followed the test car at a distance of 55 feet. They were instructed as follows: "You will follow the car ahead and think of passing it. When you come to the closest point to the line where you can still pass, using maximum acceleration of the car, indicate the spot by pushing the button." Distances between lead and subject car were maintained by instructions to speed up or slow down. Speeds of 18, 30, and 50 mph were controlled by the driver of the lead car.

In the second phase of the study, the driver followed the lead car at the scheduled pace. Instructions were: "Follow the car ahead at the distance I tell you. When you get to the line, overtake and pass the car ahead as fast as you can, and come back into the lane." When the car was fully back into the lane, the experimenter in the test car pushed the pistol button. An experimenter on the runway then recorded the position of the chalk mark.

Performance results are shown in Figure 5 with results of Matson and Forbes, Prisk, and Crawford presented for comparison. Each "government" and "own-car" point represents the average of 20 observations. The performance curves indicate that as speed increased, passing distance also increased, but

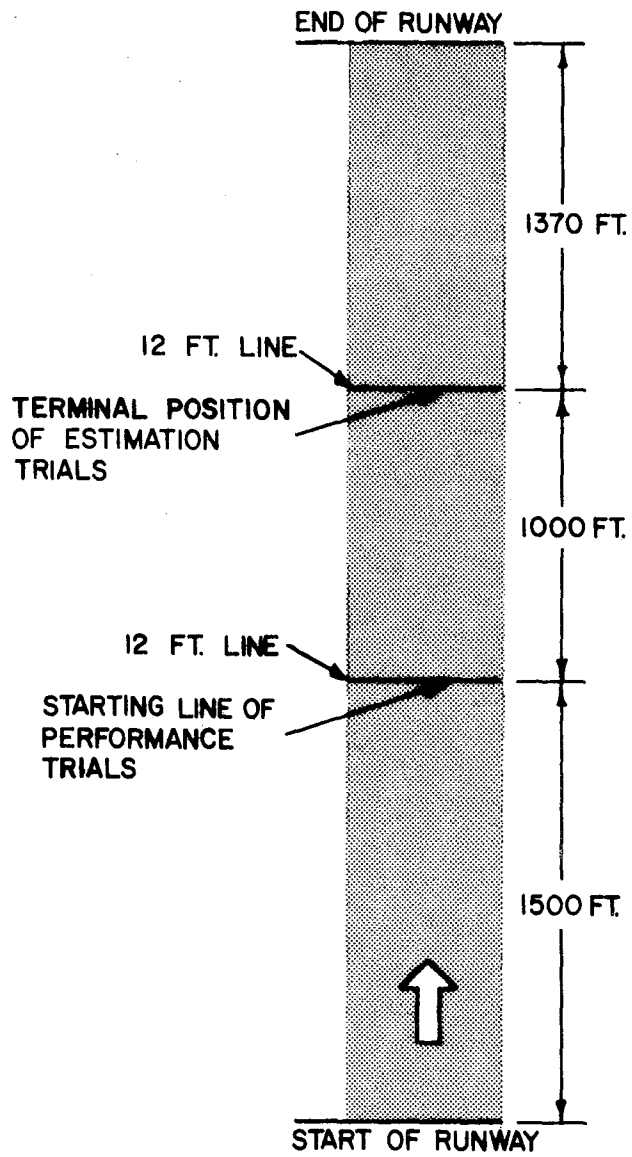


Figure 4. Experimental Track, Gordon & Mast (12).

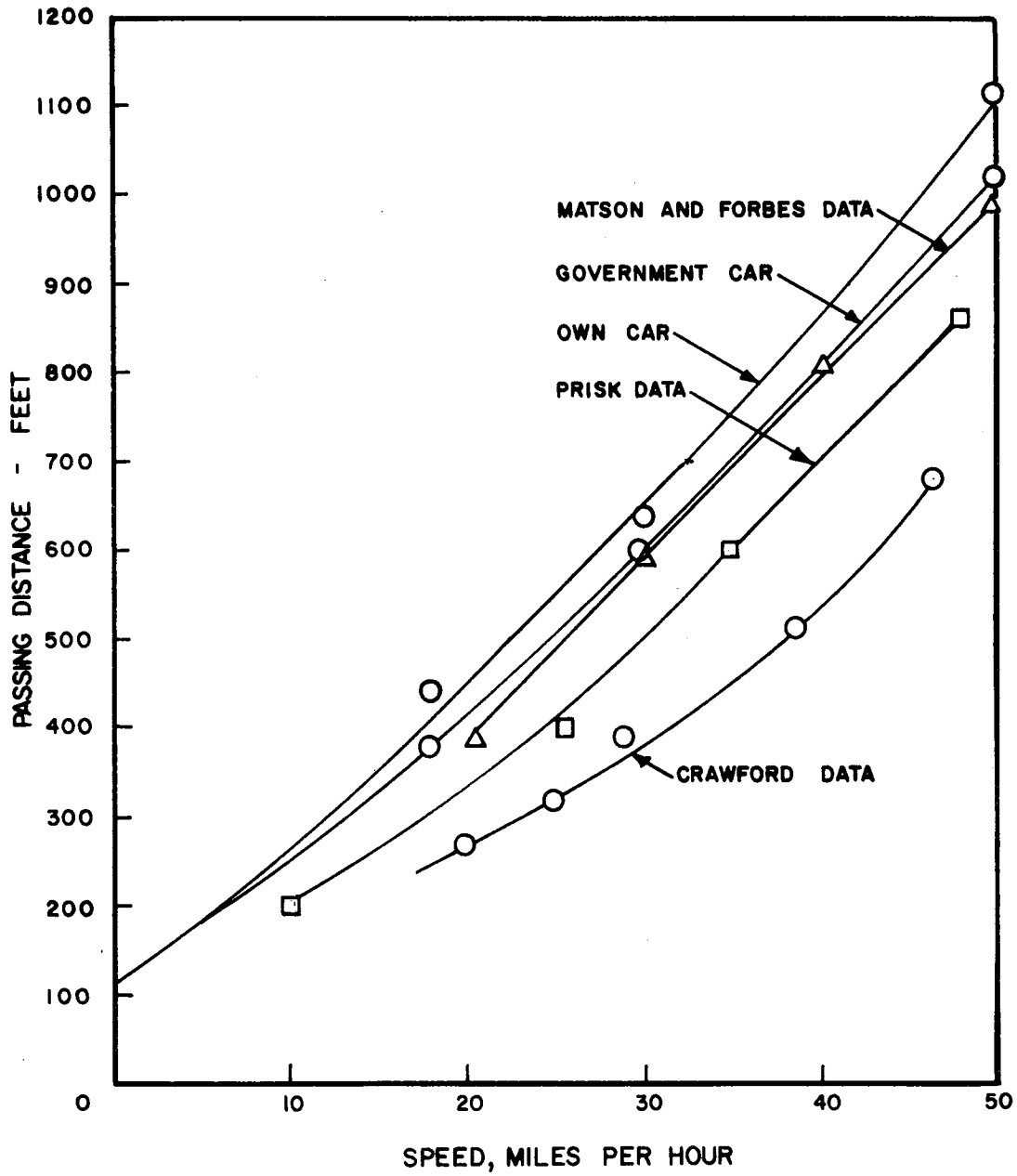


Figure 5. Passing Distance in Relation to Speed, Gordon & Mast Study (12).

at an increasing rate. The least-squares fit to the "own-car" data was given as

$$D = 112.2 + 15.2 V + 0.093 V^2$$

where D is overtaking distance in feet and V is velocity in mph. Matson and Forbes data points agreed closely with the "government car" curve, and the Prisk data displayed the same general form but distances were approximately one hundred feet less. Matson and Forbes, and Prisk defined passing distance as car travel in the left lane, which is shorter than passing distance as defined by Gordon and Mast. Crawford's curve showed still shorter distances, perhaps due to the use of trained drivers and other procedural differences.

Gordon and Mast observed that drivers differed in their ability to pass, even when using the same car. For example, one driver overtook in 284 feet, but another required 455 feet at 18 mph. At 30 and 50 mph, the variability was even greater. The frequency distribution of drivers' errors is shown in Figure 6. Figure 6 indicates that drivers were not able to estimate passing distance accurately. Negative errors of estimate involving underestimation of maneuver distance are dangerous, and the frequency of underestimation increased with higher speed. Though the precise cause of underestimation at high speeds is unknown, high speed underestimation remains a pertinent fact with which highway design engineers must contend when dealing with the overtaking and passing maneuver.

The finding that a driver was unable to accurately estimate his overtaking and passing requirements and that underestimations were frequent at high speeds implied that the maneuver required guidance in the interest of safety. Gordon and Mast suggested several possible aids to the driver:

1. Passing areas and "no-passing" signs (traditional aids to overtaking and passing),

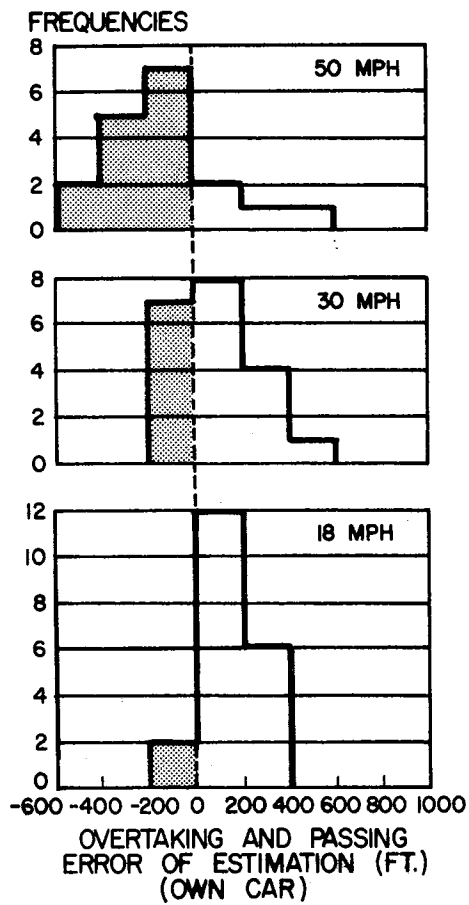
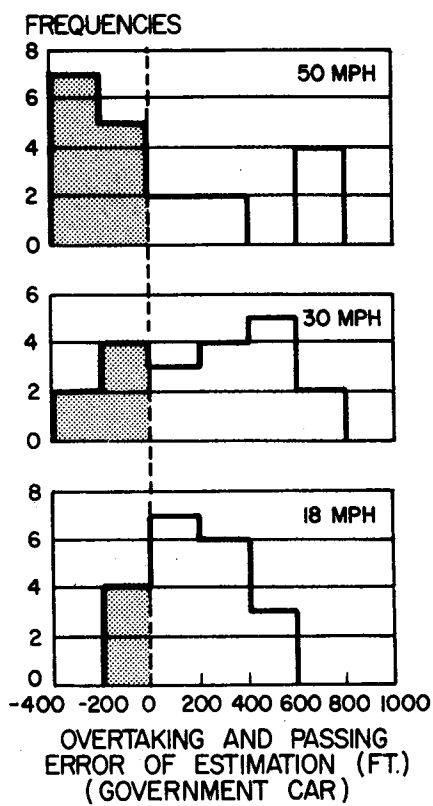


Figure 6. Frequency Distribution of Estimation Errors in Passing Gordon & Mast Study (12).

