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**PASSING PERFORMANCE
MEASUREMENTS RELATED TO
SIGHT DISTANCE DESIGN**

in cooperation with the
Department of Transportation
Federal Highway Administration

**RESEARCH REPORT 134-6
STUDY 2-8-68-134
HIGHWAY DESIGN CRITERIA**

PASSING PERFORMANCE MEASUREMENTS
RELATED TO SIGHT DISTANCE DESIGN

by

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Research Report 134-6

Highway Design Criteria
Research Study Number 2-8-68-134

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FOREWORD

The study reported here represents one phase of Research Study No. 2-8-68-134 entitled "An Examination of the Basic Design Criteria as They Relate to Safe Operation on Modern High Speed Highways."

Other active phases of this research are; (1) a field study of the degree of path taken in negotiating horizontal curves, (2) a field study of the degree of path taken in high-speed passing maneuvers, and (3) an evaluation of vehicle paths as a basis for wet weather speed limits.

This is the sixth project report. Other reports in this research project are:

Research Report 134-1, "The Passing Maneuver as it Relates to Passing Sight Distance Standards"

Research Report 134-2, "Re-Evaluation of Truck Climbing Characteristics for Use in Geometric Design"

Research Report 134-3, "Evaluation of Stopping Sight Distance Design Criteria"

Research Report 134-4, "State-of-the-Art Related to Safety Criteria for Highway Curve Design"

Research Report 134-5, "The Relationship of Vehicle Paths to Highway Curve Design"

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 the Federal Highway Administration.

ABSTRACT

This report presents a proposed passing sight distance design concept to integrate design and striping based on the safety, operational and legal aspects of the passing maneuver. Passing maneuvers under actual highway operating conditions were photographed and analyzed to determine operational characteristics during high-speed passing maneuvers.

Minimum passing sight distances and desirable lengths of passing zones are recommended. New applications of the proposed design concept that considers both the required sight distance and zone length are discussed.

SUMMARY

This report describes field studies to investigate high-speed passing maneuvers under highway conditions. The specific goals were: to examine passing behavior on rural two-lane highways; to correlate study parameters with the various passing sight distance design criteria in use; and to develop, where appropriate, passing sight distance design standards compatible with current operating conditions. Of primary concern were passing maneuvers on highways with operating speeds of 50 to 80 mph.

The current standards for design and striping are critically evaluated with particular emphasis given to the inequities between design and operations. From this evaluation, and based on the operating characteristics of the passing maneuvers observed in the field studies, a new concept is presented that integrates design and striping to accommodate the safety and operational aspects of the passing maneuver.

DESIGN AND STRIPING PRACTICES EVALUATED

Current standards for designing passing sight distance and for striping rural two-lane highways to restrict passing are based on different criteria. Passing sight distance is designed using "A Policy on Geometric Design of Rural Highways", whereas no-passing zones are set using the "Manual on Uniform Traffic Control Devices for Streets and Highways." Unfortunately, the striping operation is done "after the fact." That is, the no-passing zones are determined after the highway is constructed, when alignment changes are economically unfeasible.

In a sense, design and operations cannot be separated because the design is planning for the operations. The interaction between driver, vehicle, and roadway is complex. Designing to accommodate the driver in this interrelated system is difficult because of no "allowable stress" values for humans. Nor can a driver's response to a particular stimulus be predicted with the accuracy of that of a beam to a load, a pavement to load repetition, or other phenomena where the laws of physics apply. Therefore, many aspects of highway design must be based on statistical evaluation of operational history.

Changes in operating characteristics due to improved vehicles and highways affect the basis of highway design. These changes do not alter the design goals -- efficiency, safety, economy, and convenience -- but they do alter the interfaces in satisfying these goals. To provide the driver with a safe highway, and equally important, the sense of security he enjoys by believing the highway is safe, two things can be done. Either geometric design must be flexible enough to reflect these changes, or the design approach must consider and provide for all aspects of intended operations.

The passing maneuver is one of the most hazardous operations on a two-lane highway. The performance of this maneuver is one of the few conditions where a driver may legally operate in the left lane of a two-lane highway, and in so doing, create a potential head-on collision. Yet provisions must be made so faster vehicles may safely pass slower vehicles, if efficient highway operations are to be maintained.

To provide the passing driver adequate sight distance and passing distance, the elements comprising the maneuver must be assessed from a safety viewpoint, and the critical elements combined in a compatible design. What is the critical condition in a passing maneuver - a completed pass or an aborted pass? What distances are traveled during the perception-reaction time, while the passing vehicle occupies the left lane, or by an opposing vehicle? At what point in the maneuver does the passing driver need the greatest sight distance? What "design speed" should be used? The answers to these questions are the inputs for formulating safe passing sight distance design standards.

SIGHT DISTANCE REQUIREMENTS

Current design standards are based on studies conducted from 1938 to 1941. The minimum passing sight distances for two-lane highways were determined as the sum of four elements. From these studies of actual passing maneuvers on rural highways, distance values were established for the four elements of the maneuver - the perception-reaction distance, d_1 , and left-lane distance, d_2 , the clearance distance, d_3 , and the distance traveled by an opposing vehicle, d_4 .

Once he has started a passing maneuver, the driver has only two alternatives -- complete the maneuver, or abort the maneuver by returning to the right lane behind the vehicle he intended to pass. Assuming the passed vehicle maintains a constant speed, there is a point where the time to complete the maneuver is equal to the time to pull back. This critical condition occurs about when the two vehicles are abreast. At

this position the driver is forced to make a decision that affects the safety of the remaining portion of the maneuver.

The objective of passing sight distance design is to provide passing zones where maneuvers may be safely completed rather than aborted. Therefore, the critical completion distance is one of the elements to be included in the design. The distance required to complete the maneuver from the critical position is about $2/3 d_2$. If the speed of the opposing vehicle and the passing vehicle are equal, the opposing vehicle also travels $2/3 d_2$. Including an adequate clearance distance, d_3 , the minimum sight distance required for safe operations is $4/3 d_2 + d_3$.

The hazard associated with the passing maneuver arises when there is insufficient distance to complete the maneuver if an opposing vehicle is perceived at the critical position. The critical position can occur anywhere throughout the passing zone. To provide a safe "recovery zone" for the passing driver who faces the critical condition at the end of a passing zone, the minimum sight distance, $4/3 d_2 + d_3$, must be provided throughout the passing zone. This philosophy approaches the long zone passing concept because it provides a safe recovery area in a no-passing zone, but does not encourage drivers to initiate a passing maneuver at the end of a passing zone. Under accepted enforcement practice, completion of the maneuver in the no-passing zone would be illegal, but this striping practice would reduce the head-on collision hazard.

DESIGN SPEED

A basic inequity between design and operations is that the assumed speeds used to establish the distance elements are lower than the

highway design speed. For design speeds greater than 50-mph, the passing speed is assumed less than the design speed, with this difference increasing as the design speed increases. Existing standards specify, for a 70-mph design speed, a passed vehicle speed of 54-mph and a passing speed of 64-mph. Interpreted literally, a 70-mph passing sight distance design is, in fact, a 64-mph design.

New stopping sight distances standards are determined assuming that the vehicle travels at the design speed. This approach is compatible with the "design" concept in engineering practice. Designing for the passing maneuver is more critical than stopping sight distance due to increasing speeds rather than decreasing speeds throughout the maneuver. In the passing maneuver, the passing driver is maintaining a relatively high speed or accelerating. Yet, in designing passing sight distance, the passing and passed vehicles are assumed to be traveling less than the design speed. The speed of the passed vehicle is assumed to be the average running speed at a traffic volume near design capacity, and the speed of the passing vehicle is assumed 10 mph greater.

Since the passing maneuver represents one of the most hazardous operations on a two-lane highway, it is logical, from a critical design standpoint, that the sight distance elements be determined on the basis of the passing vehicle traveling at design speed. Also, to place all elements of the maneuver on a common basis, it follows that the opposing vehicle also should be considered traveling at design speed.

PASSING ZONE LENGTHS

Passing sight distance design is determined on the basis of sight

distance between two vehicles approaching each other at opposite sides of a crest vertical curve. A much more common situation occurs when sight distance on one crest is limited by the next successive crest in rolling terrain. Often, the driver experiences a series of short passing zones through the sags and is immediately faced with a no-passing zone as he approaches each crest. No provision is made in the current design standards to prohibit this occurrence. These standards specify that certain sight distances be provided for particular design speeds, but do not specify the length through which this sight distance must be made available. In other words, a section of highway could be designed for the required sight distance at the crest of a vertical curve, and very shortly thereafter the available sight distance could decrease to less than the design requirement.

Presently, the length of passing zones or the minimum distance between successive no-passing zones is specified as 400 feet in the MUTCD. This distance is not sufficient for modern high-speed passing maneuvers.

A desirable minimum length of passing zone for operations includes the perception-reaction distance, d_1 , and the left lane distance, d_2 . If the maneuver is initiated at the beginning of the zone, this distance permits the passing driver to abort the maneuver if an opposing vehicle is perceived at or before the critical position. This length also permits the completion of a maneuver within the passing zone if the opposing vehicle is perceived after reaching the critical position. If the critical distance elements are used, 85 percent of the desired passes

that do not have an opposing vehicle in view may be completed within the zone if the maneuver is started near the beginning of the zone.

FIELD STUDIES

A movie camera mounted in an observation box on the bed of a pickup truck was used to photograph passing maneuvers at three study sites. Passing situations were created with an impeding vehicle traveling at a predetermined speed.

The observation vehicle moved in behind a subject vehicle as it passed, about two miles upstream from the study site. As these two vehicles approached, the impeding vehicle, stationed on the shoulder near the beginning of the no-passing zone preceding the study site, moved out and impeded the subject vehicle. Filming was initiated as the three vehicles reached the study site.

Approximately 3000 subjects were tested. Of this number, about 500 completed passing maneuvers were filmed. Impeding speeds were 50, 55, 60, and 65 mph.

Each study site was marked with stripes placed perpendicular to the centerline at 40-foot intervals. This reference system allowed the determination of the speed and distance elements of the passing maneuver by analyzing the film on a Vanguard Motion Analyzer.

Cumulative percentiles of measured speed differentials were plotted for each impeding speed. The 15th percentile was selected as the critical condition. This critical differential was found to decrease as impeding speed increased, ranging from about an 11-mph differential at 50 mph to a 7-mph differential at 65 mph.

Twelve best-fit relationships were obtained by plotting passing speed against the distance elements d_1 , d_2 , and d_4 for each of the four impeding speeds. The relationships between each of these distance elements and design speed were then obtained by a best-fit plot through the four points representing the distance element at the passing speed equal to the impeding speed plus the speed differential. The relationships established between these distance elements and design speed were found to be similar to those used in current passing sight distance standards.

IMPLEMENTATION

Table S-1 presents the proposed passing sight distance and passing zone length standards for designing and striping passing zones. These values are based on the analysis of the field measurements using the proposed design concept.

Examination of the proposed standards in Table S-1 reveals several important factors to be considered in passing sight distance design. For every design speed, the passing sight distance at the beginning of the zone exceeds the current AASHO standard. To determine the available sight distance at the beginning of a zone, the end of the passing zone is established by finding the point on the profile where sight distance is limited to $4/3d_2 + d_3$; then the beginning of the passing zone is located upstream from this point a distance equal to or greater than the minimum passing zone length of $d_1 + d_2$. The sight distance at the beginning of the zone must, therefore, be at least the sum of these two distances, or $d_1 + 2.33d_2 + d_3$.

TABLE S-1

PROPOSED STANDARD FOR DESIGN
AND STRIPING PASSING ZONES

Design Speed (mph)	Minimum Sight Distance Throughout Zone (ft)	Minimum Sight Distance at Beginning of Zone (ft)	Desirable Minimum Length of Passing Zone (ft)
50	1135	2020	885
60	1480	2665	1185
65	1655	2990	1335
70	1825	3310	1485
75	2000	3635	1785
80	2170	3955	1935

Using the 70-mph design speed to illustrate, another design consideration is revealed in Table S-1. If the spacing between successive crests is greater than 3310 feet, adequate sight distance and passing zone length are automatically provided in the sag. If, however, the distance is slightly less than 3310 feet, and neither crest affords 1825 feet of sight distance, an adequate passing zone does not exist. In this case, a passing zone can be provided by minor adjustments to the grade lines.

Historically, vertical profiles have been established by the economic considerations of earthwork. Although the balance of cut and fill is important in establishing profile, it is possible that a substantial improvement in traffic efficiency may be attained by minor adjustments in grade. Flattening grade lines in a sag, in effect, moves both crests outward.

From these considerations, proper passing sight distance in gently rolling terrain is clearly influenced by profile establishment. Computer programs are used widely to establish profile. It is suggested that cost-effectiveness techniques can be incorporated to determine the benefits derived from grade adjustments for reasons other than earthwork balance.

Another consideration in design is the determination of optimum lengths of passing zones. Limited studies have indicated that utilization is very low for passing zones shorter than about 900 feet based on the current MUTCD standard of 1200 feet sight distance. Obviously, there exists a passing zone length that many drivers will

consider inadequate for the performance of a safe passing maneuver. If the acceptable length is greater than the design minimum, there would be little utilization of the zone, and its presence on the facility would not contribute to operational efficiency. Additional research is obviously warranted to provide the necessary data for cost-effectiveness evaluations.

ACKNOWLEDGMENTS

Too often, there is a tendency by the reader, and many times by the researchers, consciously or subconsciously, to give 100 percent of the credit (or blame) for the research to the author of the published document. The report represents to many the only tangible evidence of the research, and associated with this are the authors, either by personal knowledge or by name only.

It should go without saying that any study such as the one reported here represents the cooperative efforts of many. However, to give due credit to several "silent partners" who provided assistance and advice throughout this study, the authors express here their appreciation.

These include in particular, two men with the Texas Highway Department. Mr. Jack Housworth, project contact man, assisted in liaison and communications problems. Mr. Jim O'Connell, Maintenance Engineer, District 17, provided valuable assistance in site selection, and cleared red tape for the calibration of the study sites and actual conduct of the tests.

Two graduate students were instrumental in assuring completion of the study; Mr. J. R. Jones who coordinated the field measurement activities, and Mr. A. R. Luedecke, Jr. who developed the computer programs for data reduction and correlation.

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I. INTRODUCTION

Current standards for designing passing sight distance and for striping a rural two-lane highway to restrict passing are based on different criteria. Passing sight distance is designed using "A Policy on Geometric Design of Rural Highways" (1), whereas no-passing zones are established using the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD, 2). Unfortunately, the striping operation is generally done "after the fact." That is, the no-passing zones are actually determined after the highway has been constructed, when alignment changes are economically unfeasible. A more compatible sequence would include a design and striping concept that integrates safety, operations, and legality.

A state-of-the-art evaluation (3) indicated that current standards do not provide adequate factors of safety for operational characteristics found on modern high-speed highways. Examination of the state-of-the-art and practice revealed several questional features of the criteria.

1. Many of the values used in establishing passing sight distance standards are based solely on studies conducted between 1938 and 1941. Although the state of knowledge concerning highway design, driver operating characteristics and safety requirements has expanded, these criteria have remained virtually unchanged.
2. Use of assumed speeds somewhat lower than the highway design speed does not represent the critical passing situation under current high-speed operating conditions.
3. Use of the 10-mph speed differential between passing and passed vehicle to extrapolate passing sight distances for the higher speed groups may not be applicable to current passing characteristics.

4. Current striping specifications for no-passing zones are identical to those outlined in the 1940 AASHO Policy. Striping practices established for the 1940 operating conditions are highly questionable for current highway operation. Most importantly, there appears to be a definite lack of correspondence between design and operations.

This report describes field studies to investigate high-speed passing maneuvers under highway conditions. The specific goal was to examine passing behavior on rural two-lane highways; correlate study parameters with the various passing sight distance design criteria in use; and develop, where appropriate, passing sight distance design criteria that are compatible with current operating conditions. Of primary concern were passing maneuvers on highways with operating speeds in the 50 to 80 mph range.

The current standards for design and striping are critically evaluated with particular emphasis given to the inequities between design and operations. From this evaluation, and based on the operating characteristics of the passing maneuvers observed in the field study, a new concept is presented that integrates design and striping to accommodate safety, operational, and legal aspects.