2. Speed limits and other speed regulations, particularly in passing zones,
3. Driver education not to pass at high speeds and to cooperate with the overtaking driver,
4. Electronic devices informing the driver when it is safe to pass,
5. Road design modification, such as wide shoulders and addition of lanes,
6. Traffic planning to minimize use of two-lane roads.

Clearance Time Studies -- Jones and Heimstra (16)

Jones and Heimstra performed studies to determine how accurately drivers could estimate clearance time. Clearance time was defined as the time allowed by the passing driver between the completion of his own pass and the arrival of the oncoming car abreast of him.

Nineteen male college students participated in the study. All subjects had several years driving experience and had been screened for visual defects. The subject followed about four car-lengths behind the lead car which was maintained at 60 mph, and practiced passing the lead car under instructions to pass as rapidly as possible without endangering either vehicle. The experimenter measured the time in seconds from the moment the subject began his pass until he had completed the pass and was again in the proper lane of traffic. Each subject completed a number of practice passes before the beginning of the actual test session.

After completion of the preliminary training, the subject was instructed as follows:

You will follow the lead car which will be traveling at 60 miles-per-hour. However, you will not pass it. Instead, when you see an approaching car you will estimate what you consider to be the

last safe moment for passing the car ahead of you and let me know by saying "now". By safe, I mean allowing yourself enough time or "room" to pass without causing the oncoming car to reduce its speed or take any other precautionary measures. Your saying "now" is intended to indicate to me the amount of distance between your car and the approaching car that allows just enough room to pass safely. You should say "now" when you feel the distance between you and the approaching car has decreased to a distance just long enough for you to safely pass the lead car.

Each subject repeated the experiment ten times resulting in 190 clearance estimates. The mean passing time based on the preliminary practice trials was used as a correction factor which was subtracted from each clearance time estimate. For example, if a subject had made a clearance time estimate of 14 seconds, the mean passing time was subtracted from this figure. Thus, if the mean passing time were 10 seconds, the subject's clearance time estimate was considered to be an overestimate of 4 seconds. Table 9 indicates the number of underestimates and overestimates made by the subjects.

In view of the results presented in Table 9, it is emphasized that the subjects were not asked to estimate closure time; rather, they were instructed to estimate the last safe moment for passing the vehicle ahead without causing the approaching vehicle to take any evasive action. In this context, it would appear that many subjects were not capable of accurately making this judgment. An underestimate would have resulted, in actual driving, in a situation where the subject would not have had time to pass the lead vehicle. Nearly 50 percent of the judgments were underestimates. Although the typical driver is not frequently called on to make a "last safe moment" decision, the investigation suggested that when a judgment of this type is made, the average driver is not capable of making it with any degree of accuracy.

TABLE 9

CLEARANCE TIME ESTIMATION ERRORS, JONES AND HEIMSTRA (16)

Error (sec)	Under- estimates	Over- estimates
0- .9	23	24
1.0-1.9	24	20
2.0-2.9	14	15
3.0-3.9	14	13
4.0-4.9	10	12
5.0-5.9	6	5
6.0-6.9	0	1
7.0-7.9	2	0
8.0-8.9	0	2
9.0-9.9	0	0
10.0 and over	0	5

Driver Judgment and Decision Process Studies - Farber and Silver (1)

Farber and Silver sought to define requirements for the overtaking and passing maneuver (17, 18, 19, 20) and published the results of their research in four volumes (1). Eight over-the-road studies were conducted; seven were controlled experiments conducted on a closed highway and the eighth was a long-term observational study of passing practices on a rural highway. The goal of the research on driver judgment (Phase 1) and decision-making was to obtain an understanding of the driver judgment problems associated with the pass/no-pass decision. In conducting this research, the researchers determined the ability of drivers to judge and compensate for the speed, time and distance variables which collectively determine the safety of a given passing opportunity.

The second part of the research program (Phase 2) was directed toward studying driver-control processes in overtaking and passing to determine the causes of guidance-and-control errors, and reveal ways of avoiding such errors to reduce hazard. To achieve this goal, a mathematical model of the driver/vehicle/roadway system was developed. The model regarded the driver as a system-sensing and control element, described in terms of quickness, smoothness, and accuracy of response, and incorporated terms which define handling characteristics of the vehicle. Application of the model to various overtaking and passing situations provided the basis for several remedial recommendations directed toward avoiding control difficulties and improving the safety and facility of the overtaking and passing maneuver.

Phase 1 considered two types of passing maneuvers: sight distance-limited flying passes, and oncoming-vehicle-limited passes. The studies were

concentrated on the latter. The passing situation to be studied was analyzed to determine which time, speed, and distance variables were critically relevant. Experiments were then designed to evaluate the ability of drivers to judge and compensate for these variables in making the decision whether to pass. Six experiments were performed. Experiment 1 dealt with driver judgment in sight distance-limited flying passes. Experiments 2 through 6 studied oncoming vehicle-limited accelerative passes.

In Experiment 1, flying pass situations were set up on a closed roadway so that on each trial, the subject driving the passing car overtook a slower moving lead car at some point in the 2,000-foot passing zone. Absolute and relative positions and speeds of the two vehicles in the passing zone were manipulated to produce systematic trial variations in the time available and time required to pass. Each subject was instructed to pass the lead vehicle if he judged that the pass could be completed before the end of the passing zone. The primary dependent variable was whether or not the subject passed the lead car. The results indicated that drivers could judge sight distance to within 200 feet at distances up to 2,000 feet, but that their judgment of closing rate with the lead vehicle was marginal. Drivers who accepted a marginally short passing opportunity compensated for their error by passing more rapidly.

Experiment 2 was conducted to evaluate the hypothesis that poor judgment of oncoming-vehicle speed seriously limits the ability of drivers to make accurate passing decisions. The subject driving the passing car, closely followed a lead car as the lead car and an oncoming car drove toward each other from opposite ends of the test roadway. The subject was instructed to pass the lead car at the last safe moment but was cautioned not to pass when the lead

car/oncoming car separation was less than he would consider minimally acceptable on the highway. The oncoming vehicle speed was held constant for half the trials and varied randomly between 35 and 55 mph for the remaining half. It was concluded from the results that inability of drivers to judge oncoming-vehicle speed seriously limits the accuracy of passing decisions in oncoming-car-limited passes.

Experiment 3 was designed to evaluate the ability of drivers to use supplementary information about oncoming-vehicle speed. The procedure was similar to that of Experiment 2, but the subject was asked to pass the lead car when he judged the lead car/oncoming car time separation to be 12 seconds. The ability of the subjects to estimate the time separation (time available to pass) depended on their ability to judge and take into account oncoming vehicle speed and distance, and was taken as a measure of passing-judgment accuracy. Each subject performed three types of trials: constant oncoming vehicle speed, no-knowledge trials where oncoming vehicle speeds were randomly varied across trials, and verbal-knowledge trials in which oncoming vehicle speeds were randomly varied but in which subjects were told prior to each trial what the speed of the oncoming car would be. The study produced three major results: (1) driver judgment of distance to oncoming car is accurate to within 20 percent, 95 percent of the time, (2) at oncoming vehicle distances between 1,000 and 3,000 feet, subjects could not discriminate oncoming vehicle speeds as disparate as 30 and 60 mph, and (3) subjects used verbal knowledge of oncoming vehicle speed effectively to estimate time separation.

Experiment 4 was designed to establish the effect of varying lead-car speed on the ability of drivers to use knowledge of oncoming car speed. The procedure was similar to that of Experiment 3 except that lead-car speed was

varied randomly from trial to trial so that subjects were required to take their own speed into account in estimating lead-car/oncoming-car time separation. Subjects who were given verbal knowledge of oncoming-car speed made significantly more accurate passing judgments. However, they tended to overestimate the time separation at high lead-car/oncoming-car closing rates and to underestimate the time separation at low closing rates.

In Experiment 5, drivers were supplied with knowledge of the lead-car/oncoming-car closing rate in addition to oncoming-car speed. The most important result of this experiment was that, under constant closing rate conditions, subjects responded inappropriately to their own speed by passing at shorter distances when their own speed was low and at greater distances when their speed was high.

Experiment 6 was an expansion of Experiment 5. Subjects were asked to estimate the lead-car/oncoming-car time separation and pass when the time separation was 12 seconds. Three types of trial blocks were run in each of which both lead-car and oncoming-car speeds were randomly varied. In the "no-knowledge" block, subjects had no knowledge of oncoming-car speed or closing rate except what they could judge for themselves. In oncoming-car speed knowledge and closing rate knowledge blocks, subjects were told prior to the start of each trial what the closing rate or the oncoming-car speed would be. Performance with oncoming-car speed knowledge resulted in substantially better estimates of lead-car/oncoming-car time separation than did the no-knowledge condition. Closing rate information resulted in subjects initiating the pass at greater distances as lead-car increased at a given closing rate. It was concluded that knowledge of closing rate and oncoming-car speed knowledge would be equally effective as remedial aids to drivers in performing passing maneuvers.

Experiment 7 was designed to measure the ability of drivers to judge closing rate with, and distance to, a slower-moving lead vehicle in overtaking situations. On each trial, a subject overtook a slower-moving vehicle at some point on a closed roadway. Subjects were asked to estimate the time headway between the two vehicles and indicate when the time headway had closed to 10 or 5 seconds. In half the trial blocks, the speed advantage of the overtaking car (closing rate) was held constant; in the remainder, closing rate was varied randomly between 10, 20, and 30 mph. The major findings were that subjects could judge distance to the lead vehicle to within one or two car-lengths at distances up to 200 feet. Subjects displayed marginal ability to judge and compensate for closing rate in estimating time headway. It was concluded that the marginal ability of drivers to judge closing rate and use this information in overtaking situations was the factor that most seriously reduced the accuracy with which drivers decided to pass or to follow in overtaking situations.

The major findings of the driver judgment and decision-making studies were that drivers judged distance accurately in passing situations, but that their ability to judge velocity variables was marginal. Subjects could not discriminate even grossly different oncoming-vehicle speeds. Ability to judge time available to pass was substantially improved when the need to judge oncoming-car speed or closing rate was eliminated, either by providing the drivers with this information or by holding these variables constant.

Mathematical Simulation of Passing Maneuvers - Cassel and Janoff (10)

Cassel and Janoff used a mathematical simulation model to study passing maneuvers. The model was developed to evaluate traffic flow and safety benefits

arising from use of remedial devices which would aid passing maneuvers on two-lane roads. It simulated the movement of vehicular traffic for various road geometry and traffic volume conditions. During simulation, vehicles would, under certain conditions, attempt and execute passing maneuvers in order to attain and maintain their individual desired speeds. Elements of traffic (vehicles in each lane) were introduced into the model from both ends of the road. Any "mix" such that volumes, speed distribution of vehicles, and desired vehicle speed could be arbitrarily set at the discretion of the user.

At any point in time during simulation, each vehicle was in any one of four possible maneuvers states:

- State (0) traveling in its normal lane,
- State (1) deciding to initiate a passing maneuver,
- State (2) traveling in the opposing lane while passing one or more cars in its own lane,
- State (3) terminating the passing maneuver by re-entering its normal lane.

If, during maneuver state (2) , a driver had to alter his passing behavior because it became necessary to complete the pass sooner than originally anticipated or to abort the maneuver, certain latitudes of action were available. The passing vehicle could accelerate or decelerate in the proper time required to re-enter its normal lane in order to avoid a collision circumstance.

Inputs to the model consisted of road configuration data, vehicle data and passing probability data. Road data consisted of road length, no-passing zone configurations, sight distance restrictions and maximum simulation time to be used. These values did not change during a given simulation. Desired

speeds (actual speeds during entering), maximum speeds, time headways (which determined a vehicle's time of entry), and maneuver state (which was State (0) upon entering) were input for vehicle data. An acceleration rate of $5\text{ft}/\text{sec}^2$, and a maximum emergency deceleration rate of $20\text{ft}/\text{sec}^2$ were used. Passing probability data consisted of four probability curves obtained from observational studies on public highways. The curves showed percent of passing opportunities accepted as a function of lead-car speed and oncoming gap, and were based on passing behavior in which the drivers had no knowledge of opposing car speed.

The primary use of the model was to evaluate the effects of remedial aids for passing maneuvers on traffic flow and safety. Two basic applications were considered:

- (A) Use of existing no-passing zones for passing maneuvers by providing drivers with information describing the opposing traffic (e.g., positions and speeds of oncoming vehicles).
- (B) Providing drivers with oncoming vehicle speed or closing rate on level tangent sections.

Each simulation for application (A) was accomplished using a 30,000-foot road, a 50-50 traffic directional distribution, 10 to 15 percent heavy trucks, and the no-knowledge passing rule. Passing was allowed only on tangent sections. The same series was re-run using the passing rule derived when knowledge of oncoming vehicle speed was provided to the drivers.

From the results the following conclusions were drawn:

1. When drivers were given knowledge of oncoming 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.

2. As the percentage of no-passing zones increased, there was a decrease in throughput as indicated by average speed, time delay, and number of passing maneuvers. The safety on the road, seemed to increase slightly.

Drivers' Understanding of No-Passing Zones - Bacon, et. al. (8)

Bacon, et.al., conducted a study of passing practices and no-passing policies to determine how drivers understood and acted at no-passing zones on the highway. Questionnaires, administered to drivers applying for renewal of their drivers' licenses at six licensing offices in Michigan were used to obtain data. The questionnaire included eight questions with sketches inquiring about passing behavior under various highway markings. Each sketch illustrated certain passing practices and the question for each sketch asked only if the driver had ever passed in that manner. Check boxes were provided for three possible answers for each sketch: "yes," "no," and "only in rare cases". The latter answer was included to distinguish between habitual and exceptional execution.

A total of 1,368 completed questionnaires were collected. Patterns revealed in the evaluation were analyzed with respect to the characteristics of the respondents. Passing patterns were considered from two points of view. The engineering or design intention was used as one basis for comparison, and the patterns themselves were compared to other driver characteristics such as age and sex, years of driving experience, attitudes toward driving, etc., in an attempt to find possible relationships. The research revealed that only 30

percent of the sample (424 respondents) claimed to observe no-passing zones according to enforcement intentions.

A group containing 307 responses violated the end of the no-passing line. This pattern with its sizeable representation could be cause for concern for highway engineers. Rare violations of the beginning of a no-passing zone were considered to be involuntary, i.e., a driver thought he had enough distance to complete his maneuver before the zone, but could not. A third grouping comprised those drivers who freely violated both ends of the no-passing zone. This group, containing 117 respondents, represented almost 10 percent of the sample.

The questions asked what drivers had done, but did not elicit their opinions about this behavior or their reasons for it. There were, however, clear indications that personal characteristics were significantly related to the patterns of passing behavior. Additional data concerning the social and economic status of the drivers, the extent and type of formal education, and the amount of driving experience would be extremely valuable in analyzing passing behavior. Examination of the overall passing behavior gave evidence of a much wider variety of actual behavior than may be anticipated in design for typical, average or ideal patterns of practice.

Distance and Speed Impedance Effects on Passing - Hostetter and Seguin (21)

Research was conducted by Hostetter and Seguin to determine the singular and combined effects of impedance distance, impedance speed, passing sight distance, and traffic volume on driver acceptance of passing opportunities on rural two-lane highways.

A van-type vehicle which was instrumented to facilitate observation and

recording of appropriate measurements was driven over selected test sites. The sites contained specified passing sight distances in the observation zone. The observation zone was located between two no-passing zones of sufficient length within which to impede subject drivers. Thus, a test site existed whereby a subject driver could be impeded for a specified distance at whatever speed the experimenter vehicle was driven, and was subsequently faced with a geometrically restricted passing opportunity. A schematic of a typical test site is shown in Figure 7.

Studies were conducted at five test sites, each representing a different level of passing sight distance; the distance being 929, 1,086, 1,292, and 1,693 feet. Impedance speeds corresponding to 10, 20, or 30 percent reduction in the personal desired speed of the subject driver were used. Subject drivers were chosen by an experimenter located upstream from the impedance zone. The speed of the subject car was measured and relayed ahead by radio to the van waiting near the impedance zone. The van then pulled out onto the highway ahead of the subject vehicle and accelerated to the selected impedance speed. The van then continued through the test site collecting the necessary data. Impedance time, judgment time and passing time were recorded. Passing distance and judgment distance were recorded by 16-mm cameras mounted in the front and rear of the van. All measurements were made without the subject driver's knowledge through the use of one-way mirrors in the van.

Impedance distance was defined as the distance over which a subject driver was forced to follow the experimenter vehicle until presentation of a passing opportunity. Distances of 1, 3, and 5 miles were used. Impedance speed was defined as the speed at which the subject driver was forced to drive over the impedance distance. Judgment time (or distance) was the interval between the

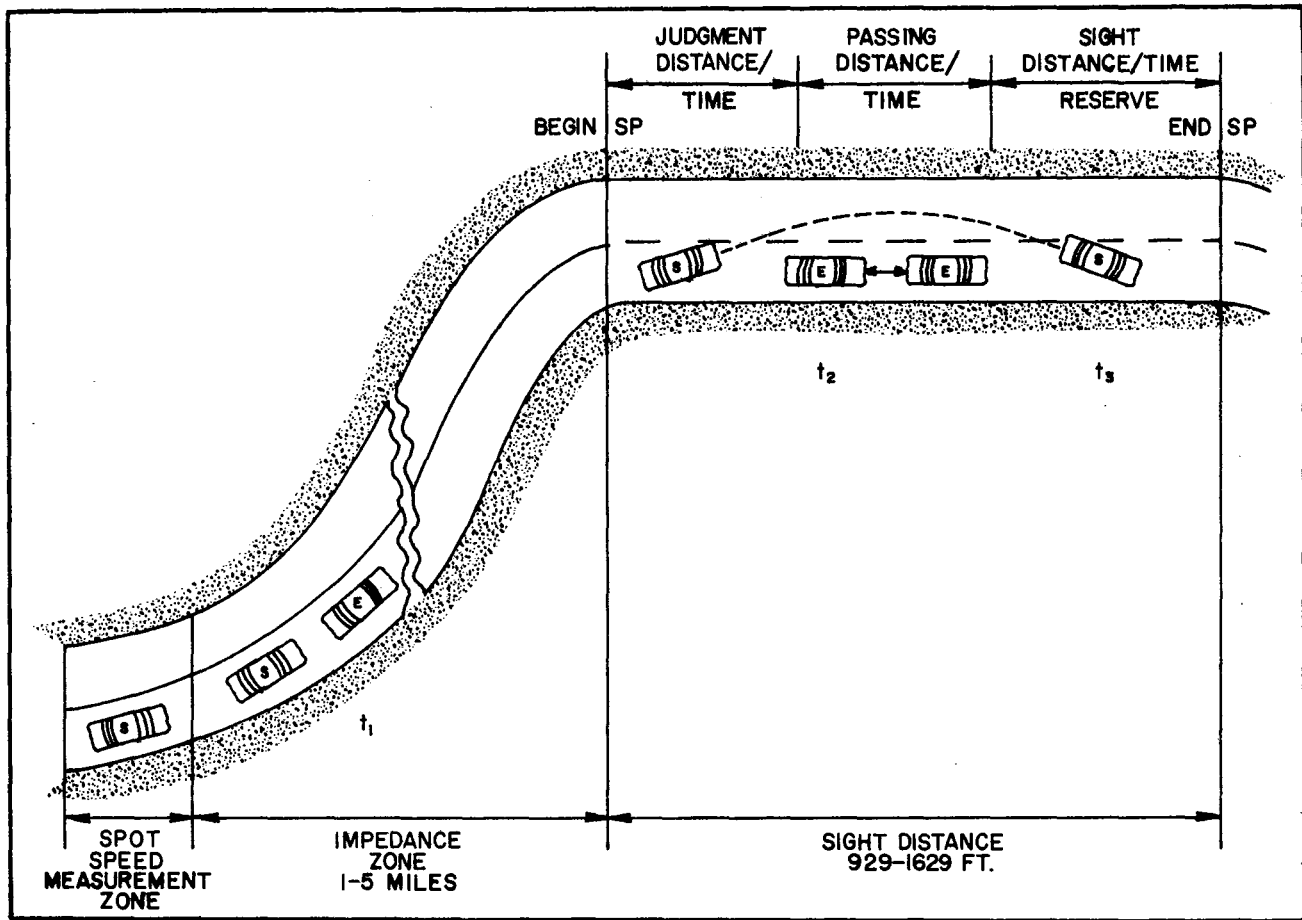


Figure 7. Test Site Schematic, Hostetter, & Seguin Study (21).