II. CURRENT PRACTICE

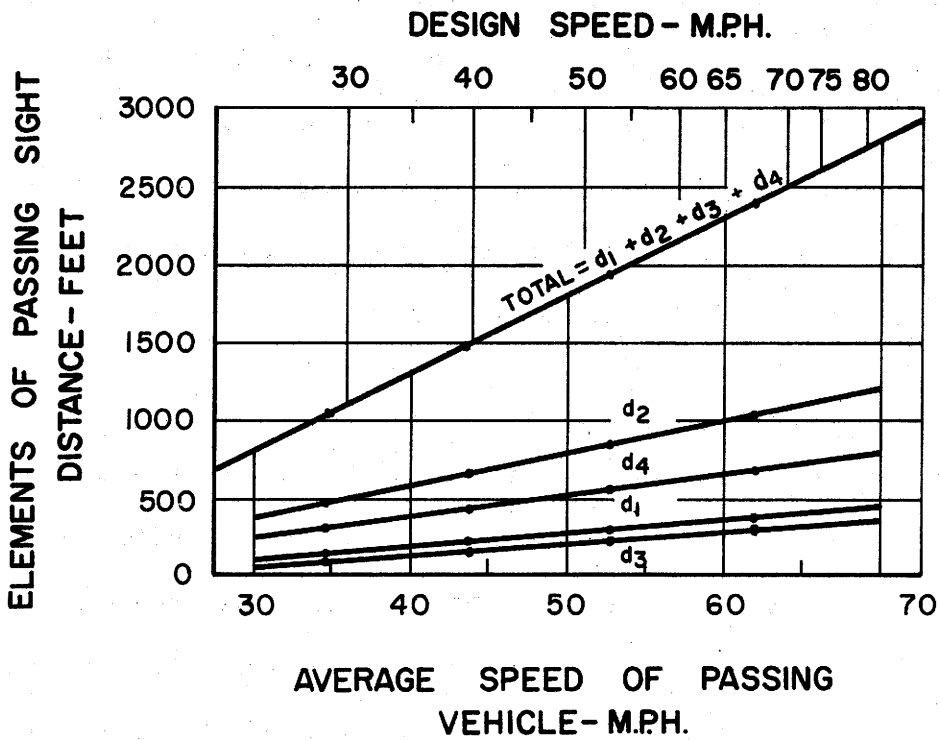
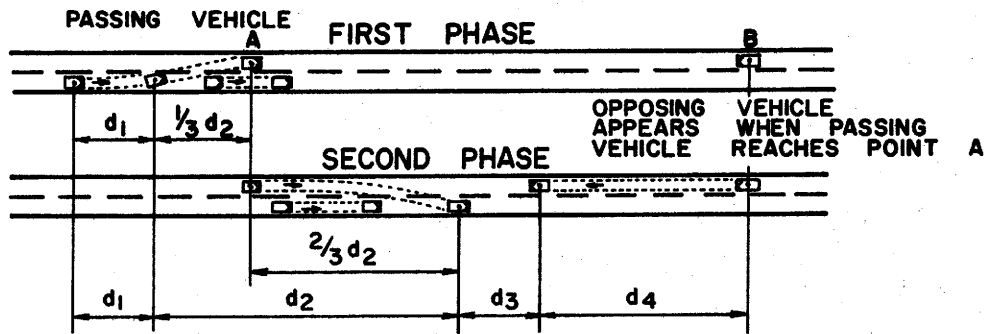
Current standards for designing passing sight distance and for striping a rural two-lane highway to restrict passing are based on different criteria. Passing sight distance is designed using "A Policy on Geometric Design of Rural Highways" (1), whereas no-passing zones are established using the "Manual on Uniform Traffic Control Devices for Streets and Highways." (2) Unfortunately, the striping operation is done "after the fact." That is, the no-passing zones are actually determined after the highway has been constructed when alignment and profile changes are economically unfeasible.

DESIGN STANDARDS

Current design standards are based primarily on the results of field studies conducted from 1938 to 1941. From these studies of actual passing maneuvers on rural highways, certain distance values were established for the four elements of the maneuver - the perception and reaction distance, d_1 , the left-lane distance, d_2 , the clearance distance, d_3 , and the distance traveled by an approaching vehicle, d_4 . The elements of passing sight distance are shown in Figure 1. The minimum passing sight distance for two-lane highways is determined as the sum of the four elements.

DESIGN CRITERIA

The current AASHO design criteria for computing minimum passing sight distance are based on certain assumptions for traffic behavior.



AASHO passing sight distance criterion curves (1)

Figure 1

These are outlined below: (1)

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 passing driver requires a short time to perceive the clear passing section and react in starting 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 opposing lane.

While some of these assumptions are valid for current high-speed operations, an examination of the state-of-the-art indicated that criteria based on these assumptions do not provide adequate safety factors for modern high-speed facilities. The above assumptions represent a logical basis to analyze and design for the passing maneuver. Several inequities exist between design and actual designation of passing (or no-passing) zones. No provision exists to establish a length over which the design passing sight distance must be made available to the passing driver. Assumed speeds considerably lower than design speed are used in design. The speed differential between the passing and passed vehicle is assumed to remain constant for all maneuver speeds.

PASSING ZONE LENGTH

Passing sight distance for design is determined on the basis of sight distance between two vehicles approaching each other on opposite

slopes of one crest vertical curve. Obviously this represents a critical condition, and should be considered when sight distance is limited only by an occasional crest vertical curve in generally flat terrain. A much more common situation occurs when sight distance on one crest is limited by the next successive crest in rolling terrain. Often the driver experiences a series of short passing zones through the sags and is immediately faced with a no-passing zone as he approaches each crest. No provision is made in the current design standards to prohibit this occurrence. Design standards specify that certain sight distances be provided for particular design speeds, but the standards do not specify the actual length through which this sight distance must be made available. In other words, a section of highway could be designed to provide the required sight distance at the crest of a vertical curve, and very shortly thereafter the available sight distance might decrease to less than the design requirement. Although this is undesirable from an operations aspect, it is allowable with present design standards.

There is a distinct difference between passing sight distance and passing zone length. Presently, the length of passing zones or the minimum distance between successive no-passing zones is specified in the MUTCD as 400 feet. This does not represent a distance suitable for modern high-speed passing maneuvers (4).

ASSUMED SPEEDS

A second basic inequity between design and operations lies in the use of assumed speeds lower than the highway design speed under current design standards. For design speeds of 50-mph and less, the passing

vehicle is assumed to be traveling at a speed in excess of the design speed. For design speeds greater than 50-mph, the passing speed is assumed to be less than the design speed with this difference increasing as the design speed increases. Existing standards specify for a 70-mph design speed, a passed vehicle speed of 54-mph and a passing speed of 64-mph. Interpreted literally, this would indicate that, a 70-mph design passing sight distance design is, in fact, a 64-mph design.

In most engineering fields, the term "design value" connotes "critical value," or the most severe situation that can reasonably be expected to occur in operation. In structural design, the design loads represent the critical expected combination of live and dead loads. Suitable safety factors are then applied.

Minimum stopping distances on dry pavement are determined assuming the vehicle to be traveling at the design speed. This approach is compatible with the "design" concept in engineering practice. Designing for the passing maneuver is more critical than stopping distance design due to increasing speeds rather than decreasing speeds throughout the maneuver. In the passing maneuver, the passing driver is maintaining a relatively high speed or accelerating. Yet, in designing passing sight distance, the passing and passed vehicles are assumed to be traveling less than the design speed. The speed of the passed vehicle has been assumed to be the average running speed at a traffic volume near design capability, and the speed of the passing vehicle is assumed 10 mph greater.

Historically, highways have been designed for speeds greater than the initially planned posted speed. Therefore, drivers obeying the posted speed limit were considered to be operating safely. As speed limits were increased, considerable modifications to alignment and profile were required to provide safety for the higher operating speeds that accompanied the increase. The concept of designing highways for greater than existing speed limits can be argued pro and con, particularly for the lower design speed highways which normally carry low volume traffic. The difference between design speed and assumed speed is not nearly so critical for the lower design speeds as it is for the design speeds in excess of 60 mph. Use of assumed speeds somewhat lower than the highway design speed becomes more incompatible with current operating speeds for the higher speed passing maneuvers. Studies (5) conducted in 1968, indicated that the average 85th percentile speed on all major highways in Texas was 70 mph and the 15th percentile speed was 54 mph. It is interesting to note that the assumed passed vehicle speed for current 70 mph sight distance design corresponds to only the 15th percentile operating speed.

The important point is that drivers on modern rural highways tend to establish their own "safe" speed. This speed is limited to the posted speed only by the threat of a citation for excessive speed. The speed limit for many rural two-lane highways throughout the country is 70 mph. Glennon (6) concluded that under the present driver-vehicle-roadway configuration, operating speeds above 70 mph are not desirable. He further concluded that until geometric design criteria can be

established on an objective basis and integrated into a systematic approach, the use of a design speed that is 10 mph greater than the planned operating speed is recommended.

It is apparent from the 1968 speed study (5) that many passing maneuvers are being performed at speeds greater than 70 mph if the 10-mph speed differential between passing and passed vehicle is valid. Under current passing sight distance standards, the minimum design speed to permit safe operations would be 80 mph. This would also agree with Glennon's conclusions assuming that posted speed limit was 70 mph. Under current standards, design speeds of 75 and 80 mph are applicable only to highways with full control of access or where such control is planned in the future. Therefore, it would appear that the assumed speeds for "design speed" are not compatible with operating speeds. A design approach using the passing vehicle speed as design speed is discussed in the following section of this report.

STRIPING STANDARDS

The 1971 MUTCD specifies that a vertical or horizontal curve shall warrant a no-passing zone and shall be so marked where the sight distance is equal to or less than that listed in Table 1 for the prevailing (offpeak) 85th-percentile speed. Sight distance on a vertical curve is defined as the distance at which an opposing vehicle 3.75 feet above the pavement surface can just be seen by a passing driver 3.75 feet above the pavement.

The reasoning for selecting these minimum sight distances is not stated in the MUTCD, nor is the source given. However, MUTCD distances

TABLE 1
MINIMUM SIGHT DISTANCES FOR
STRIPING NO-PASSING ZONES

<u>85th Percentile Speed (mph)</u>	<u>1971 MUTCD Distance (ft)</u>
30	500
40	600
50	800
60	1000
70	1200

are identical to those presented in the 1940 AASHO publication, "A Policy on Criteria for Marking and Signing No-Passing Zones or Two- and Three Lane Roads" (7) which outlines the basic assumptions for establishing striping practice. The 1940 AASHO Policy 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 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 1940 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 distance and corresponding assumed design speeds presented in the 1940 AASHO Policy have been unchanged since then.

EXAMINATION OF STRIPING CRITERIA

Although it is desirable from a safety aspect to allow passing only when the design sight distance is available, it is realized that a passing maneuver can be safely performed under certain circumstances in a lesser distance. The 1940 AASHO Policy reasoning that the minimum passing sight distance should be a compromise is logical from an operational aspect. This minimum distance can be determined by analyzing the various distance elements in the passing maneuver and selecting the combination necessary for safe operations.

Of course the absolute minimum passing distance would be the length in which it is physically possible to execute a passing maneuver. This would be merely the left-lane distance, assuming no perception-reaction time (the driver crossed the center line at the end of the yellow stripe), and no clearance distance between the passing vehicle and an approaching vehicle. Obviously this would produce knife-edge design and would be unsafe in a majority of circumstances. The next best assumption would include some additional distance for perception-reaction and clearance distance.

Although not stated in the MUTCD, it appears that this type of reasoning may have formed the basis for selection of the minimum sight distance requirements shown in Table 1. The minimum distances for each

85th percentile speed can be approximated by summing the AASHO perception-reaction distance, d_1 , the left-lane distance, d_2 , and the clearance distance, d_3 , if the 85th percentile distance is assumed to be design speed as shown in Figure 1. In each case, however, the MUTCD minimum sight distance is less than the sum of these three distance elements.

III. CONCEPT FOR INTEGRATED DESIGN

In a sense, design and operations cannot be separated because the design is planning for the operations. The interaction between driver, vehicle, and roadway is complex. Designing to accommodate the driver in this interrelated system is made more difficult because there are no "allowable stress" values for humans. Nor can a driver's response to a particular stimulus be predicted with the accuracy of that of a beam to load, a pavement to load repetition, or other phenomena to which the laws of physics apply. Therefore many aspects of highway design must be based on statistical evaluation of operational history.

Changes in driver characteristics due to improved vehicles and highways affect the basis of highway design. These changes do not alter the design goals -- efficiency, safety, economy, convenience, capacity and others -- but they will alter the interfaces in satisfying these goals. To provide the driver with a safe highway, and equally important, the sense of security he enjoys by believing the highway to be safe under current operations, two things can be done. Either geometric design must be flexible enough to reflect these changes, or the design approach must consider and provide for all aspects of intended operations.

The passing maneuver is one of the most hazardous operations that a driver undertakes on a two-lane highway. The performance of this maneuver represents one of the few conditions where a driver may legally operate in the left lane of a two-lane highway, and in so

doing, create a potential head-on collision. Yet it is accepted that provisions must be made whereby faster vehicles may safely pass slower moving vehicles if efficient highway operations are to be maintained.

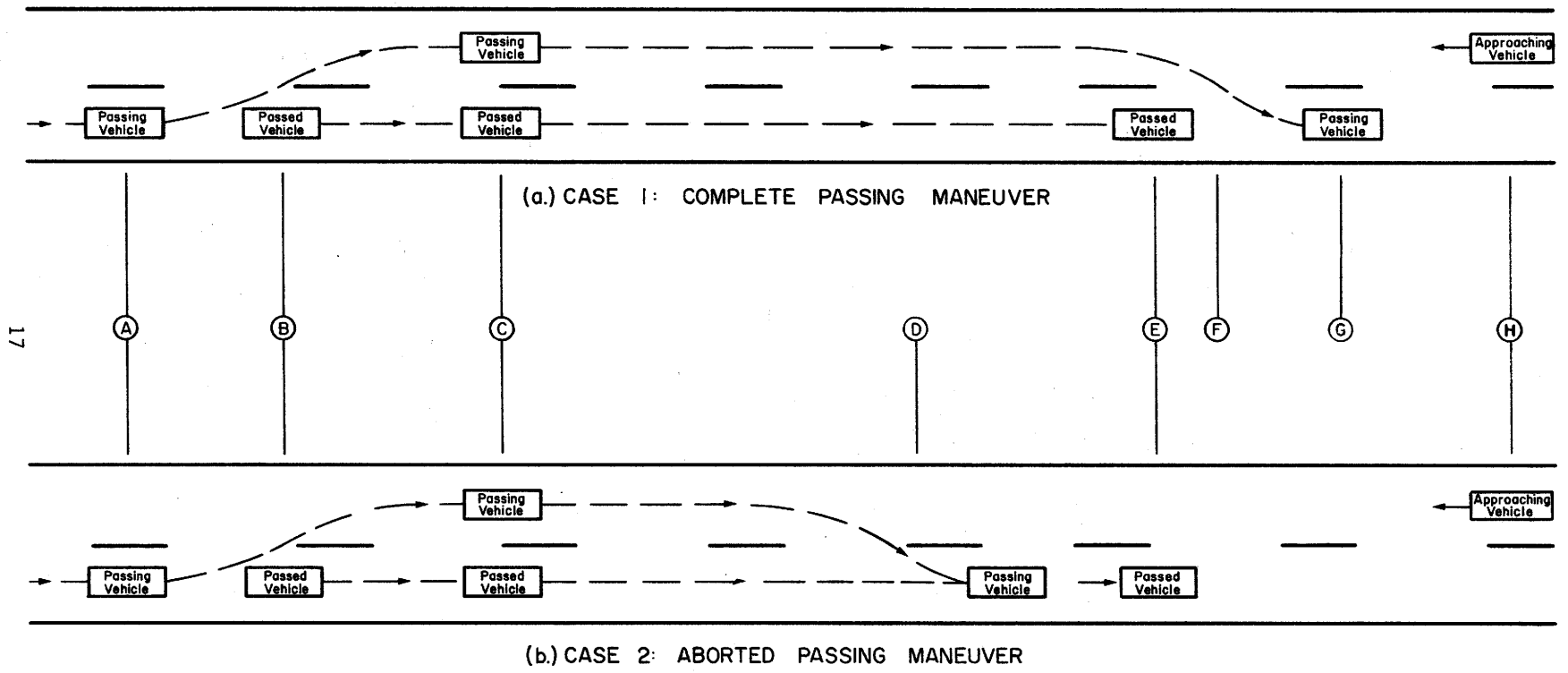
To provide the passing driver sufficient sight distance and passing distance in which to perform a safe passing maneuver, the elements comprising the maneuver must be assessed from a safety viewpoint, and the critical elements combined in a compatible design. What is the critical condition in a passing maneuver - a completed pass or an aborted pass? What distances are traveled during the perception-reaction time, while the passing vehicle occupies the left lane, or by an approaching vehicle? At what point during the maneuver does the passing driver require the greatest sight distance? What "design speed" should be considered? These questions and others represent the inputs in formulating a total design and a basis of evaluation for the current passing sight distance standards. The answers to these and other related questions will provide a safe design for passing sight distance.

Included in this section of the report is an evaluation of the passing maneuver from an operational aspect. It forms the nucleus of a suggested passing sight distance design approach based on the performance of a safe passing maneuver under current high-speed highway operations. Passing maneuvers under actual highway conditions were photographed and analyzed to provide operational data to evaluate current passing sight distance design standards and values for the suggested design approach. The field studies are discussed in Section IV of this report.

CRITICAL POSITION DURING PASSING MANEUVER

Once he has initiated a passing maneuver, the passing driver has only two alternatives - complete the maneuver, or abort it and return to the right lane behind the vehicle he intended to pass. Assuming that the passed vehicle maintains a constant speed, there exists a point at which the time to complete the maneuver is equal to that of returning to the right lane behind the passed vehicle. This point differs for each speed of passing and passed vehicle.

In establishing the current criteria for passing sight distance design standards, this phenomenon was considered. The critical condition during the maneuver was considered to occur when the passing and passed vehicles were abreast, because at this position, the passing driver must decide whether to complete or abort the maneuver. Figure 2 shows the relative positions of the vehicles for the two alternatives. The critical condition is assumed to occur when the two vehicles are abreast at Point C. In either case, the passed vehicle will be at Point E when the approaching vehicle is at Point H. If, at Point C, the passing driver perceived an approaching vehicle and decided to complete the maneuver, he would travel a distance CF before returning to the right lane. The resulting clearance distance between the passing and approaching vehicle would be FH. On the other hand, had the passing driver aborted the maneuver and returned to the right lane behind the passed vehicle, the distance traveled in the left lane would be CD resulting in a much greater clearance distance, DH. Since the time in



Critical position during passing maneuver

Figure 2

both cases is constant, the completed maneuver produces the more critical condition. The objective of passing sight distance design is to provide passing zones in which maneuvers may be safely completed rather than aborted. Therefore, the critical completion distance, CF becomes one of the distance elements to be included in the safe design.

Based on field studies of passing maneuvers in 1938, it was determined that the distance required to complete the maneuver from the critical abreast position was approximately two-thirds of the total left lane distance, d_2 . As will be discussed in more detail in a later section of this report, this approximation remains valid for current operating conditions.

DESIGN SPEED

As mentioned previously, the passing maneuver represents one of the most hazardous operations that a driver must perform on a two-lane highway. As such, from a critical design standpoint, it is logical that distance elements be determined on the basis of a passing vehicle traveling at the design speed rather than a lower assumed operational speed. This is analogous to stopping sight distance design for dry pavement conditions. To place all elements of the maneuver on a common design base, it follows that an approaching vehicle should be considered to be traveling at the design speed.

Current standards are based on a 10-mph speed differential between passing and passed vehicle. As will be discussed in more detail later, this criteria does not reflect current operations, particularly in the higher speed passing maneuvers. The extrapolated passing sight distances for the higher speed maneuvers are based on a constant 10-mph speed

differential whereas the field studies indicated that the speed differential decreased as the passing speed increased. By establishing design criteria based on the passing and approaching vehicle traveling at the design speed, and incorporating the effect of the varying speed differential on an 85th percentile basis, passing sight distance design becomes more meaningful. From this respect, passing speed, approach vehicle speed and design speed become synonymous.

MINIMUM LENGTH OF PASSING ZONE

Passing distance and passing sight distance are not one and the same. Obviously a passing driver should be provided more sight distance than the minimum distance in which he can physically perform a passing maneuver if he is to perceive and respond to the presence of an opposing vehicle after he initiates the maneuver. A desirable minimum length of passing zone for operations would include the perception-reaction distance, d_1 , and the left lane distance, d_2 . If the maneuver is initiated at the beginning of the zone, this distance would permit the passing driver to abort the maneuver if an approaching vehicle is perceived at or before reaching the critical position as shown previously in Figure 2. Also, it would permit a completed maneuver if an approaching vehicle is perceived after the passing driver has reached the critical position.

It is important to realize that the minimum passing zone lengths stated above would provide safe operational distances only if the passing driver was provided sufficient sight distance throughout the passing zone.

SIGHT DISTANCE REQUIREMENTS FOR SAFETY

At what distance must a passing driver perceive an approaching vehicle if he is to safely complete his maneuver? The distance required to complete the maneuver from the critical position is closely approximated by $0.67 d_2$. If the speed of the approaching vehicle and the passing vehicle are equal, the approaching vehicle travels an equal distance, $0.67 d_2$. Including an adequate clearance distance, d_3 , the minimum sight distance required for safe operations would become $4/3 d_2 + d_3$.

The hazard associated with the passing maneuver arises when there is insufficient distance to complete the maneuver if an approaching vehicle is perceived at the critical position. The critical position can occur anywhere throughout the passing zone. This can, and often does, occur if the passing driver does not realize that he is approaching a no-passing zone when he initiates his pass. If he reaches the critical position at or near the end of the passing zone, he must immediately decide to complete the maneuver or abort. In either case, he would be forced to encroach on the no-passing zone.

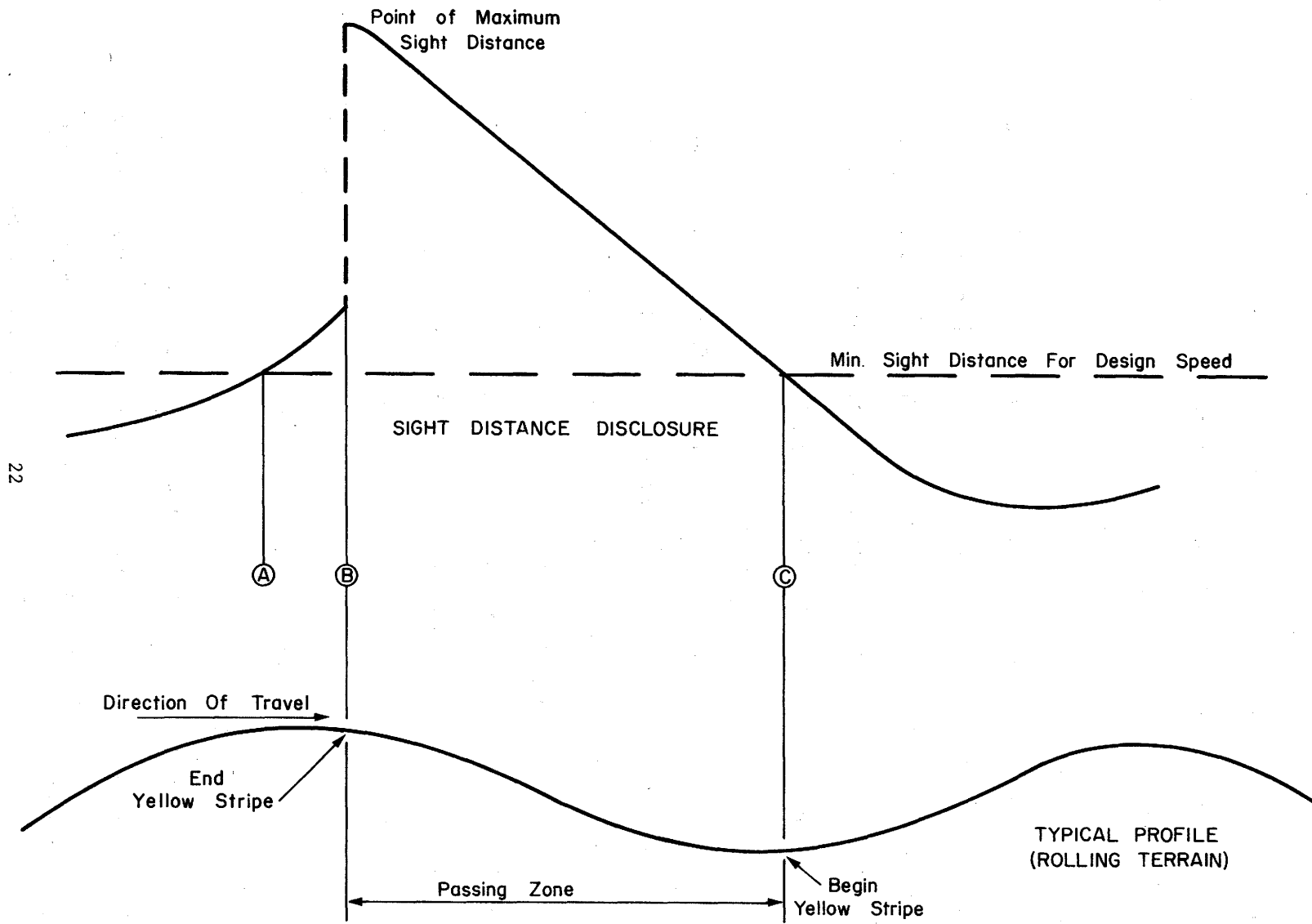
To provide a safe "recovery zone" for the passing driver who is placed in the critical position at the end of a passing zone with an approaching vehicle, the minimum sight distance, $4/3 d_2 + d_3$, must be provided throughout the entire passing zone. This philosophy approaches the long zone passing concept to a certain degree in that it provides a safe recovery area in a no-passing zone, but does not necessarily encourage drivers to initiate a passing maneuver at the end of a passing

zone. Under accepted enforcement practice, completion of the maneuver in the no-passing zone would be illegal, but this design practice would reduce the head-on collision hazard.

SIGHT DISTANCE DISCLOSURE

The manner in which sight distance becomes available to a driver as he traverses a crest vertical curve or through a series of crests and sags is shown schematically in Figure 3. This pattern is quite representative of sight distance disclosure for gently rolling terrain. As the driver approaches the crest of the curve (Point B) through a no-passing zone, available sight distance is limited by the crest vertical curve on which he is driving. Shortly before reaching the crest, the available sight distance increases almost instantaneously. Sight distance is no longer restricted by that crest, but by the next crest vertical curve downstream. If there is no subsequent crest, sight distance at Point B becomes virtually unlimited. However, in gently rolling terrain, as shown in Figure 3, short passing zones usually occur in the sags. As the driver travels through the passing zone, the available sight distance decreases, limited by the impending crest. This pattern of sight distance disclosure is repeated as the driver travels along the highway.

Under existing passing sight distance standards, minimum sight distances are specified for particular design speeds. These distances apply at the beginning of a passing zone (Point B, Figure 3), but no length is specified over which this sight distance must be made available. Employing the concept developed in this report, the sight



22

Sight distance disclosure between crest vertical curves

Figure 3

distance required at the downstream end for safe recovery is established as $4/3 d_2 + d_3$. The minimum length of passing zone is established as $d_1 + d_2$. Therefore the minimum available sight distance at the beginning of the zone is established as the total of these distances.

SUMMARY OF DESIGN CONCEPT

The design concept developed above is based on an evaluation of the sight distance requirements and operational distances for the performance of safe passing maneuvers. The concept combines the safety requirements for sight distance and the operational requirements for passing distance. Current practice involves design of passing sight distance and determination of no-passing zones on the completed highway. The concept developed here integrates the requirements for passing sight distance and passing zone length for both design and operations. It is in the design stage that profile and alignment can be most easily adapted to provide the operational requirements.

The concept is summarized below:

1. Design speed, passing vehicle speed, and approach vehicle speed are synonymous.
2. The minimum length of a passing zone is $d_1 + d_2$, where
 - d_1 = perception-reaction distance
 - d_2 = left-lane distance
3. The minimum sight distance at any point throughout the passing zone is $4/3 d_2 + d_3$.

4. The minimum available sight distance at the beginning of the passing zone would become the sum of the minimum passing zone length and the minimum sight distance: therefore, sight distance = $d_1 + 2.33 d_2 + d_3$.

FIELD MEASUREMENTS

Passing maneuvers under actual highway conditions were photographed to obtain operational data with which to determine the distance elements described above. Of primary concern were passing maneuvers on highways having operating speeds within the 50 to 80 mph range. The field studies are described in Section IV of this report and the results are evaluated in the subsequent sections.

IV. FIELD MEASUREMENTS

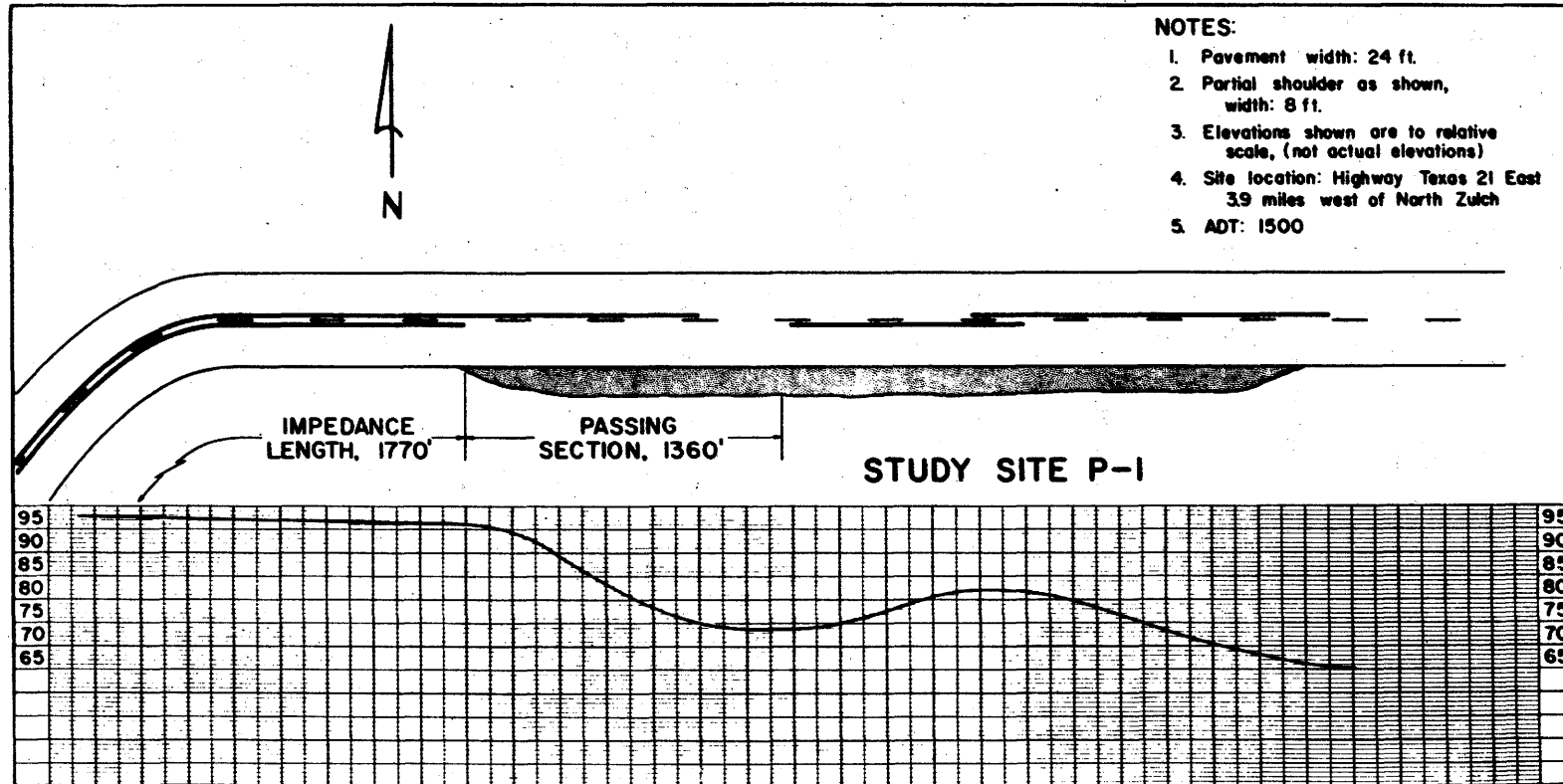
The general methodology involved the use of an impeding vehicle and an observation vehicle equipped with a 16-mm movie camera. Subject drivers approaching the study sites through a striped no-passing zone were impeded at selected speeds by the impeding vehicle. The observation vehicle followed immediately behind the subject driver. Upon entering the passing zone, the impeding vehicle maintained a constant speed while the subject's passing maneuver was photographed from the observation vehicle.

Included in this section are descriptions of the study sites, the equipment used, and the procedure followed and a discussion of the operating characteristics for the study sections.