arrival of the subject driver at the beginning of passing zone and the indication of the passing maneuver. This indication was defined as the point where the right-front tire of the subject vehicle crossed the highway centerline. Where this occurrence was not followed by an actual passing, the situation was termed an "abort", and these data were excluded from data collection. The end of a pass was defined as that point at which the right-rear tire of the subject vehicle crossed the centerline. Sight distance reserve was the interval of time or distance from the end of the pass to the end of the passing zone.

The observed increase in passing frequency as a function of sight distance is shown in Figure 8. The passing frequency was related to Silver and Farber's (1) data for comparison. Silver and Farber's research involved studies of passing opportunities restricted by an oncoming vehicle. Although the restricted passing opportunities differed in definition, there was evidence that, in general, the probability of a pass increased as the sight distance opportunity increased. The difference in magnitude was attributed to the differential perception of risk in the two circumstances. In the Hostetter and Seguin study, the passing driver had to estimate the probability of an oncoming vehicle whereas in the Silver and Farber situation, the probability of an oncoming vehicle was unity in all cases. It was also noted that in the Silver and Farber study, drivers dealt with a closing rate of two vectors, one of which was not subject to their control; while in this study, the closing rate in the absence of oncoming vehicles was determined by the speed of the potential passer.

Mean judgment distance and time are shown as a function of sight distance in Figure 9. Intra-site differences were considered in an attempt to explain the increase between Sites 2 and 3. The factors considered were gradient in

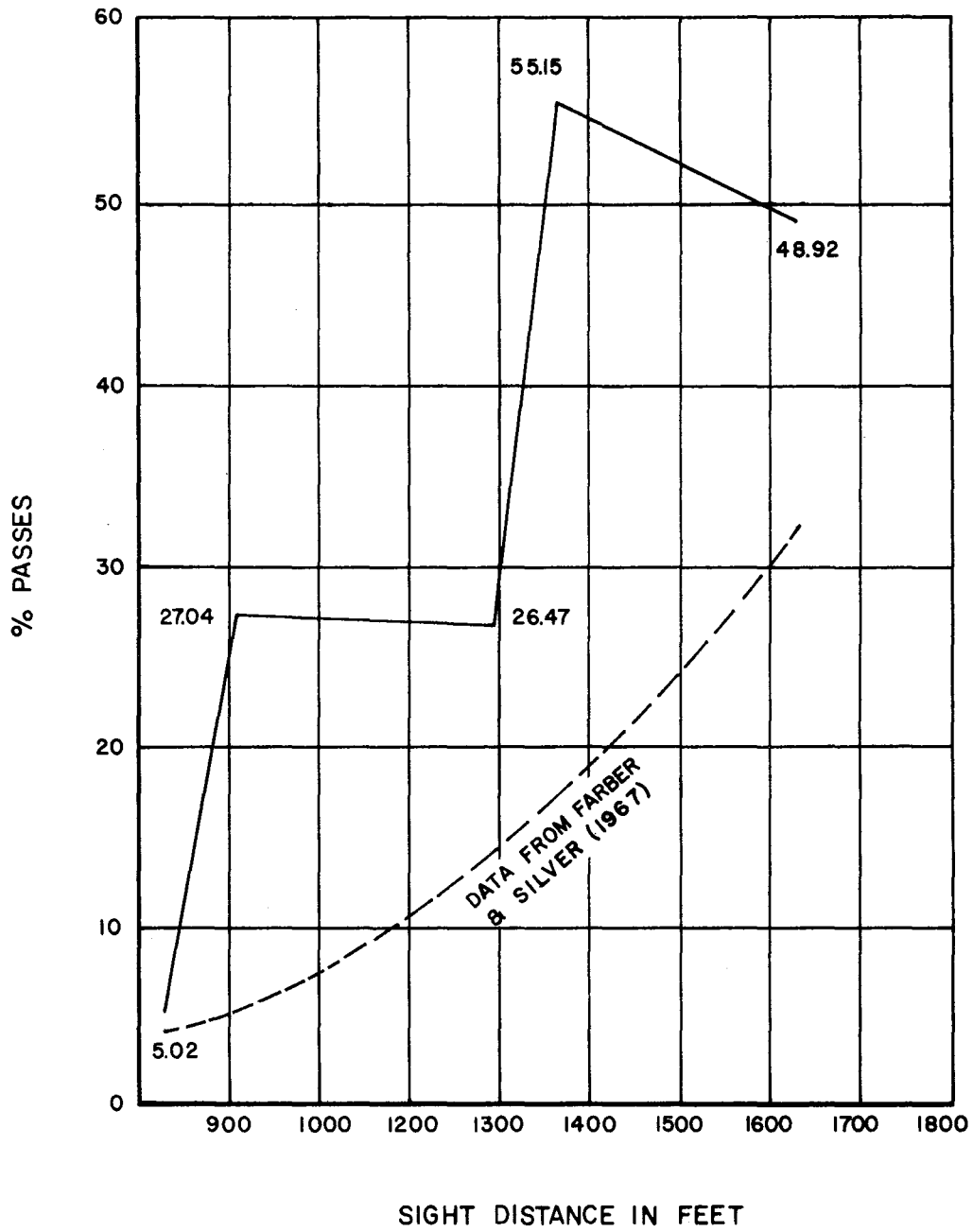


Figure 8. Relation Between Sight Distance and Percent of Passes Accepted Hostetter & Seguin Study (21).

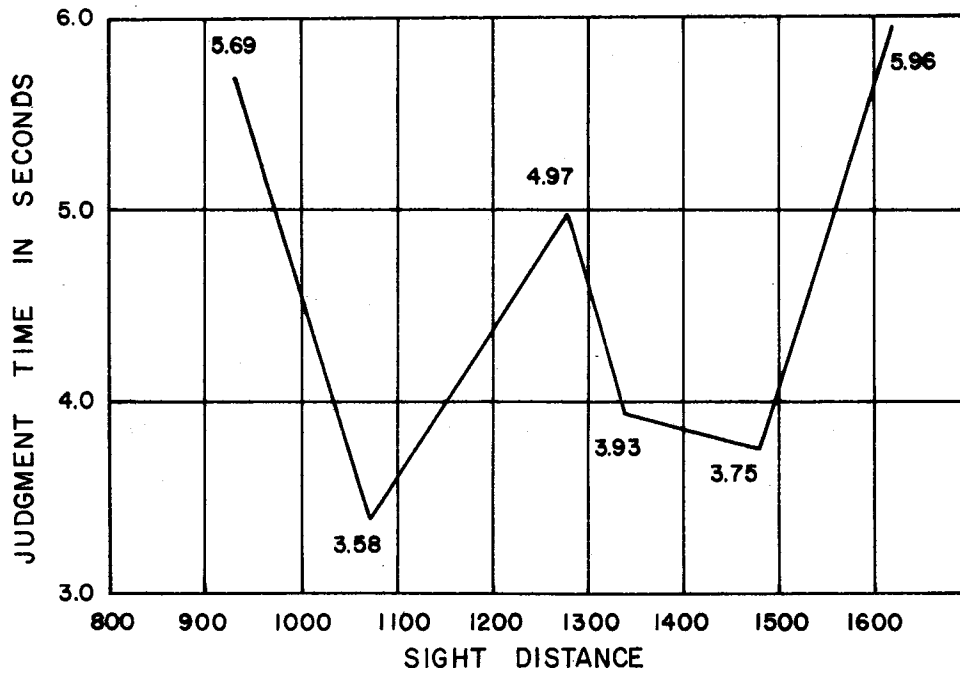
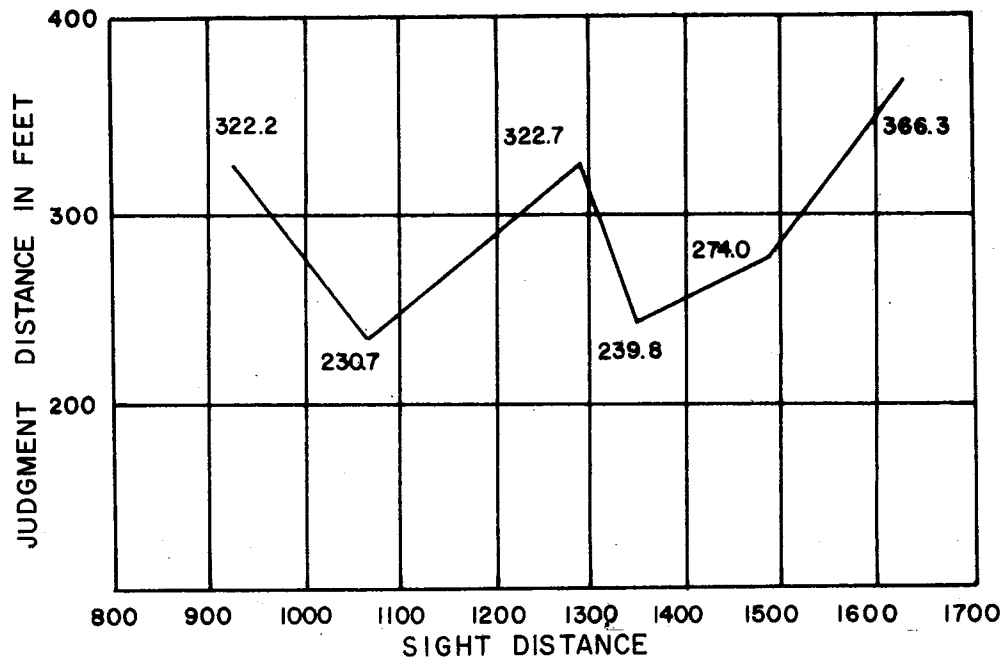


Figure 9. Mean Judgment Distance and Time in Relation to Sight Distance
Hostetter & Seguin Study (21).

the passing zone approaches, gradient in the passing zone, and proximity of the passing zone to a town. Only Site 3 contained all three characteristics, and these factors collectively may have caused an increase in judgment time and distance.