SITE SELECTION AND DESCRIPTION

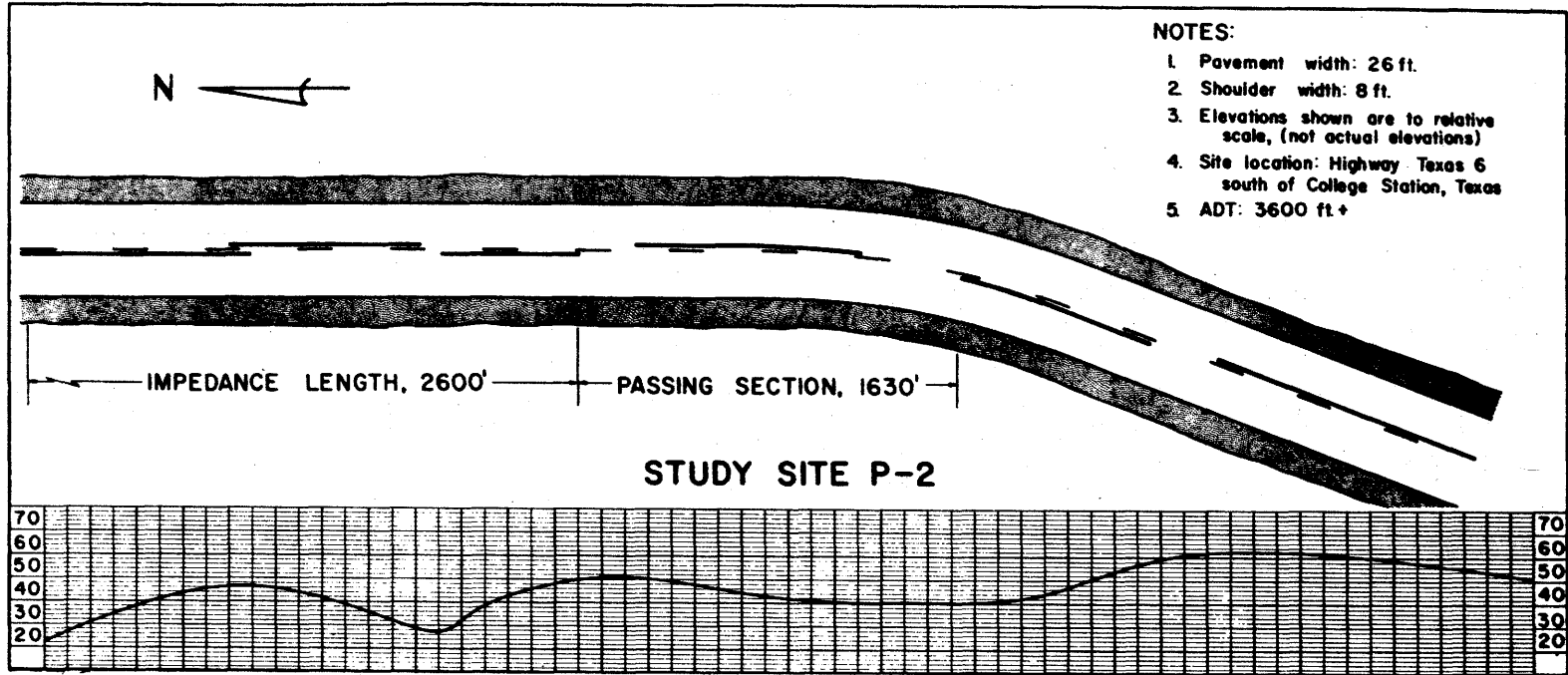
Three study sites having passing zones of 1360, 1630, and 2680 feet in length were selected within a 20-mile radius of College Station, Texas. Geometric details of the study sites are shown in Figures 4 through 6.

The study sites were selected to be free of external distractions that might affect the driver's normal operating procedure. That is, the driver was not subjected to drastic changes in environment, horizontal alignment, or cross-section; nor were there any intersections, railroad crossings, narrow bridges or other such unique features. Each site was preceded by several miles of relatively unrestricted geometry. Drivers approaching each site, therefore, had become accustomed to



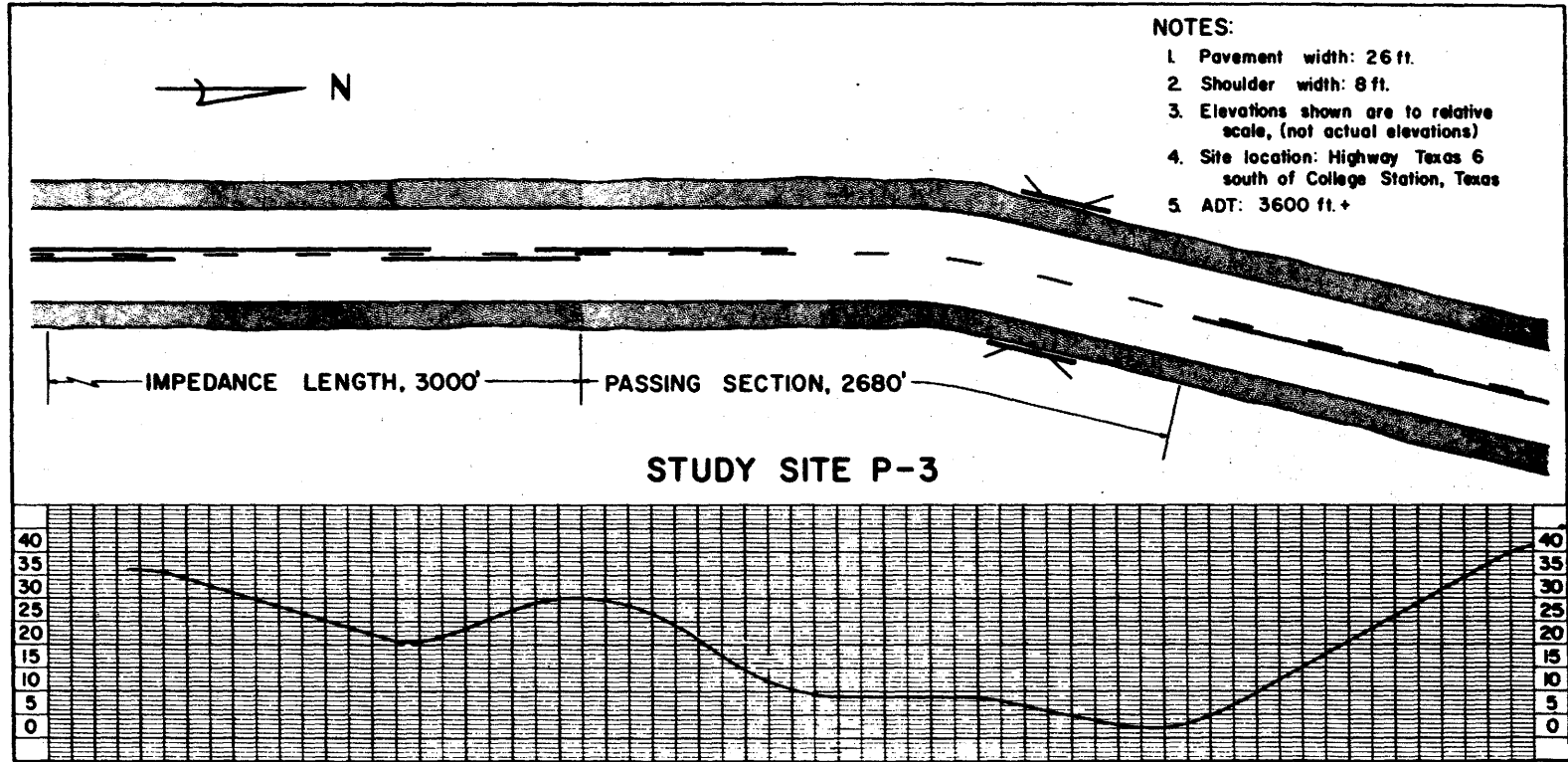
Geometrics of study Site P-1

Figure 4



Geometrics of study Site P-2

Figure 5



Geometrics of study Site P-3

Figure 6

relatively unrestricted passing opportunities and, with minor exceptions, to free-flowing traffic conditions.

Prior to each study zone, drivers were restricted from passing by a double-yellow barrier stripe. No-passing zone lengths for the respective sites were 1770 feet, 2600 feet, and 3000 feet. All double-yellow pavement striping was existing marking; no false striping was placed to provide an impeding zone. Careful attention was directed toward the selection of sites that gave drivers no advance warning of an impending passing zone. Each passing zone began on the downgrade of a crest, extended through a sag, and terminated on the upgrade of the next crest. The passing zone in Site P-2 differed from the other two sites in that it contained a right horizontal curve of approximately two degrees.

Sites P-2 and P-3, located on State Highway 6, had similar cross-sectional characteristics. Each contained 13-foot asphaltic concrete travel lanes and 8-foot asphalt shoulders. The right-of-way received normal maintenance from the Texas Highway Department, was clear of all large vegetation, and was mown throughout the study area. Horizontal alignment was relatively straight.

Site P-1, located on State Highway 21, differed from Sites P-2, and P-3 in cross-section. Travel lanes were 12 feet in width and, in general, no paved shoulders were present. An asphaltic concrete shoulder existed throughout the passing zone on only one side, but terminated shortly thereafter. The right-of-way was well-maintained throughout the study area. The approach to Site P-1 differed from the other two sites. Whereas, Sites P-2 and P-3 were restricted from view

to an approaching driver by rolling vertical alignment, Site P-1 was restricted by a horizontal curve immediately prior to the vertical curve on which Site P-1 began.

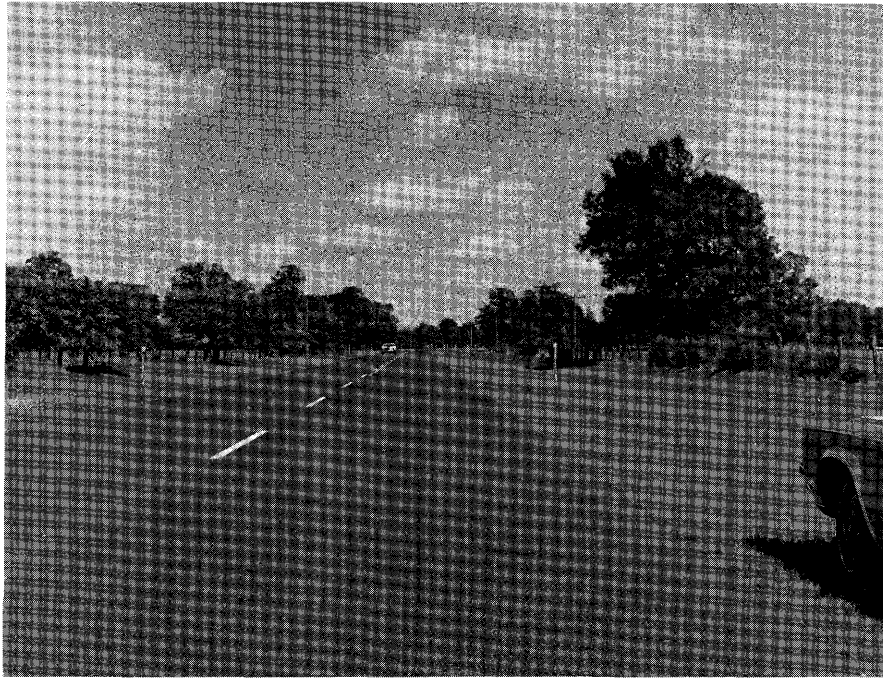
Figures 7, 8, and 9 show details of the study sites and present views of the roadway as seen by a driver traveling through the sites.

CALIBRATION MARKING

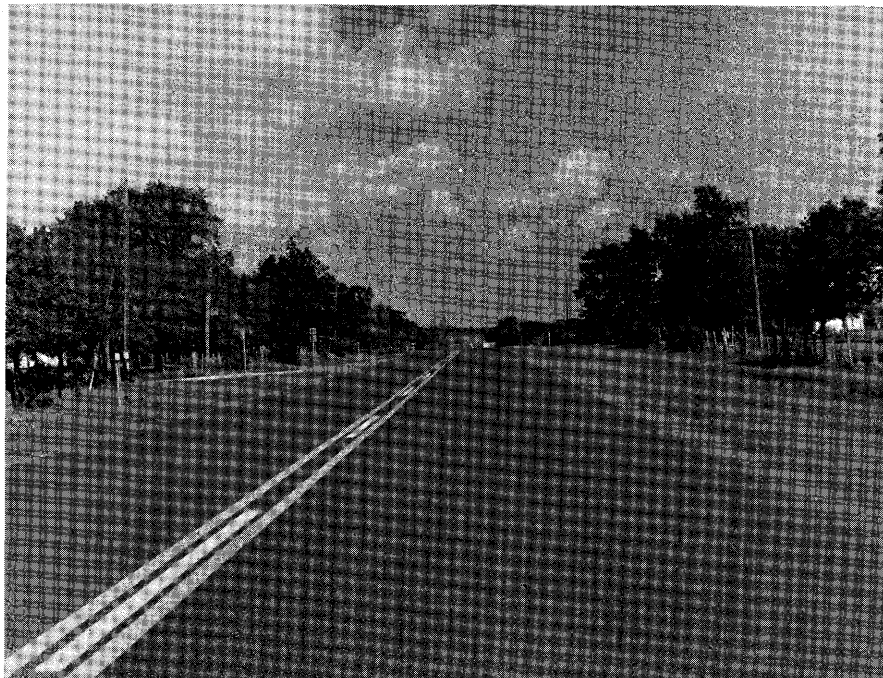
To permit film data reduction, a system of reference calibration marks was placed throughout each study site. Two-foot sections of 6-inch wide white reflectorized temporary pavement striping tape were placed transverse to and on 40-foot centers along the highway centerline. Calibration markings extended throughout the passing zone and for approximately 400 feet at each end of the zone. Markers can be seen in Figures 7, 8, and 9.

The reference marks served several functions. They provided a common reference point to begin photographing the passing maneuver. Longitudinal distance could be quickly determined from the film by counting reference marks. The primary function was to provide a precise reference base from which to measure lateral position of the passing vehicle during lane-change. Although not included in this report, concurrent research is being conducted to investigate the safety of the passing maneuver from the aspect of pavement frictional requirements for the lane change maneuvers.

The 2-foot marker length was the minimum with which desired accuracy in lateral wheel position could be obtained using the Vanguard



(a) Driver's view when approaching horizontal curve prior to Site P-1



(b) Driver's view of roadway immediately prior to passing zone at Site P-1

Figure 7

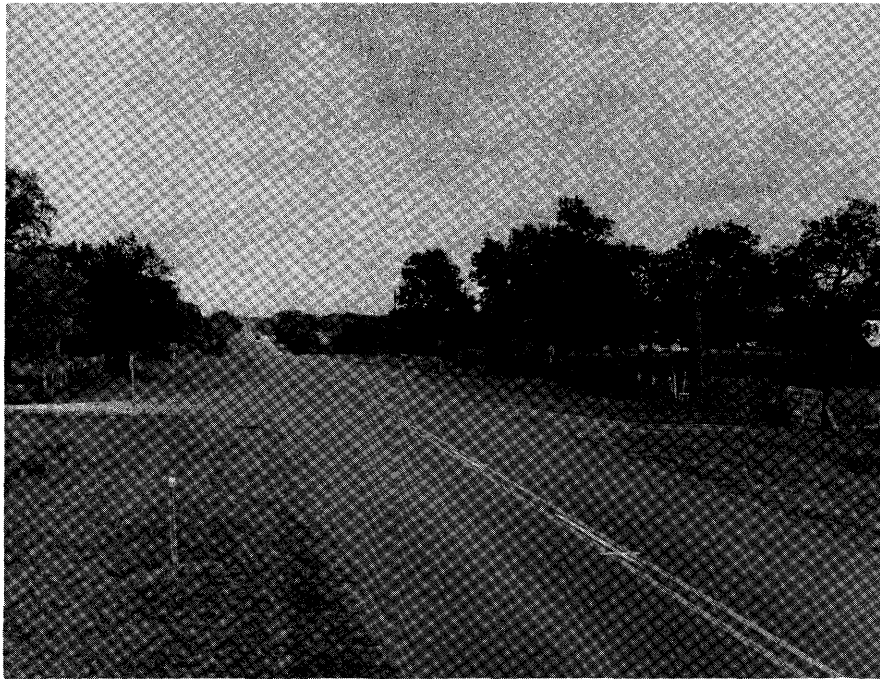


(c) Driver's view of Site P-1 passing zone as seen at beginning of zone

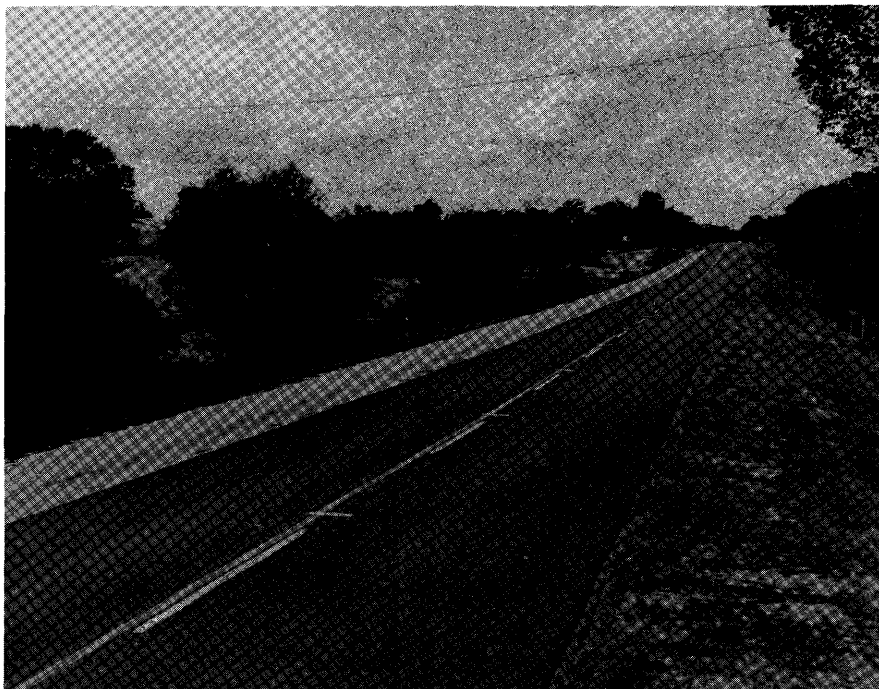


(d) Impeding vehicle, subject, and photographic chase vehicle in test condition, Site P-1

Figure 7

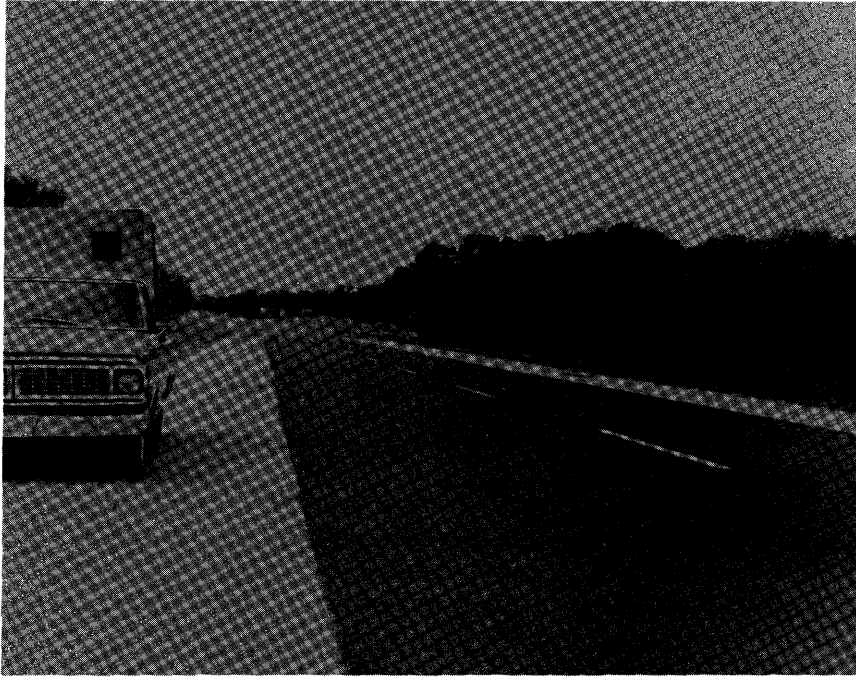


(e) Panoramic view of Site P-1 viewed in the study direction



(f) Panoramic view of Site P-1 viewed from terminal end toward the beginning of the passing zone

Figure 7



(a) Subject selection point, 1 mile prior to Site P-2



(b) Chase zone prior to Site P-2 viewed from subject-selection point



(c) View from beginning of Site P-2 passing zone
looking back through impeding zone



(d) Driver's view of Site P-3 passing zone as
seen at the beginning of the zone

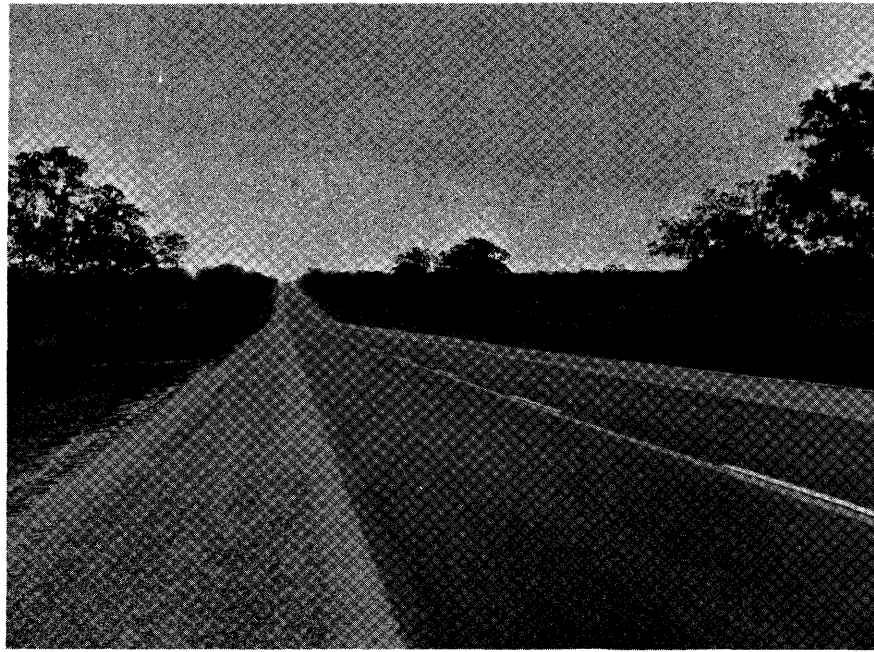
Figure 8



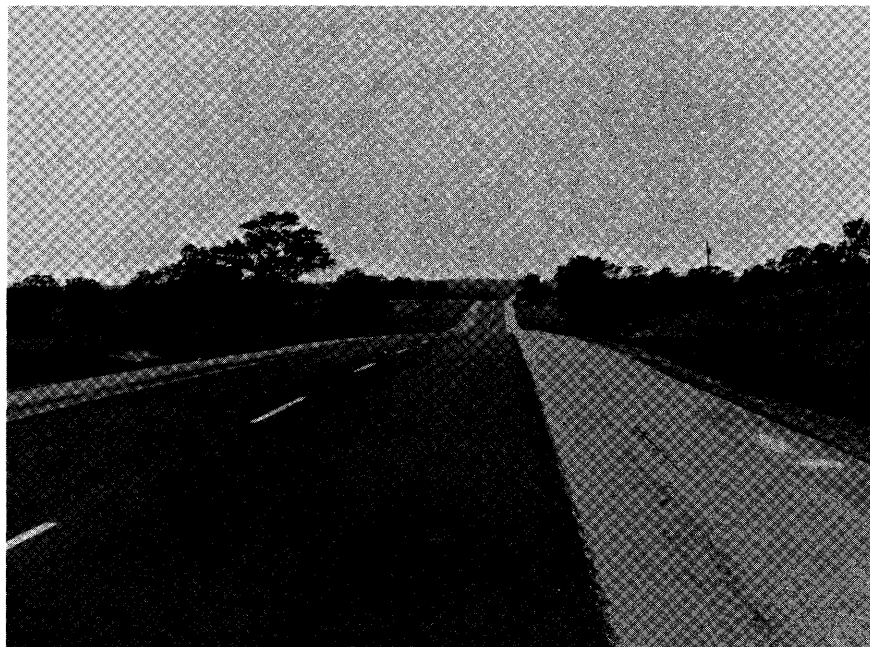
(e) Driver's view of Site P-2 passing zone as seen at a point approximately one-third through the zone



(f) Driver's view of Site P-2 passing zone as seen at a point approximately two-thirds through the zone

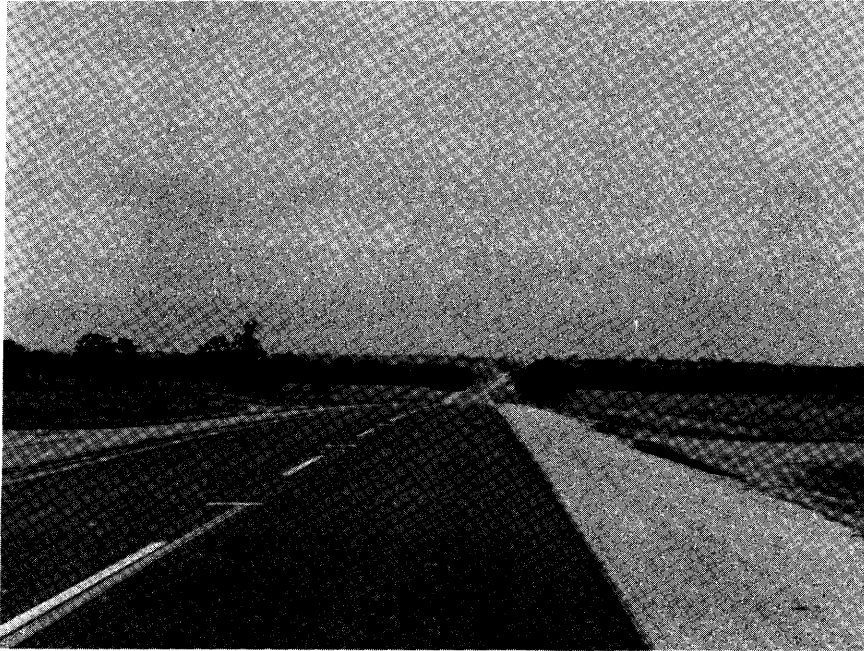


(a) View from crest vertical curve prior to Site P-3 looking back through subject impeding zone



(b) View from crest through short passing zone toward Site P-3

Figure 9



(c) Driver's view of Site P-3 passing zone as seen from the beginning of the zone



(d) Driver's view of terminal end of Site P-3 passing zone as seen from a point approximately one half way through zone

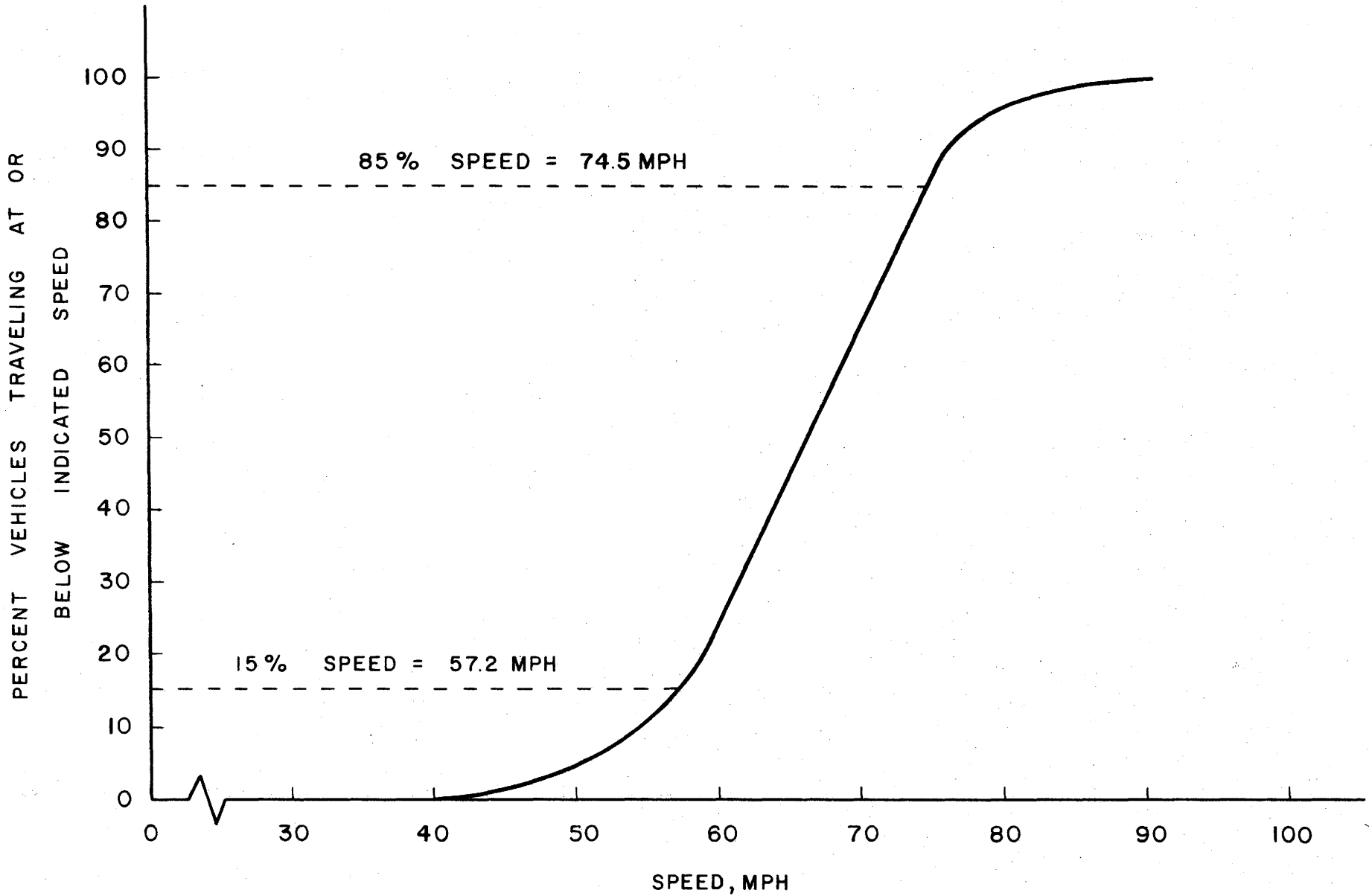
Motion Analyzer. Although the markers were apparent from the height at which the camera was located, they were quite unobtrusive from normal driver eye-height, and apparently did not affect the passing behavior.

TRAFFIC OPERATING CHARACTERISTICS

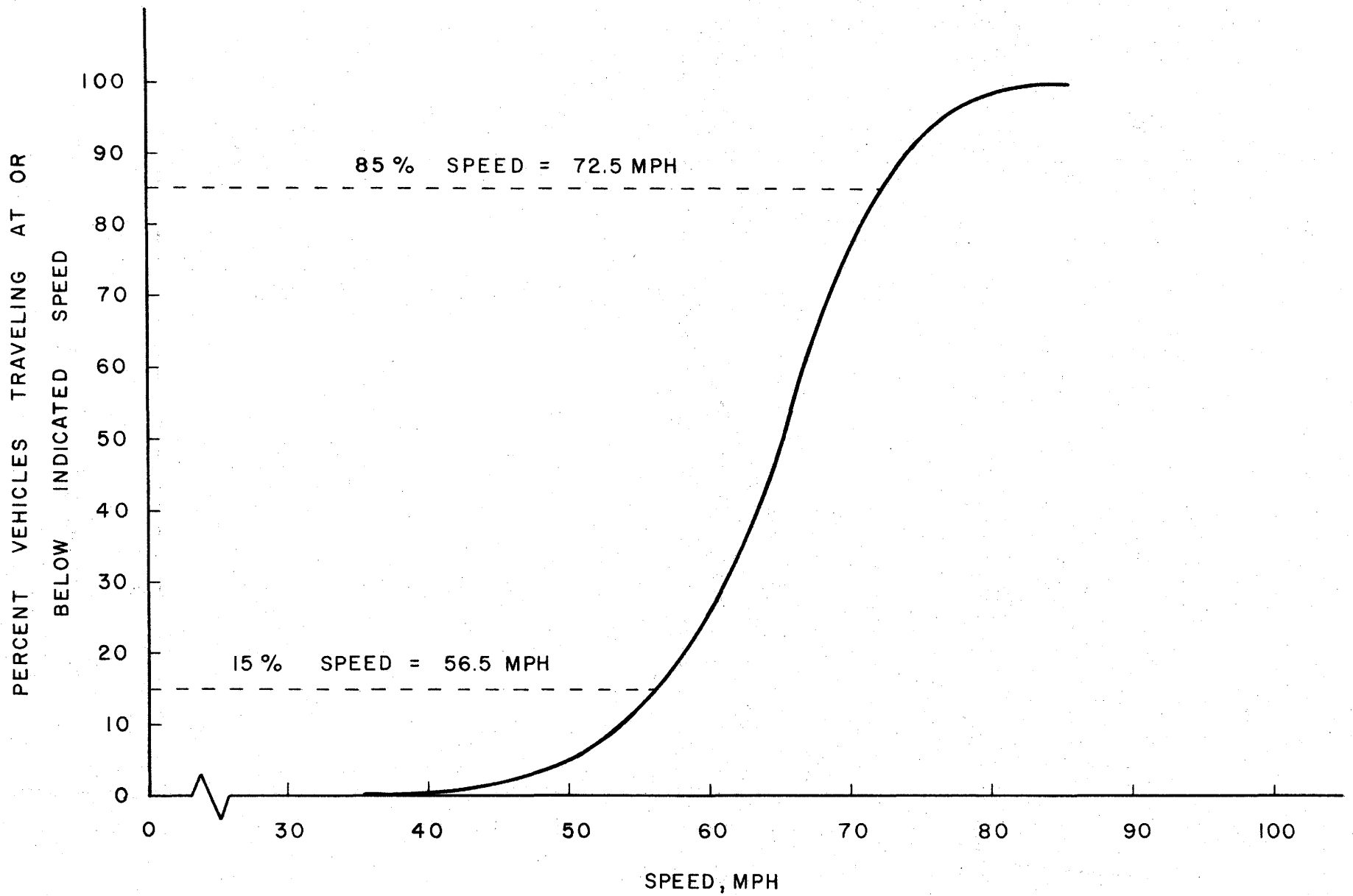
Traffic flow was quite uniform throughout each study section from day to day. There were no major access points or intersections within, or close to, the study sites; thus, built-in volume and speed distribution controls were provided. The average daily traffic (ADT) was approximately 3600 vehicles per day for Sites P-2 and P-3, and 1500 vehicles per day for Site P-1. Posted speed on both highways is 70 mph. Speed distribution studies, shown in Figures 10, 11, and 12, indicated the 85th and 15th percentile speeds to be as follows:

<u>Site</u>	<u>85th % Speed</u>	<u>15th % Speed</u>
P-1	74.5 mph	57.2 mph
P-2	72.5 mph	56.5 mph
P-3	70.5 mph	54.5 mph

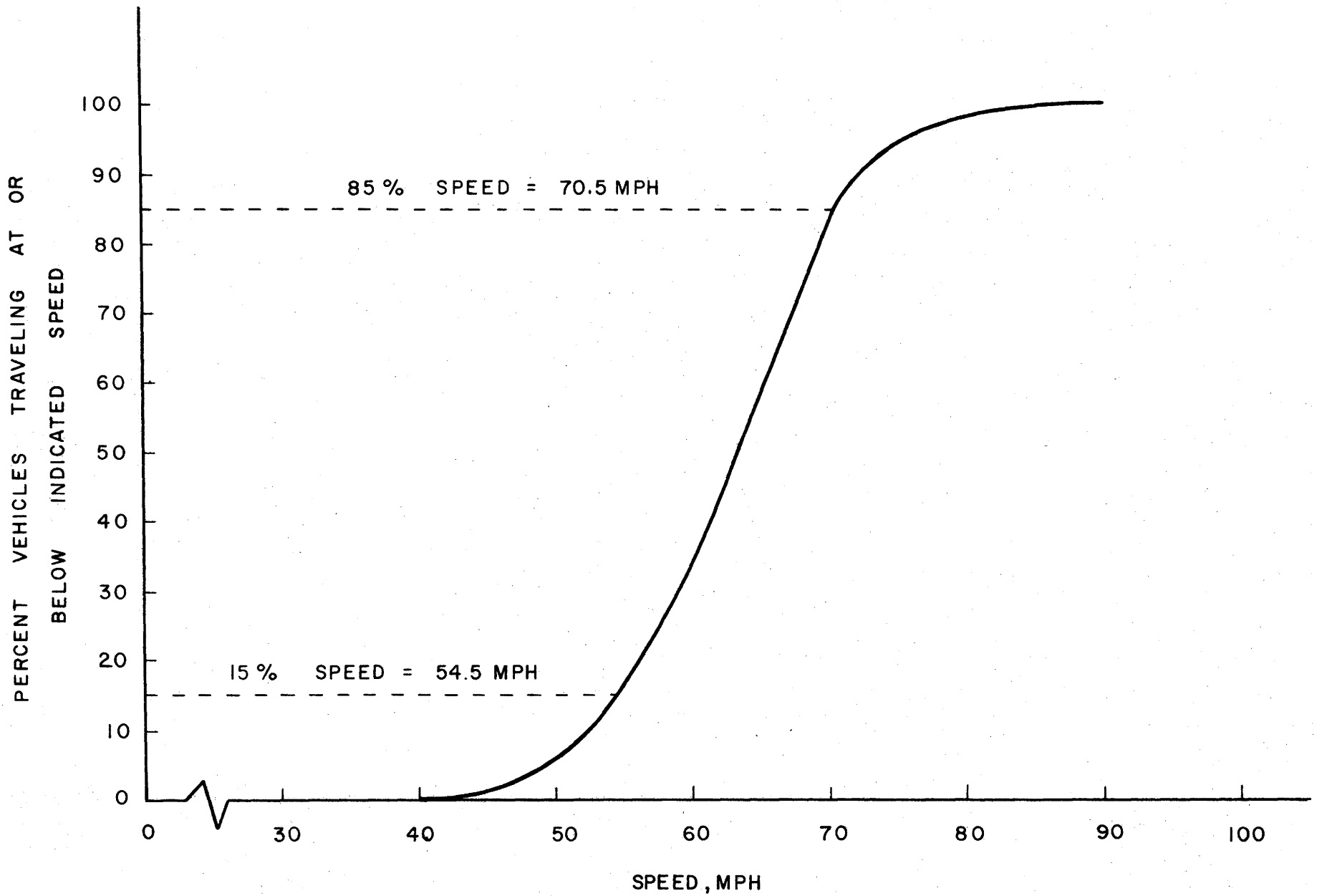
These values compare with speed studies conducted by the Planning and Survey Division of the Texas Highway Department in 1968, (5) which showed the average 85th percentile daytime speed for all major highways in Texas to be 70 mph, with a 15th percentile speed of 54 mph. Considering only the speed characteristics, the passing maneuvers observed in the three study sites should be indicative of those expected on similar high-speed facilities.



Cumulative distribution of operating speed, Site P-1
Figure 10



Cumulative distribution of operating speed, Site P-2
Figure 11



Cumulative distribution of operating speed, Site P-3
Figure 12

IMPEDING VEHICLE

A 1969 Plymouth sedan was used to impede subjects through the study sites. During the first several days, drivers were hesitant to pass the impeding vehicle, although ample passing distance was available. It was suggested that drivers might think the impeding vehicle was a highway patrol vehicle because it was white and displayed the official State of Texas exempt license plates. Therefore, all identifying Texas Transportation Institute door legends were masked, and conventional license plates were substituted during data collection periods. To an overtaking driver, the impeding vehicle then appeared to be simply another passenger car.

PHOTOGRAPHIC OBSERVATION VEHICLE

A 1970 Ford 1/2-ton pickup was used as the observation vehicle. So test subjects were not aware that their maneuvers were being photographed, the camera and operator were concealed. Since normal operating characteristics could be severely altered by the obvious presence of photographic equipment, an observation box resembling a tool shed was placed in the pickup bed immediately behind the cab, extending 24 inches above the cab roofline. The box contained a small front window over the driver's side of the cab through which the subject's passing maneuver was photographed. Since the subject's attention was directed toward the impeding vehicle and the available passing distance, and also, because the small photographing window was above the line of sight of his rear vision mirror, it is doubtful that drivers were aware of

the camera. With the window being the only opening, and because light was reflected from the glass, the interior of the box appeared dark and unoccupied. The observation vehicle is shown in Figure 13.

CAMERA

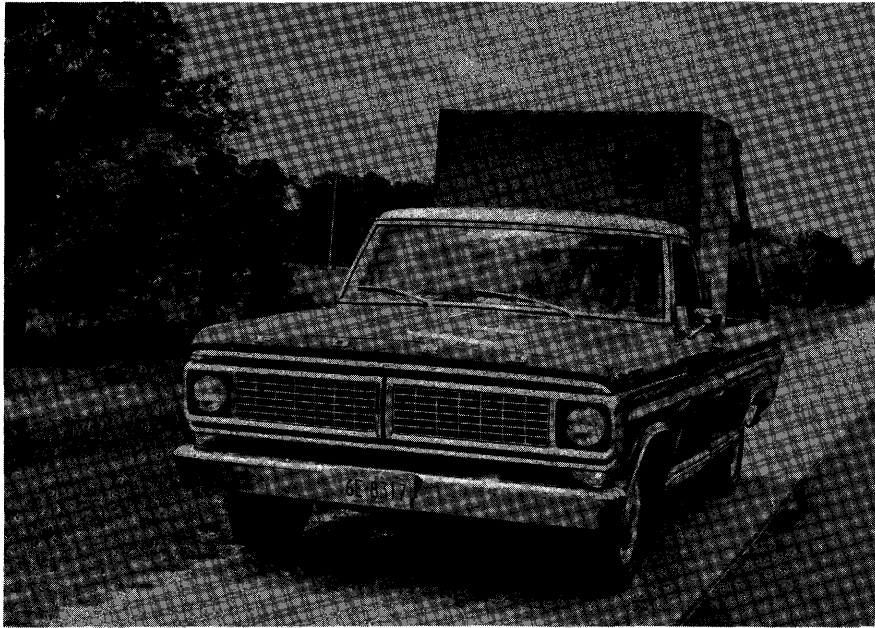
An Arriflex 16-mm movie camera was used to photograph the passing maneuvers. Black and white Plus-X reversal film (Kodak, ASA 50) on 400-foot rolls was used throughout the study. Power was supplied by an 8-volt battery through a governor-controlled motor to produce a constant 24 frame-per-second film advance. Subject vehicles were photographed with a zoom lens (17.5-mm to 70-mm) permitting the camera operator to maintain full field of view under varying distance requirements. The camera was mounted on a "ball-head" rigid base mount attached to a shelf. The camera and mounting configuration are shown in Figure 13.

SELECTION OF SUBJECTS

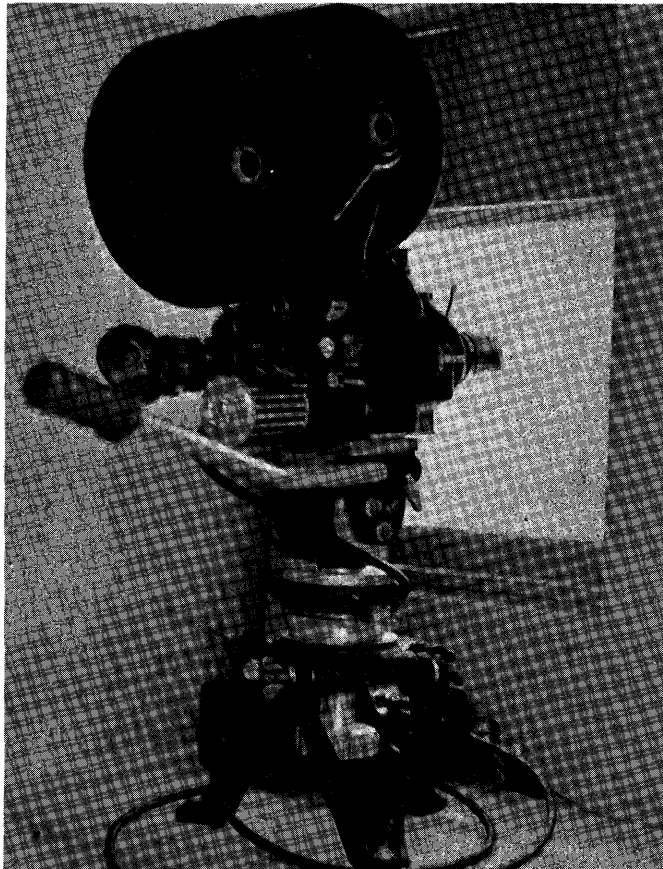
The two criteria used in the selection of subjects were (1) that the vehicle approach speed was in excess of 60 mph, and (2) that the vehicle was not registered locally.

The study concerned primarily high-speed passing maneuvers. It was felt that drivers approaching the study site at a high rate of speed wished to maintain that speed if possible, and, therefore, would pass the slower impeding vehicle when afforded a safe passing opportunity.

Sites were selected where the geometry precluded any advance indication of a passing zone. Therefore, local drivers were declined



(a) Photographic chase vehicle



(b) Arriflex 16-mm movie camera and mounting system in recording vehicle

Figure 13

as subjects because they would be aware of the impending passing zone. Local drivers were recognized by the vehicle license plate code letters.

SAMPLING TECHNIQUES

Approximately 500 completed passing maneuvers were photographed during the study. The sample consisted of 50 maneuvers at each site for impeding speeds of 50, 55, and 60 mph (450 total occurrences). Approximately 40 maneuvers were photographed at a 65 mph impeding speed, primarily on Site P-3; and 10 maneuvers at a 70 mph impeding speed. The number of tests was established simply to meet time and monetary constraints for data collection and film analysis. It was not determined by a particular statistical basis.

The presence or lack of opposing traffic must be evaluated by a passing driver. To avoid altering the traffic conditions that normally would be encountered, and thus affecting the passing characteristics, opposing traffic was not stopped during the study. More than 3000 subjects were photographed to achieve the desired number of completed passing maneuvers because many maneuvers were aborted or declined due to opposing traffic in the passing zone. It is highly probable that many more passing maneuvers would have been performed had there been no opposing traffic in the passing zone.

STUDY PROCEDURE

The observation vehicle was stationed about one mile upstream from the impeding zone. The impeding vehicle was parked on the shoulder near

the beginning of the zone. As a subject driver passed, the chase vehicle pulled out into the travel lane and the impeding-vehicle driver was notified by radio that a subject had been selected and was approaching at a specified speed. The impeding vehicle then moved from the shoulder to the travel lane and accelerated to the predetermined impeding speed (50, 55, 60, or 65 mph). The subject was forced to follow the impeding vehicle through the zone (or illegally cross the double yellow line). During this time, the observation vehicle caught and trailed the two vehicles through the remainder of the zone. Figure 14 shows the relative position of the three vehicles during a test.

Filming was initiated as the subject vehicle reached the calibration markers prior to the passing zone, and was continued throughout the passing zone, or until it was obvious that the subject had declined the passing opportunity. The impeding vehicle maintained constant speed throughout the passing zone. Data were recorded by observers in both the impeding and observation vehicles from which the film could be cross-checked. Included in the field data were type of vehicle, license number, subject speed, presence of opposing traffic, and other data.

After photographing a maneuver, the study vehicles returned to their initial positions, another subject was selected, and the procedure was repeated.



Impeding vehicle, subject, and photographic chase vehicle in test condition

Figure 14

V. ANALYSIS OF RESULTS

FILM ANALYSIS

The study film was analyzed on a Vanguard Motion Analyzer. This device is a film reader used to evaluate photographic data. Its principal components are a projection head and a ground glass screen which permit precise observation and measurement of distance, angles, and time from 16-mm film. Film may be viewed a single frame at a time or at variable speeds up to 30 frames per second. Displacement or rotation with respect to time may be determined since the original film advance speed is known.

The ground glass screen contains an X-Y grid system (0.001-inch measurement capability) on which the image is projected. These movable crosshairs, in conjunction with a fixed reference line in the plane of the screen, allow determination of the object displacement between successive frames. An angle measurement screen containing an azimuth scale with parallel reference lines which can be rotated and shifted perpendicular to the lines permits determination of angular alignment of any point on the image. Angle-measurement accuracy is 0.25 degrees.

To analyze the passing maneuver samples, the passing vehicle longitudinal and lateral positions throughout the study site were determined from the film. The left rear tire (edge of tread) was used as the vehicle measurement target for all position measurements. Longitudinal position was referenced to the beginning of the passing zone (end of yellow line), and lateral position was referenced to the



Vanguard Motion Analyzer

Figure 15

right edge of the calibration markers placed on 40-foot centers along the centerline of the highway.

The beginning of vehicle movement toward the left lane to initiate the passing maneuver, and the beginning of the return movement at the completion were determined by repeatedly running the film through the Vanguard Motion Analyzer to detect the position where lateral movement was first noticeable. The position where the passing vehicle was traveling parallel to the centerline defined the ends of both transition movements. By definition, encroachment on the left lane and return to the right lane occurred when the passing vehicle left rear tire crossed the centerline of the highway.

Film frame numbers were determined at every calibration mark and the particular positions throughout the transition movements described above. By correlating the film speed, distance between calibration markers, and film frame numbers, the speed, time, and average acceleration of the passing vehicle were determined by the following relationships:

$$\begin{aligned} \text{Vehicle Speed} &= \text{distance} \div \text{time} \\ &= \frac{\text{No. of calibration intervals} \times 40}{\text{No. of frames} / 24 \text{ frames per sec.}} \end{aligned}$$

$$\text{Vehicle Acceleration} = \frac{\text{change in speed}}{\text{time}}$$

(An average acceleration over two adjacent 40-foot intervals was computed).

$$\therefore \text{Acceleration} = \frac{\text{Speed}_2 - \text{Speed}_1}{(\text{Frame No. 2} - \text{Frame No. 1})} \times \frac{1}{24 \text{ frames per sec.}}$$

where subscripts denote the calibration markers at respective ends of the interval.