Mean passing distance and time are shown in Figure 10. Sight distance reserves in distance and time are presented in Figures 11 and 12, respectively, as a function of sight distance. The relatively small sight distance reserves observed for the shorter sight distances supported the postulate that within a range of restrictive sight distances, the driver passed as quickly as possible to minimize the probability of meeting an oncoming vehicle. Sight distance reserve increased almost linearly as sight distance increased (Figures 11 and 12). Sight distance reserve was the dependent variable most affected by sight distance variation. Sight distance was found to be the most influential determinant of the probability that a driver would accept a given passing opportunity.

Trends in Dimension and Performance Characteristics Study - Stonex (9)

Stonex reviewed the trends of dimension and performance characteristics of American passenger cars which were relevant to highway and traffic engineers. He included trend studies of ten factors. The three factors considered in this report are driver eye height, passing performance and acceleration characteristics.

One of the dimensions most interesting to highway designers is that of driver eye height. For more than twenty years, the AASHO design policies had based passing sight distance criteria on a driver's eye height of 4.5 feet above the ground. In 1965, the AASHO Policy adopted the height of 3.75 feet. Stonex

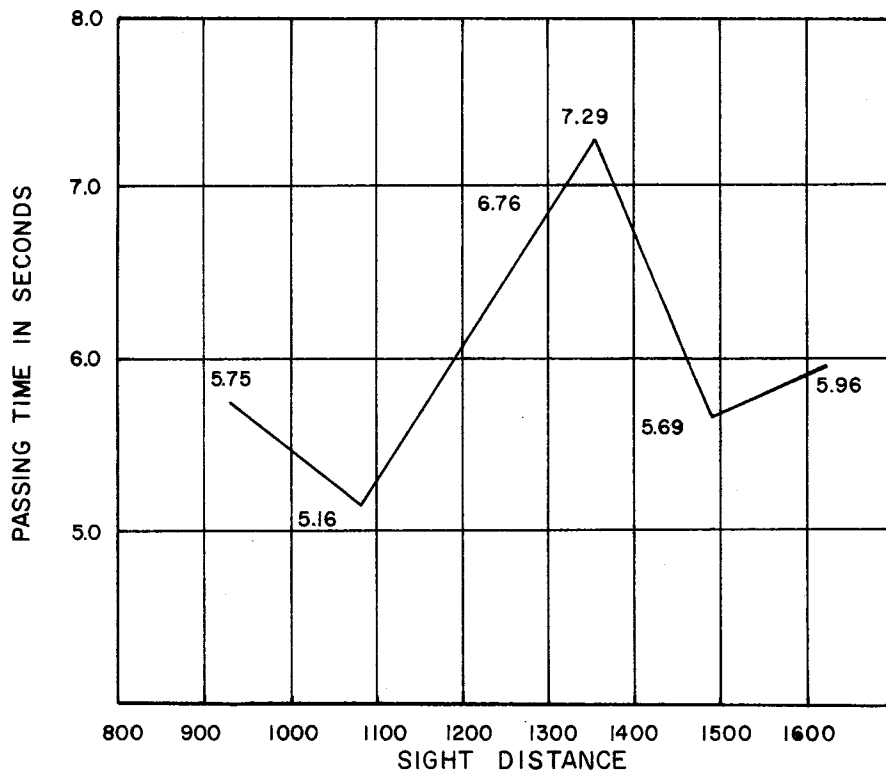
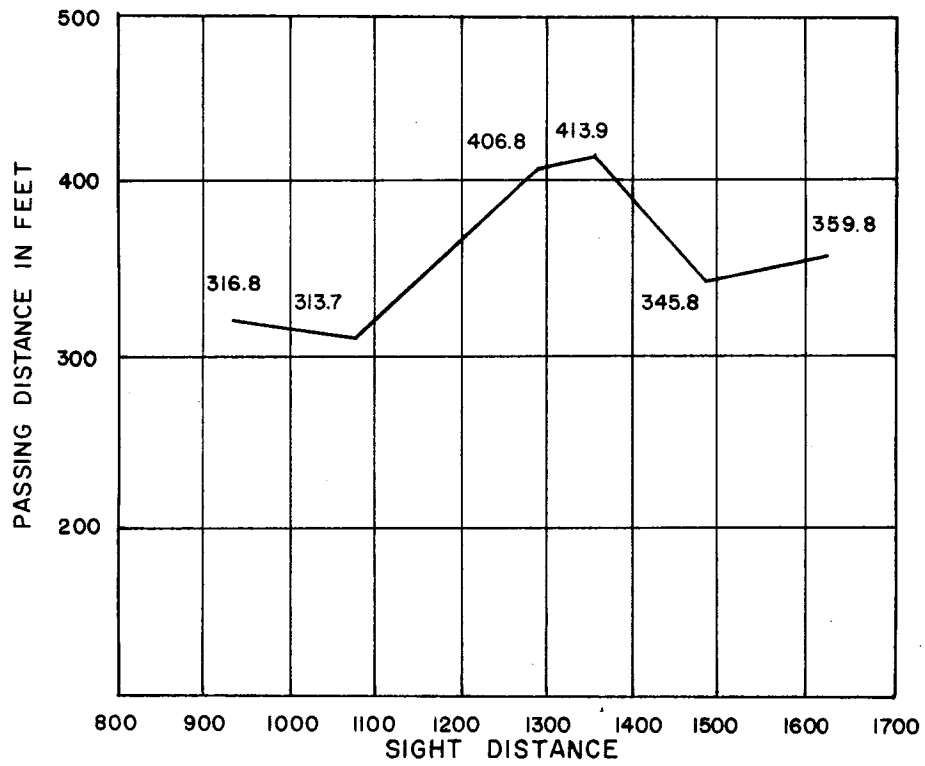


Figure 10. Mean Passing Distance and Time in Relation to Sight Distance
Hostetter & Seguin Study (21).

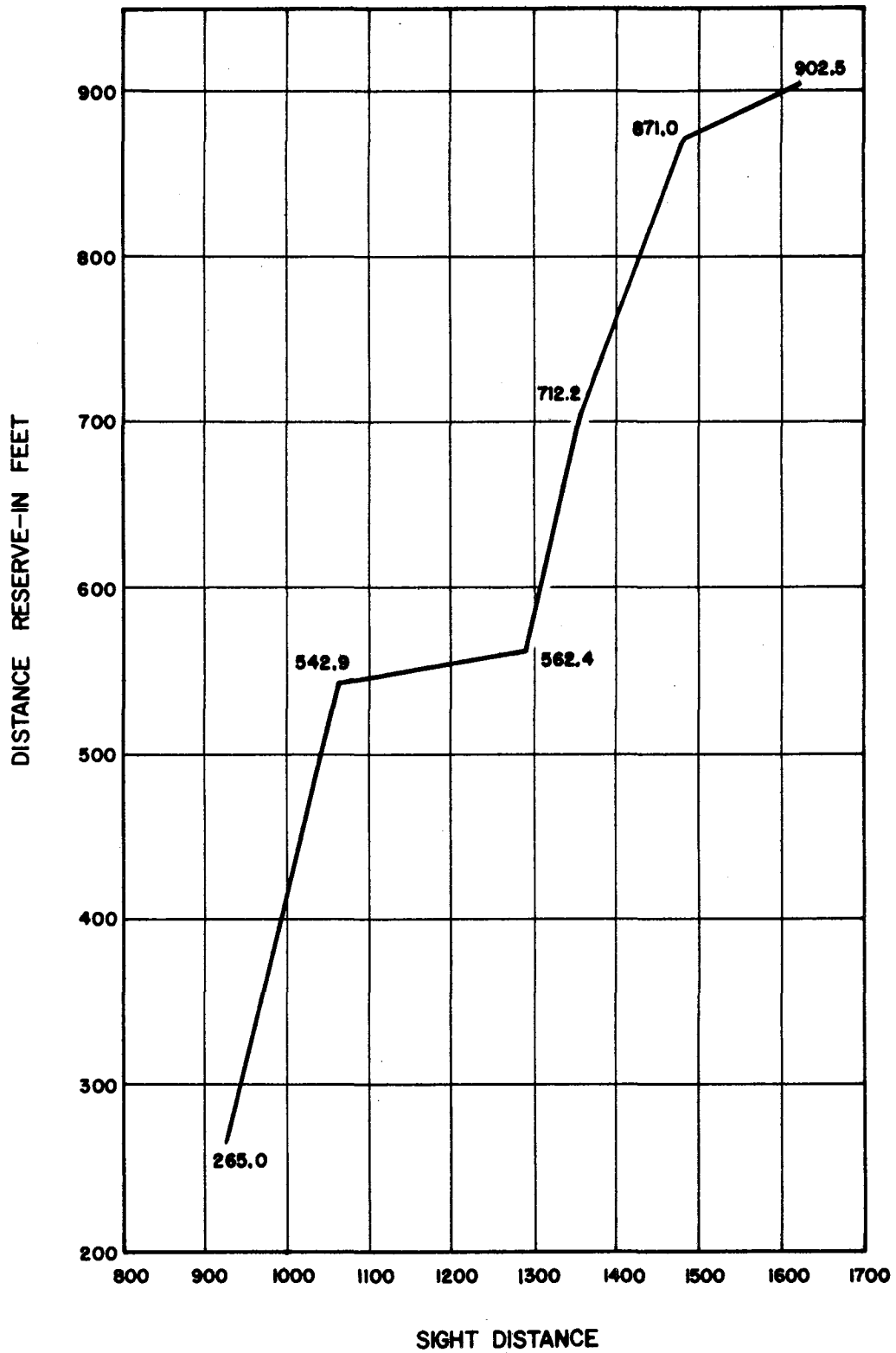


Figure 11. Mean Sight Distance Reserve in Relation to Sight Distance Hostetter & Seguin Study (21).