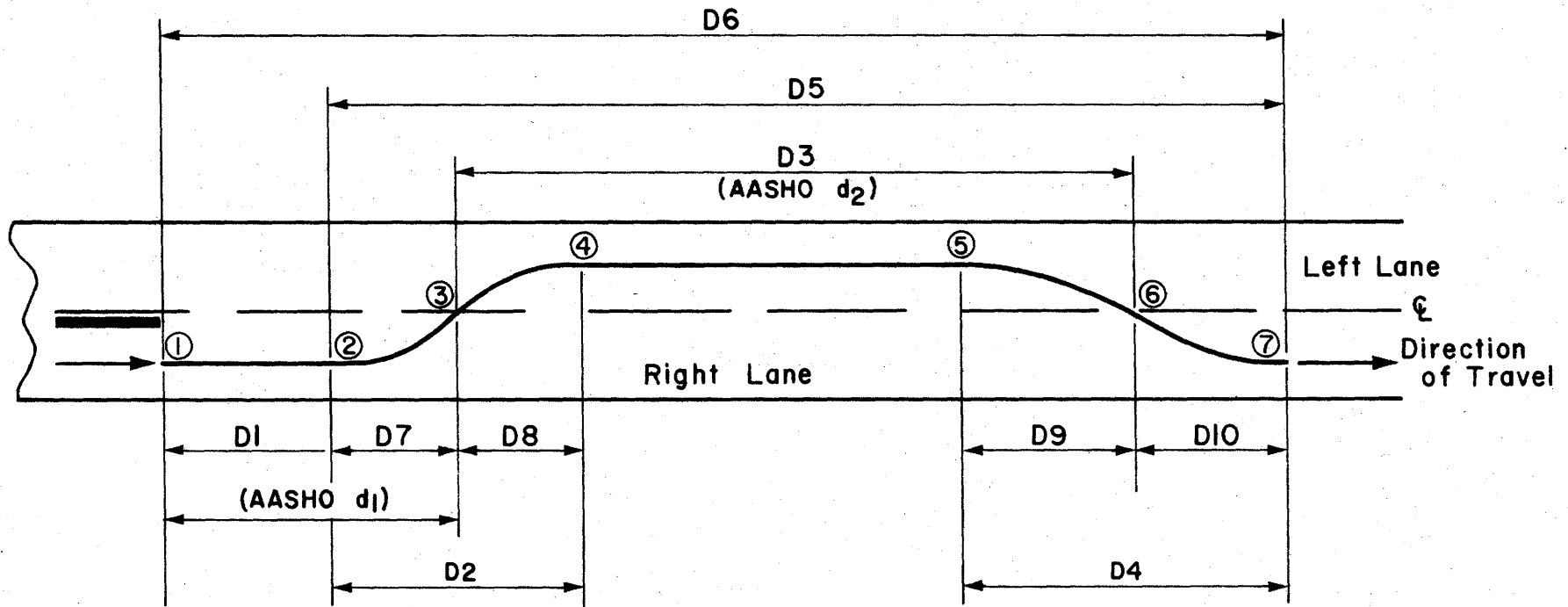
ELEMENTS OF PASSING MANEUVER

Passing vehicle speed, acceleration, and distance traveled, during several portions of the passing maneuver, were obtained for each maneuver. These data were computed from the film analysis by two computer programs written in Fortran V for the IBM 360 computer. Average speed and acceleration were computed for each distance element shown in Figure 16. Also, travel time for each element was determined. The passing maneuver was subdivided into ten distance elements to permit detailed analysis of the complete maneuver. The distance elements (D1, D2, etc.) shown in Figure 16 represent arbitrary nomenclature and are not to be confused with the distance elements (d_1 , d_2 , etc.) used in the AASHO Policy. Where appropriate, the corresponding AASHO distance elements are identified in parentheses in Figure 16.

SPEED DIFFERENTIAL DURING PASSING MANEUVER

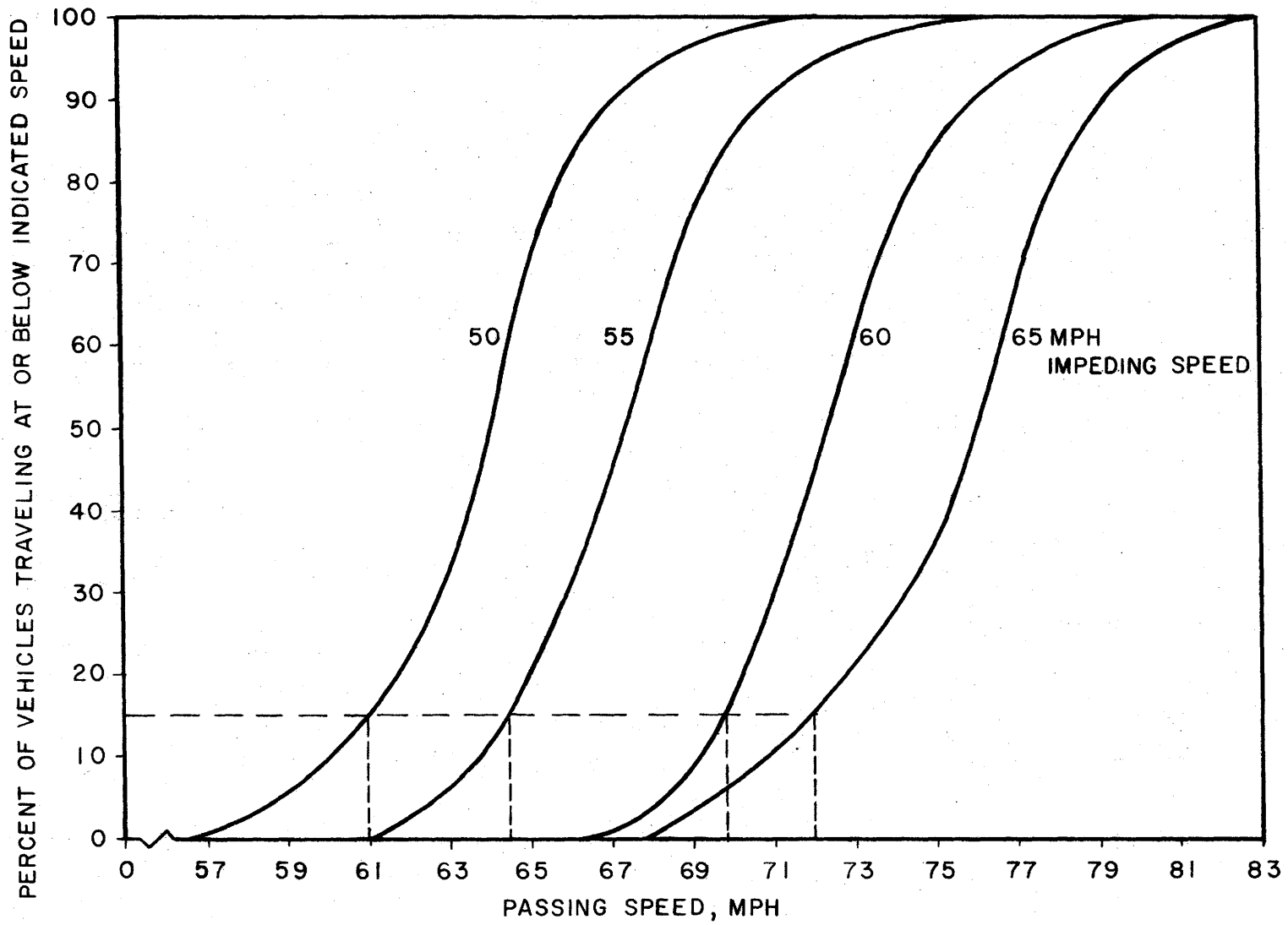
Shown in Figure 17 are cumulative distributions of passing speed during all maneuvers at each of the four impeding speeds. These distributions were computed to investigate the practical minimum speed differential occurring during passing maneuvers with different passed vehicle speeds. Although the current design criteria are based on a constant 10-mph speed differential, it was hypothesized in this study that the speed differential would decrease as the passed vehicle speed increased. In general, this is verified in Figure 17 and Table 2.

From the speed differential distributions at each individual study site, the 15th percentile passing speed was determined for each



- ① End of yellow stripe, beginning of passing maneuver
- ② Point at which passing vehicle begins to move to left lane
- ③ Point of enroachment on left lane
- ④ Point at which passing vehicle completes transition to left lane
- ⑤ Point at which passing vehicle initiates return transition
- ⑥ Point at which passing vehicle clears left lane
- ⑦ Completion of transition to right lane

Elements of passing maneuver analyzed
Figure 16



Cumulative distributions of passing speeds determined from field measurements
Figure 17

TABLE 2

SPEED DIFFERENTIALS BETWEEN PASSING AND PASSED VEHICLES

Study Site	15th Percentile Speed Differential				85th Percentile Speed Differential			
	Passing Vehicle Speed (mph)				Passing Vehicle Speed (mph)			
	50	55	60	65	50	55	60	65
P-1	11.6	11.8	8.7	--	15.47	14.98	14.03	--
P-2	10.9	7.9	10.8	--	13.83	11.99	12.47	--
P-3	10.4	8.9	10.0	6.8*	15.11	13.31	13.82	11.37*
Average	10.97	9.53	9.83	6.8*	14.71	13.32	13.38	11.37*
Weighted Avg. of all Speeds	9.78 mph				13.56 mph			

* Based on approximately 40 samples at Site P-3 only.

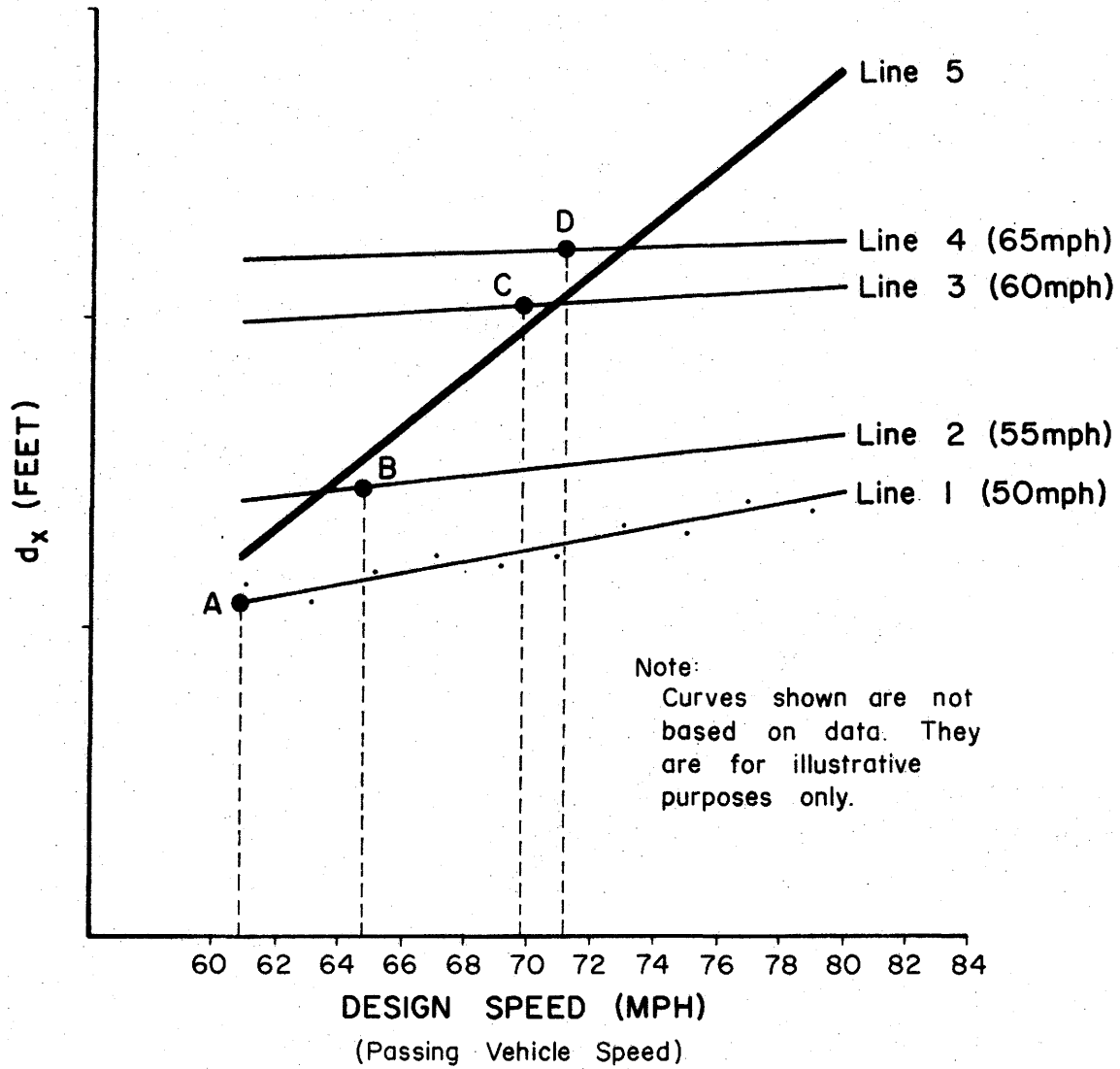
impeding speed. Eighty-five percent or less of the passing vehicles would be expected to perform the maneuver at a speed differential greater than the 15th percentile value. This value can be used to represent the critical maneuver for a particular passed vehicle speed. Table 2 presents the 15th and 85th percentile speed differentials determined from the field measurements for the four impeding speeds at each study site. Passing situations were analyzed on the basis of the average 15th percentile speed differential corresponding to the respective passed vehicle speed.

DEVELOPMENT OF SPEED-DISTANCE RELATIONSHIPS

To evaluate the existing criteria for passing sight distance under current operating conditions, and to obtain values for the various distance elements discussed earlier in this report, the relationships between passing speed and distance were determined from the field measurements for each of the four distance elements, (d_1 , d_2 , d_3 , and d_4). The manner in which the speed-distance relationships were determined is discussed below with reference to Figure 18. A general development of a hypothetical distance, d_x , is presented for illustrative purposes. The speed-distance relationships for d_1 , d_2 , and d_4 were determined similarly from the field measurements. The relationship for d_3 (clearance distance) was not derived from the field data; it was taken directly from the current AASHO Policy (1).

The development of the speed-distance relationships is outlined below:

- (1) Passing speed data for each impeding speed were grouped



Development of speed-distance relationships

Figure 18

in 2-mph class intervals (56.0-57.9, 60.0-61.9, ...
82.0-83.9 mph).

- (2) An average d_x over each 2-mph class interval was considered to represent the best estimate of the distance. Therefore the average d_x was plotted at the midpoint of each class interval, shown schematically in Figure 18 as a data scatter along Line 1.
- (3) The "best fit" curve through these data was obtained by least squares linear regression analysis. First, second, and third order curves were derived. First order curves produced the best "fit" in all cases. Regression correlation factors (R^2) were computed for each linear curve.
- (4) The above procedure was repeated for all impeding speeds, producing four "best fit" linear speed-distance relationships; one each for 50, 55, 60, and 65-mph impeding speeds. These lines are designated Line 1, Line 2, Line 3, and Line 4 in Figure 18.
- (5) The ordinate of each line at the abscissa corresponding to the impeding speed plus the appropriate speed differential (Ref. Table 2) was determined. For example, the point on Line 1 in Figure 18 would be the ordinate at the passing speed of speed 50 + 10.97 or 60.97 mph represented by Point A. Points B, C, and D were obtained similarly using the speed differential corresponding to the respective impeding speed.
- (6) The "best fit" line through Points A, B, C, and D was

obtained by least squares linear regression. The points were "weighted" before application of the regression techniques. Passing data were available at impeding speeds of 50, 55, and 60 mph for Sites P-1, P-2, and P-3, but only for Site P-3 at 65 mph impeding speed. Therefore, the points on the 50, 55, and 60 mph line were weighted three times that of the 65-mph data (Point D).

- (7) The resulting relationship between distance and passing speed (design speed) is shown in Figure 18 as Line 5.

The equation of this line was determined from the regression fit.

DISTANCE ELEMENTS OF PASSING MANEUVER

The four distance elements of the passing maneuver determined by the above procedure are presented in Table 3. Figure 19 shows the relationship between distance and design speed (passing vehicle speed). The relationship between distance and the current AASHO Policy design speed is shown in Figure 19 for comparison.