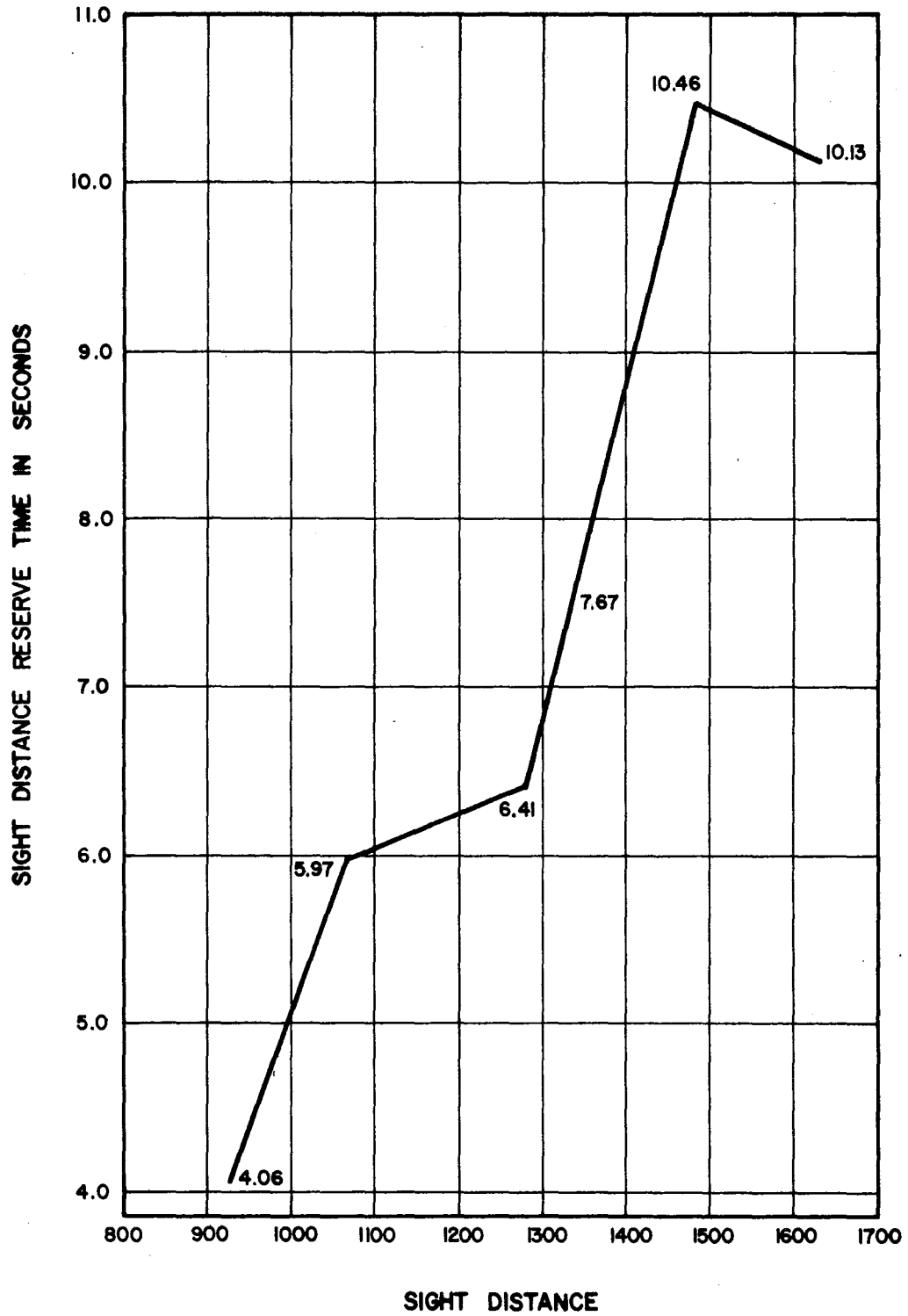


Figure 12. Mean Sight Distance Reserve Time in Relation to Sight Distance Hostetter & Seguin Study (21).

conducted extensive studies of driver eye height. In a sample of 196 male drivers at the General Motors Proving Ground, the mean value of vertical distance from a depressed seat to the eye point was 29.4 inches, and in a sample of 205 males, observed as they were driving on a public highway, the mean distance was 30.1 inches. Distribution ranged from approximately 26 inches to more than 33 inches. The chosen single value was 29.1 inches.

Percentile distribution of "average" driver eye heights above the road for 1960 cars is shown in Figure 13, together with percentile distributions of the best estimate of average driver eye height above the ground since 1936. Median driver eye height above the ground has decreased from 56.5 inches in 1936 to 47.5 inches in 1960. Stonex anticipated that average driver eye heights would not fall below 42 to 43 inches due to the practice of designing vehicles to conform with the stopping sight distance design of existing highways.

Figures 14 and 15 depict passing and acceleration characteristics of domestic cars during performance of a passing maneuver from a 40 mph start. In the schematic at the top of Figure 14, it was assumed that car B is proceeding uniformly at 40 mph and that the driver of car A wishes to pass. Car C is approaching at 40 mph. It was assumed that car A starts in the left lane with its front bumper even with the rear bumper of car B, accelerates full throttle until it passes car B and pulls back into the right lane 200 feet ahead of car B. The distance measured is that required to gain 60 feet on car B, plus the 200-foot clearance distance, plus the distance car C would travel in this length of time. Cars with optimum performance in 1959 completed this maneuver in 648 feet and 3.3 seconds. Those with lowest performance required 1,023 feet and 6.5 seconds. Figure 15 presents percentile distribution with

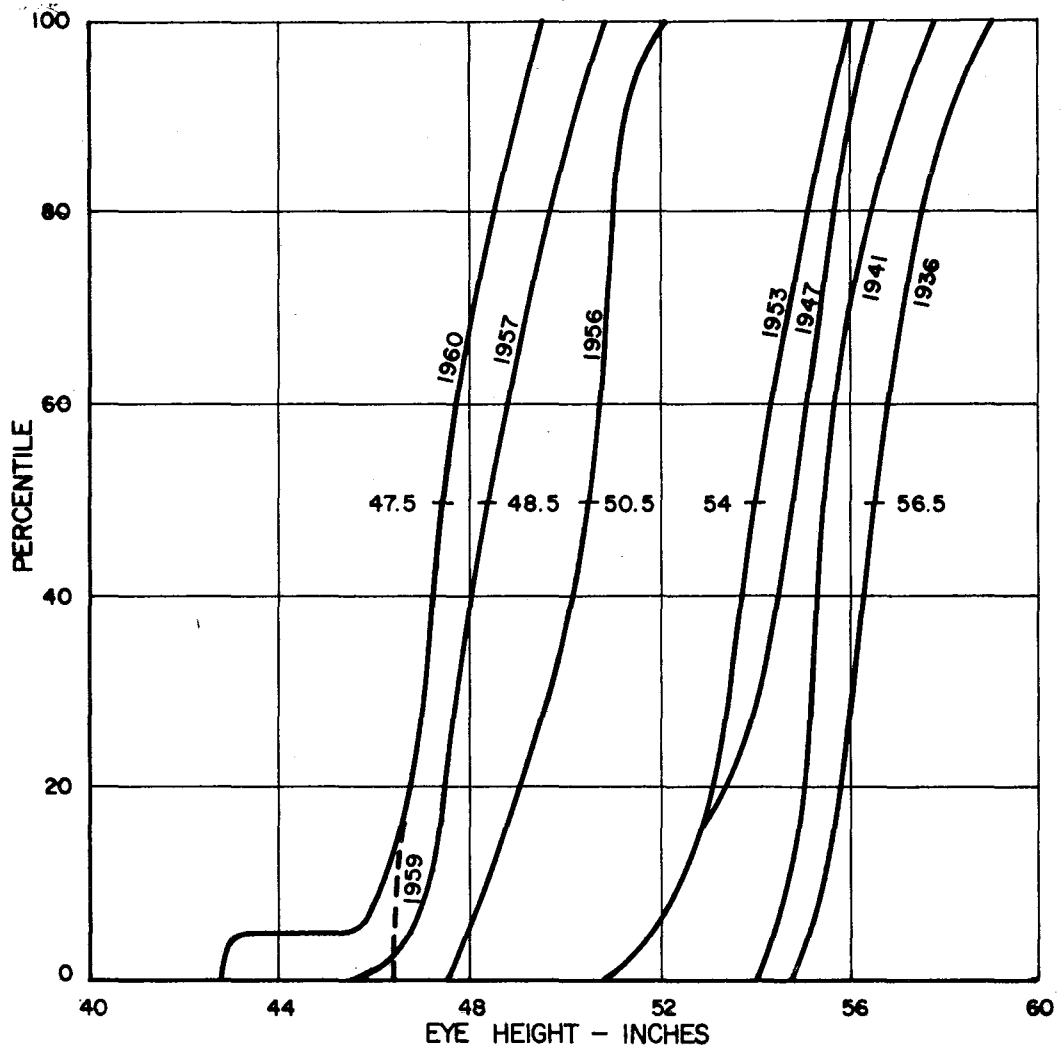


Figure 13. Percentile Distribution of Driver Eye Height Above the Ground Since 1936, Stonex (9).

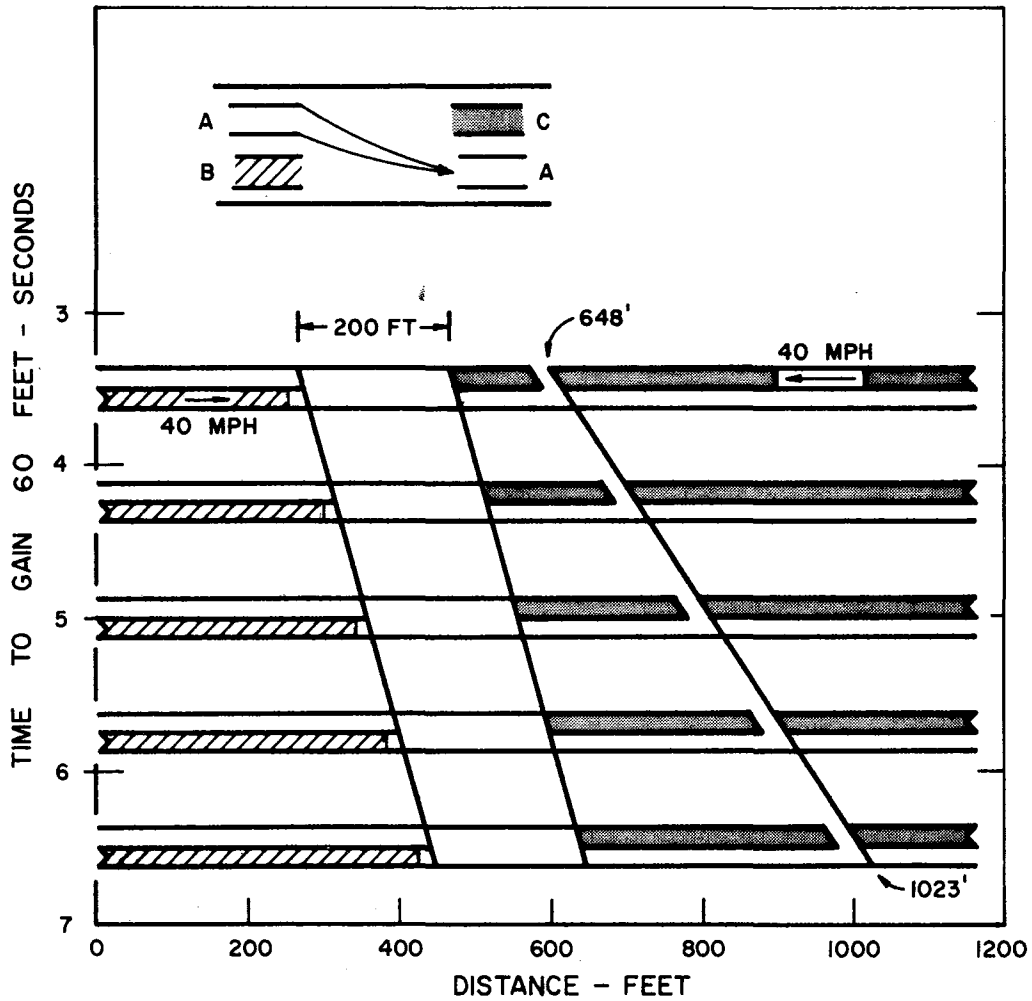


Figure 14. Range of Passing Distance from a 40-mph Start for 1959 Domestic Passenger Cars, Stonex (9).

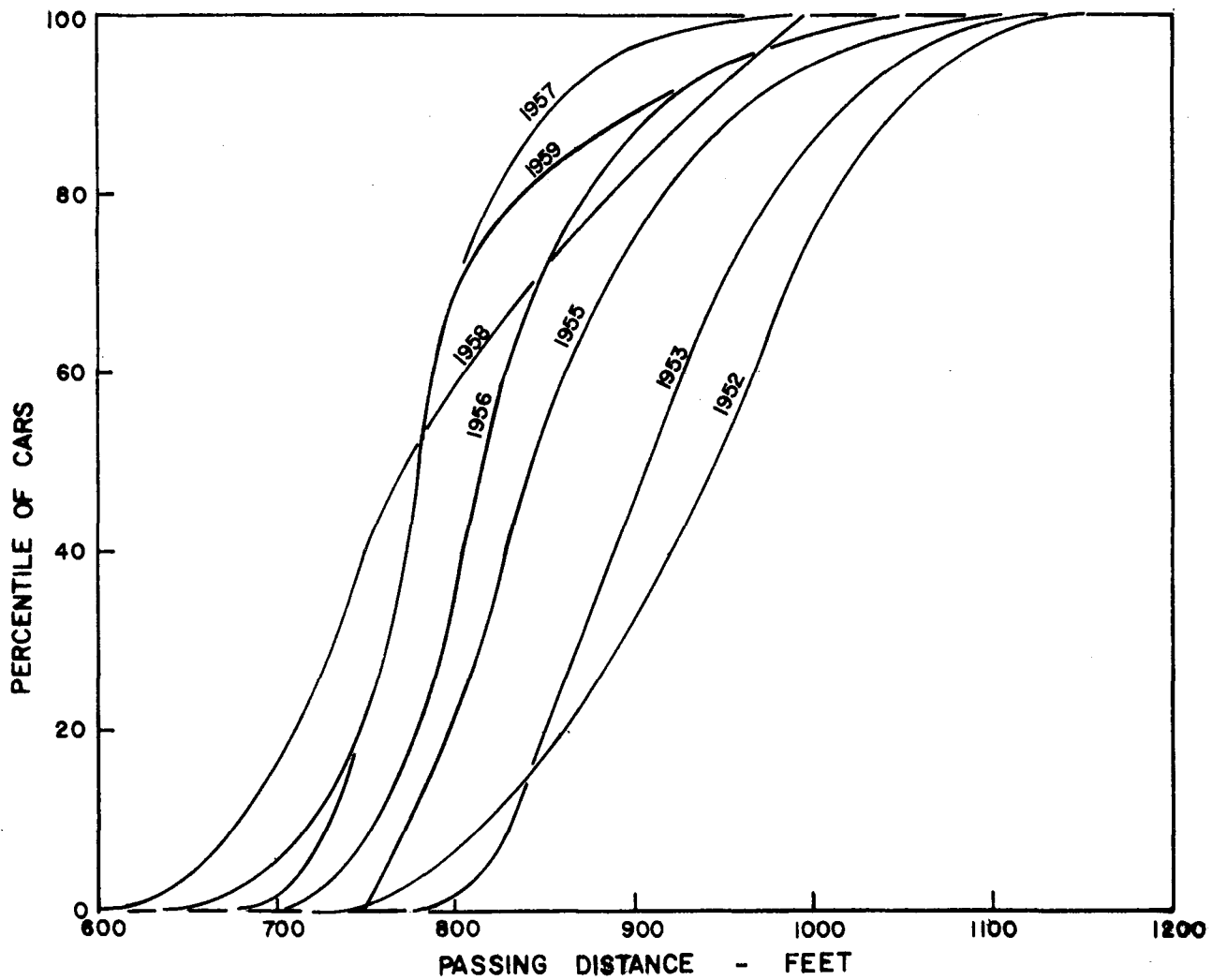


Figure 15. Percentile Distribution of Passing Distance from a 40-mph Start for Successive Model Years from 1952 to 1959, Stonex (9).

a minimum passing distance of 600 feet, a maximum distance of 1,050 feet, and a median distance of 775 feet for 1959 model vehicles.

A steady decrease in median passing distance until 1957 is revealed in Figure 15. Stonex anticipated that the median passing distance would remain near the 1957 value because the passing distances required by economy cars were generally greater than those of the larger higher-powered cars, thus somewhat offsetting the general decrease in median passing distances.

EVALUATION OF PASSING SIGHT DISTANCE DESIGN CRITERIA

Although extensive research has been conducted on the various aspects of the passing maneuver, only small segments of it have been applied directly to improving or validating design policy for current conditions. It was stated previously in this report that the current AASHO Policy is based primarily on studies conducted between 1938 and 1941. Therefore, an evaluation of current policy is in truth an evaluation of the assumptions which were formulated from the results of these studies. The fact that the numerous studies on driver judgment and decision processes have not yet been applied directly to the design criteria should not be interpreted to mean that the state of the art has remained dormant for nearly 30 years. This is not so. The revision of the AASHO Policy in 1965 to incorporate a driver eye height of 3.75 feet as a basis for measuring sight distance is one example. Only through increased knowledge of driver performance and vehicle characteristics can the design criteria be modified to reflect changing characteristics, thus providing safer highways.

To evaluate the current design criteria, the assumptions upon which the AASHO Policy is based (see Section I) were examined and are discussed in this section. It is emphasized that the criteria are evaluated from a safety aspect. The fact that passing sight distances provided under current standards have produced adequate distances in which to physically perform a passing maneuver does not necessarily mean that these distances represent safe distances for modern traffic conditions. It is further emphasized that many of the values used to compute passing sight distances under current policy are average values determined from observation of approximately 20,000 passing maneuvers performed on the highway. Extensive research on driver judgment conducted since

1938 has provided substantial evidence that "average" drivers are notoriously poor in judging speeds of oncoming vehicles, closure speeds between lead vehicles or approaching vehicles, and time of distance required to perform a safe passing maneuver.

10-mph Speed Differential

Current AASHO Policy assumes that the passing vehicle travels 10 mph faster than the passed vehicle. This 10-mph speed differential is used for all speed range groups (see Table 2). Table 4 indicates that this assumption is valid for approximately 51 percent of the drivers observed in the 1938-41 study, and is especially valid for vehicle speeds in the 31-40 mph speed group. However, Table 4 also indicates that, as the speed of the passed vehicle is increased, the speed differential between the passing and passed vehicles is greatly reduced.

As highway design speeds were raised, it became necessary to extend passing sight distance standards to reflect the higher speed groups. The data from the 1938-41 study provided time/distance relations for speed groups only up to 50-60 mph. Therefore, the 60-70 mph speed group data were extrapolated. However, the assumed 10-mph speed differential between passing and passed vehicle was maintained for the higher speed group although the average acceleration rate was increased to 1.50 mphps (see Table 1). The extrapolation of passing sight distance criteria yields a linear relationship with respect to passed vehicle speed. The studies by Gordon and Mast revealed that as speed increased, passing distance also increased but at an increasing rate. Therefore, the sight distance standards presented for the higher speed groups are questionable without objective documentation of high-speed passing maneuvers under highway conditions.

Assumed Speeds for Design

The AASHO Policy states that it is unrealistic to assume travel at full design speed. Therefore "assumed" speeds are used in determination of passing sight distance. The speeds of the passed vehicle are assumed to be the average running speed at a traffic volume near design capacity as represented by the curve for "intermediate" volumes in Figure 2 of this report. The AASHO Policy stated that this curve was developed from field data which related average spot speed to the design speed on horizontal curves, but no documentation of these data could be found by the research staff. There is one obvious fallacy in using these assumed speeds: passing maneuvers are normally performed on level tangent sections, not on horizontal curves.

Table 2 indicates that the passed vehicle assumed speed is 4 mph less than design speed for a 30 mph design and for a 70 mph design, it is 16 mph less. Passing vehicle speed is assumed to be 10 mph greater than that of the passed vehicle. Therefore, for a design speed of 70 mph, passing sight distance is computed on a 54 mph speed for the passed vehicle and 64 mph speed for the passing vehicle. This does not necessarily represent the critical speed combination from a safety viewpoint. Consider the driver who wishes to travel at 70 mph but to do so must pass a vehicle which is traveling at 65 mph. Passing sight distances under current policy may be inadequate for this circumstance although it is a logical occurrence. Speed surveys conducted on Texas highways in 1968 (1), for example, revealed that 85th percentile day operations speeds either approached or exceeded posted speeds. The Statewide speed limit throughout most of Texas is 70 mph for day operations on main rural highways. Posted speed on many existing two-lane highways equals or exceeds the speed for which they were originally designed. However, when many drivers wish to travel at

speeds approaching the posted speed, it is apparent that passing maneuvers are being performed at speeds equal to or higher than posted speeds. When this occurs, margins of safety decrease greatly. These facts, coupled with the decrease in speed differential between passing and passed vehicle as speed increases, can create dangerously short passing sight distance for the higher speed passes under the current policy. Further study on high-speed passing maneuvers is required before this potentially critical situation can be fully evaluated.

Clearance Distance

Examination of clearance lengths under current policy indicates that the distances specified in Table 2 are extremely short. Under the assumption that an opposing vehicle is traveling at the same speed as the passing vehicle, the travel time for the specified clearance lengths ranges from slightly under 1 second (30-40 mph speed group) to approximately 1.7 seconds (60-70 mph speed group). These clearance times appear to be shorter than those required for safety, especially in the higher passing speed groups because studies have shown that drivers are unable to discriminate even grossly different oncoming vehicle speeds.

Object Height for Passing Sight Distance

Current design policy specifies driver eye height and object height to be 3.75 feet and 4.5 feet, respectively. The driver eye height specification was changed from 4.5 feet to the current height in the 1965 revision of AASHO Policy. The reduction in height was made based on studies in which measurements of driver eye height and vehicle height were measured.

The current policy states that the object which must be seen when performing a passing maneuver is another vehicle of at least the height of a passenger car. The top of a current passenger car is approximately 4.5 feet above the pavement. Stonex (19) anticipated that the minimum height of volume-production passenger cars would not become less than 52 or 53 inches. The selection of the "top" of the vehicle as the governing dimension for sight distance is open to question. As vehicle rooflines (that portion above the windshield) are slimmed, driver perception of the top of an opposing vehicle as it appears over a crest vertical curve becomes increasingly more difficult. A compromise in object height between that of the headlights and the top of the vehicle would represent a height which provides a safer passing distance and also improves the safety margin with respect to visibility of smaller vehicles. A comparison of Figure 16 (based on eye and object heights of 3.75 feet) and Figure 3 indicates that lowering the object height criteria to 3.75 feet would increase design sight distances approximately ten percent for the longer vertical curves.

Striping Practices for No-Passing Zones

In striping a highway to restrict passing of vehicles where sight distance is inadequate, the current practice in choosing factors is totally different from that in choosing factors for design of the highway. Highways are striped for no-passing zones according to the specifications set forth in the Manual on Uniform Traffic Control Devices for Streets and Highways (22). The minimum sight distances on which no-passing zones are based are presented in the 1961 MUTCD as follows:

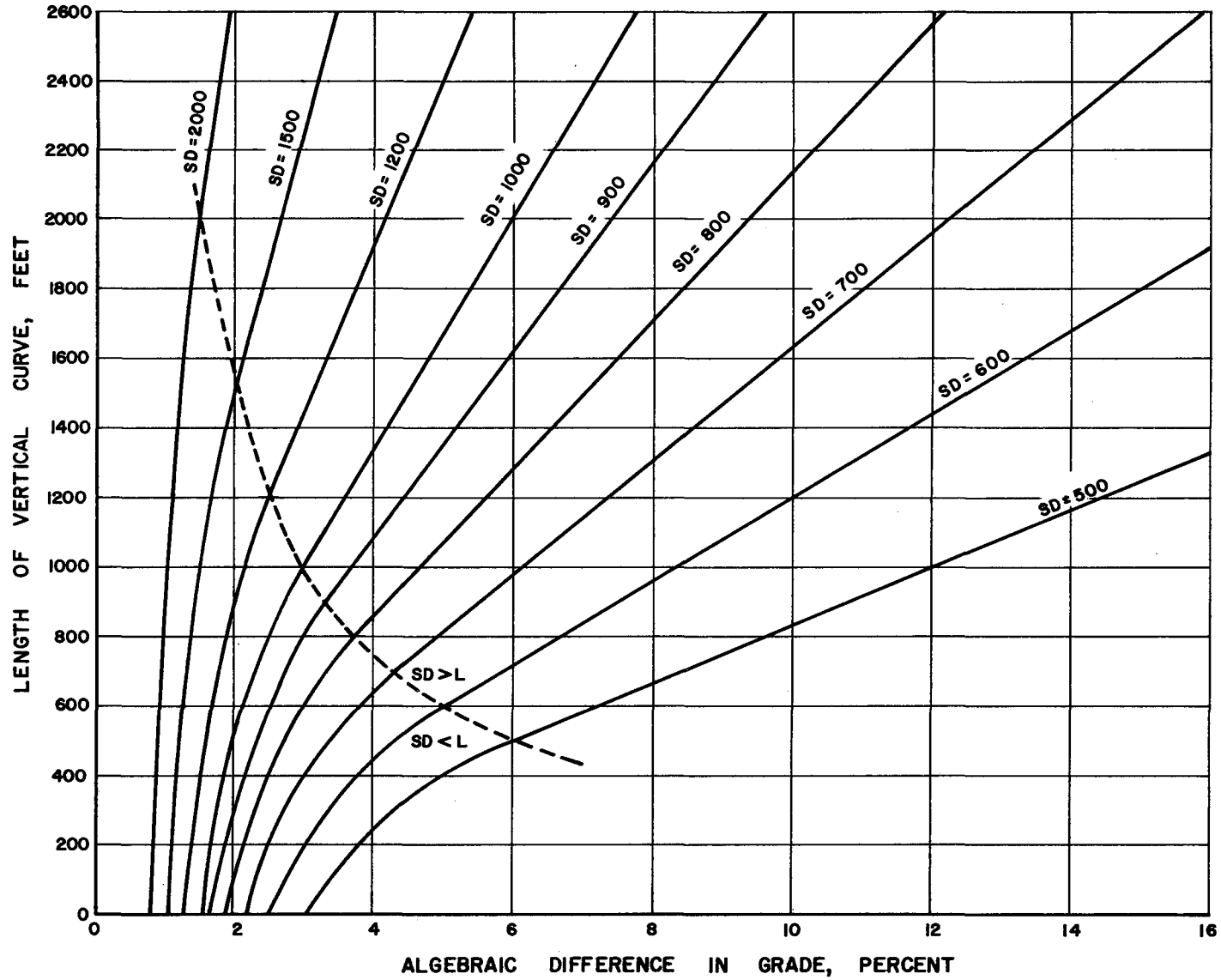


Figure 16. Passing Sight Distance Chart Based on Eye Height of 3.75 Feet and Vehicle Height of 3.75 Feet.

85-Percentile Speed (mph)	Minimum Sight Distance (feet)
30	500
40	600
50	800
60	1,000
70	1,200

The 1961 MUTCD states that a no-passing zone at a horizontal or vertical curve is warranted where the sight distance is less than the minimum necessary for safe passing at the prevailing speed of traffic. Sight distance on a vertical curve is defined as the distance at which an object 4 feet above the pavement surface can just be seen from another point 4 feet above the pavement. Sight distance on a horizontal curve is the distance measured along the center line between two points 4 feet above the pavement on a line tangent to the embankment or other obstacle that cuts off the view on the inside of the curve.

The reasoning for selecting the minimum sight distances above is not stated in the 1961 MUTCD nor is the source of data given. However, it is interesting to note that the distances are identical with those presented in the 1940 AASHO Policy on Criteria for Marking and Signing No-Passing Zones of Two and Three Lane Roads (23). The 1940 AASHO Policy outlined the basic assumptions by which striping practice was established. It stated that if a highway were striped in accordance with distances used in design (based on the delayed passing of a vehicle traveling 10 mph less than the assumed design speed of the highway in the face of opposing traffic traveling at the assumed design speed), passing would be restricted when it could frequently be accomplished with safety under one or more of the following conditions:

- (1) The passing vehicle may not be delayed or slowed down to the speed of the overtaken vehicle. If the opposing lane is clear, the overtaking vehicle may pass at a higher speed, thus reducing time and distance to pass.
- (2) The overtaken vehicle may be traveling at a speed slower than 10 mph less than the assumed design speed of the highway. The average speed of travel, particularly on the 60- and 70-mph highways is slower than 10 mph less than the assumed design speed, and overtaken vehicles are likely to be traveling at speeds less than average.
- (3) The opposing vehicle which appears after the passing maneuver has begun may be traveling slower than the assumed design speed of the highway. It is more likely to be traveling at the average speed.

The policy stated that the minimum sight distance on which to base restrictive striping should therefore be a compromise distance based on a passing maneuver such that the frequency of maneuvers requiring shorter sight distances was not great enough to seriously impair the usefulness of the highway. The minimum striping sight distances and corresponding assumed design speeds presented in the 1940 Policy appear to have been unchanged since then. The distances stated in the 1940 Policy were based on a driver eye height and top-of-vehicle height of 4.5 feet above the pavement surface.

The fact that current striping criteria are identical to those established in the 1940 AASHO Policy is somewhat disconcerting when viewed from a safety viewpoint since these criteria excluded perception distance, did not include a clearance interval, and used lower overtaking and opposing speeds. It is suggested that the striping distances specified in the MUTCD require detailed evaluation to validate the criteria for current design and operating conditions.

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