COMPARISON OF STUDY RESULTS TO EXISTING POLICY

The studies conducted in 1938 to 1941, upon which the current passing sight distance criteria are based, included data from considerably more passing maneuvers than recorded during this study. Over 20,000 passing maneuvers were studied in seven states during the 1938-41 studies (8, 9). Normann (8) and Prisk (9) reported the results of over 5100 passing maneuvers. Approximately 500 completed passing

TABLE 3

AVERAGE DISTANCE ELEMENTS OF PASSING MANEUVER
DETERMINED FROM FIELD MEASUREMENTS

Design Speed, V (mph)	d ₁ (ft)	d ₂ (ft)	d ₃ (ft)	d ₄ (ft)	d _{total} (ft)
50	193	692	211	410	1506
60	289	896	285	574	2044
65	337	998	322	656	2314
70	386	1100	359	739	2583
75	434	1202	396	821	2852
80	482	1304	433	903	3122
85	531	1406	470	985	3391

EQUATIONS OF SPEED-DISTANCE RELATIONSHIP

d₁ = 9.655V - 290.111

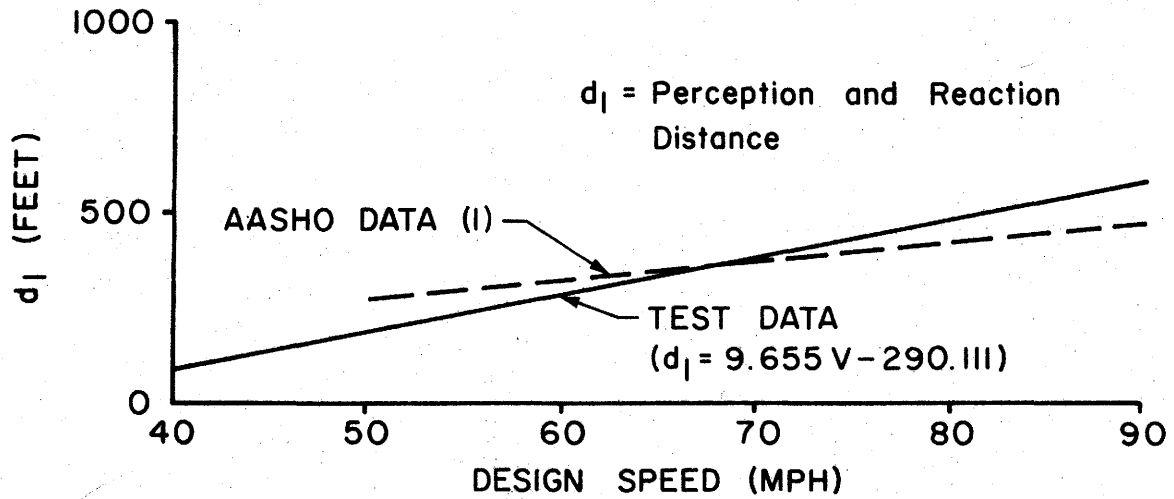
d₂ = 20.408V - 328.811

d₃ = 7.38V - 157.56

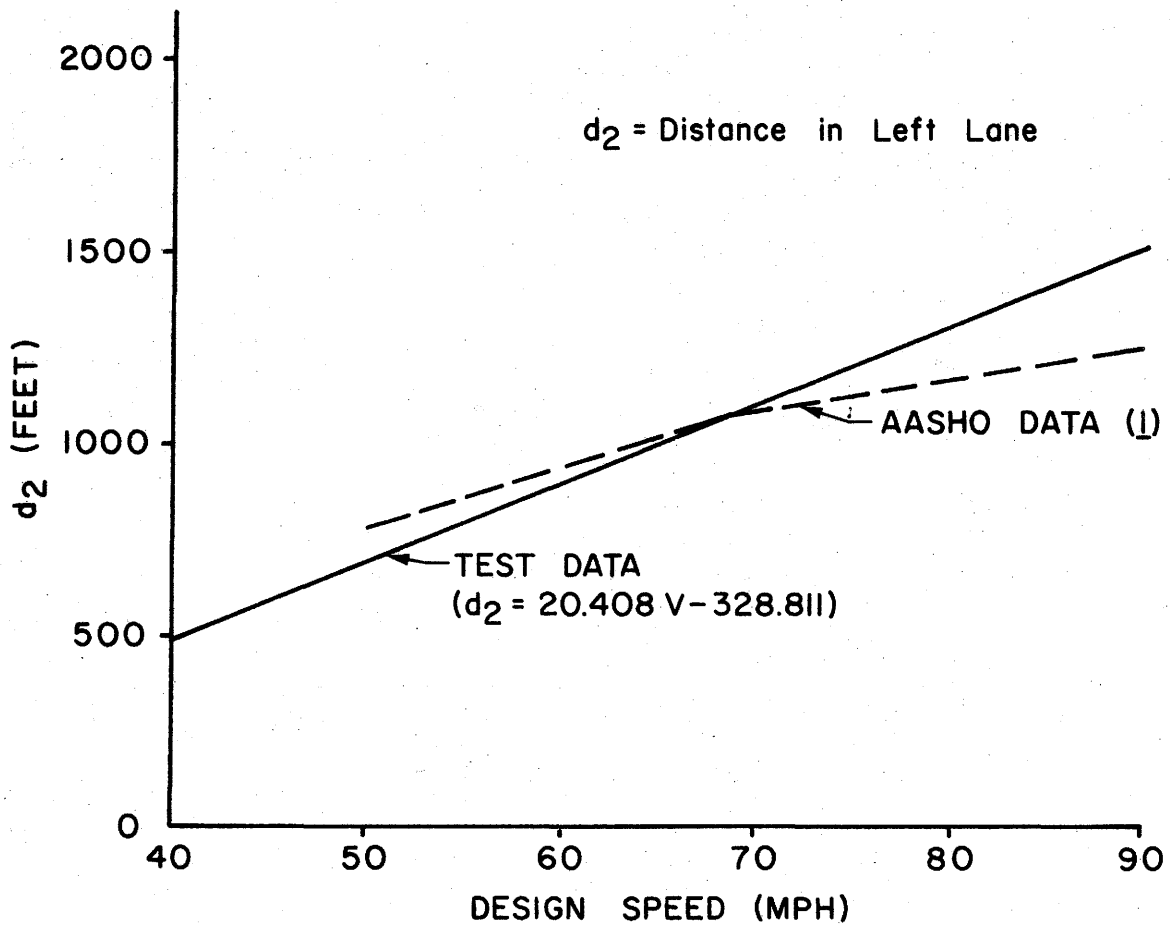
d₄ = 16.430V - 411.156

d_{total} = 53.873V - ~~187.998~~
1187.998

error in equations

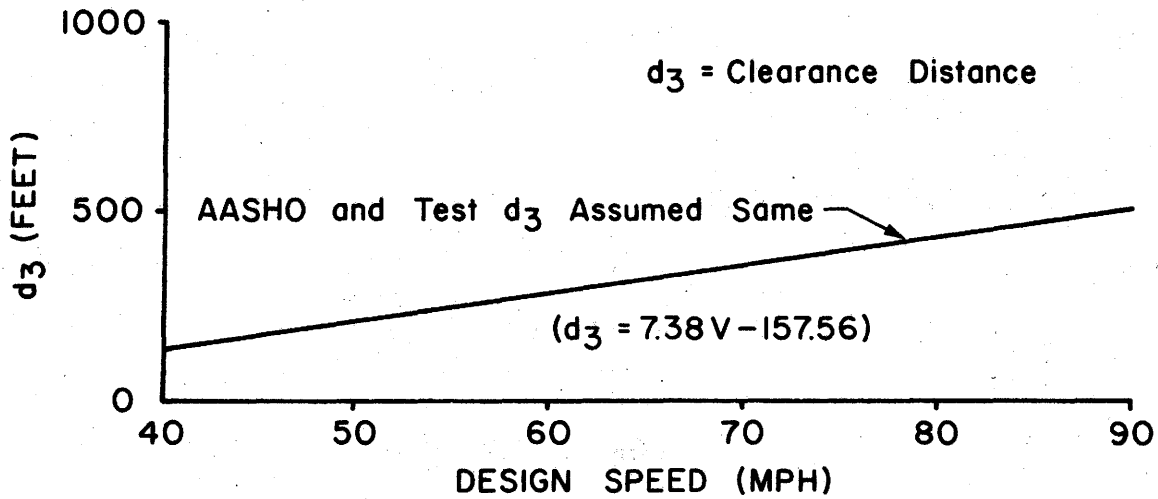


(a) Relation of perception and reaction distance to design speed

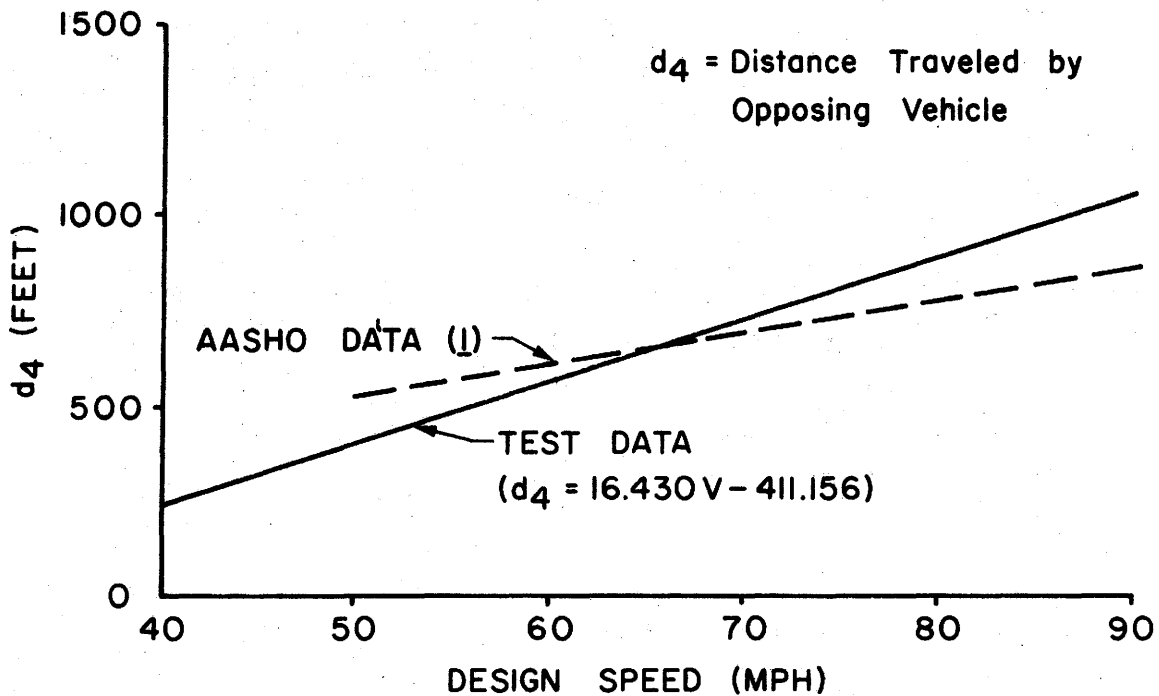


(b) Relation of left-lane distance to design speed

Figure 19

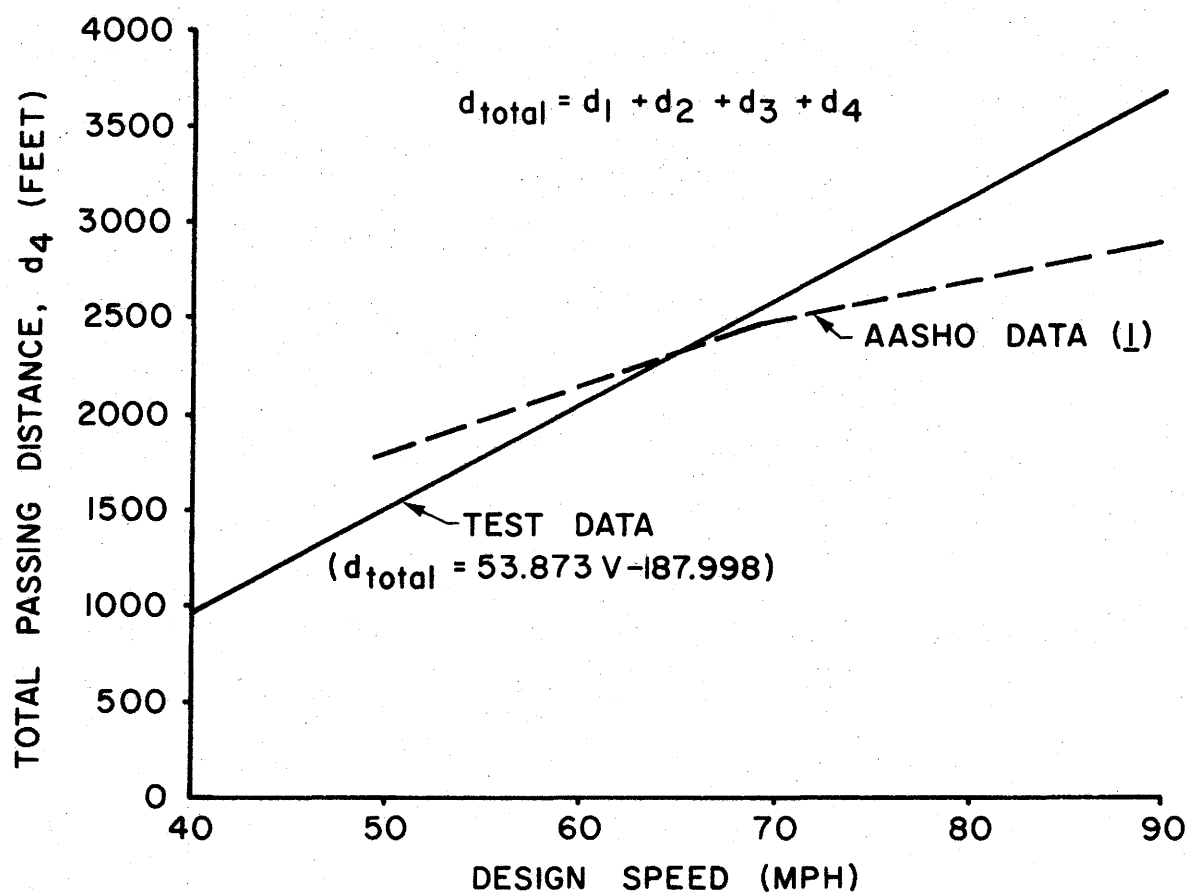


(c) Relation of clearance distance to design speed



(d) Relation of opposing vehicle distance to design speed

Figure 19



(e) Relation of total passing sight distance to design speed

Figure 19

maneuvers (out of more than 3000 selected subjects) were analyzed in the study reported here. Although this represents only a 1:10 ratio of reported data analyzed, many of the assumptions that evolved from the 1938-41 studies were found to remain applicable to current operating characteristics. Comparison of data acquisition methods between the two studies was not possible because no published information was found concerning the equipment used during the 1938-41 studies.

A basic AASHO criterion is that the speed differential between the passing and passed vehicle remains constant at 10 mph regardless of the passing speed. It is important to note that the speed differential decreases as the passed vehicle speed increases. This, in part, explains the divergence of the test and AASHO speed-distance relationships in Figure 19 for the maneuvers above 65 mph. The average 85th percentile speed differential observed during this study was slightly higher than the 10 mph average differential assumed by the AASHO Policy. However, the average 15th percentile differential, which represents the critical operating condition, was less than 10 mph and decreased as the passed speed increased. The net result of the decreasing speed differential was that, for design speeds less than approximately 65 mph, the measured left-lane distances were less than those specified by AASHO. For design speeds in excess of 65 mph, the left-lane distances were greater than the AASHO specifications. Therefore, it appears that the AASHO distance elements are conservative (possibly containing some built-in safety factors) for design speeds less than 65 mph. However, they appear to be unconservative for design speeds above 65 mph. The hazard associated with the passing maneuver increases with passing speed, particularly

when the required left-lane distance is increased due to the reduction in speed differential.

The average left-lane distance traveled by the passing vehicle in accelerating from a trailing position to the critical point adjacent to the passed vehicle was $0.34d_2$. The assumption made during the 1938-41 studies that an approaching vehicle travels a time equal to that of traversing $2/3d_2$ during the "critical" portion of the maneuver appears to be valid for current operating characteristics.

DRIVER CHARACTERISTICS

Other driver characteristics were noticed during the field measurements. Most drivers trailed the impeding vehicle by about two car-lengths as they approached the beginning of the passing zone. After perceiving ample passing distance, they accelerated rapidly until nearly adjacent to the passed vehicle, then completed the passing maneuver at a relatively uniform speed. Many were decelerating during the return transition, which indicated a "coasting" action. This was evident to the observers in the study vehicles, and was verified by the film analysis.

VI. PROPOSED DESIGN FOR PASSING SIGHT DISTANCE

The primary objective of this research was to evaluate existing passing sight distance standards for high-speed passing maneuvers under current rural highway operating conditions, and develop, where appropriate, compatible passing sight distance design criteria. Based on the evaluation of existing criteria and standards presented in Section II, a design concept was developed to incorporate the operational aspects of the passing maneuver. This concept is based on the safety requirements of the passing maneuver, and includes sight distance design and striping provisions. Having established the concept, passing maneuvers under actual highway conditions were photographed and analyzed to provide operational data.

In this section, the proposed design concept is summarized, the distance elements obtained from the field measurements are tabulated, the resulting criteria are compared to the AASHO and MUTCD passing sight distance standards, and design implications are discussed.

PASSING SIGHT DISTANCE DESIGN CRITERIA

The concept discussed previously in Section II is summarized below:

1. Design speed, passing vehicle speed, and approach vehicle speed are synonymous.
2. Minimum length of passing zone is $d_1 + d_2$.
3. Minimum sight distance at any point throughout the passing zone is $4/3d_2 + d_3$.

4. Minimum available sight distance at the beginning of a passing zone is the sum of the minimum length of passing zone and the minimum sight distance throughout the zone, $d_1 + 2.33d_2 + d_3$.
5. The distance elements in the above criteria represent average distances for the critical speed differentials.

d_1 = perception and reaction time to initiate the maneuver.

d_2 = distance traveled in the left lane.

d_3 = clearance distance between the passing vehicle and an opposing vehicle at the time the passing vehicle returns to the right lane.

APPLICATION TO DESIGN AND OPERATIONS

Not only should passing sight distance and striping standards be based on the same criteria, but the operational aspects should be incorporated at the design stage where alignment and profile changes are economically feasible. Design distances for various design speeds determined under the criteria summarized above are discussed in this section. Passing sight distance design values are presented in Table 4. Minimum sight distances for striping no-passing zones are presented in Table 5, and minimum lengths of passing zones are shown in Table 6. The AASHO Policy passing sight distance design values are shown in Table 4 for comparison. In Tables 5 and 6, the MUTCD values are compared to those determined from the proposed design concept in this research.

TABLE 4

PASSING SIGHT DISTANCE DESIGN
DISTANCES BASED ON FIELD MEASUREMENTS

Design Speed (mph)	Minimum Length of Passing Zone (ft)	Minimum Sight Distance Throughout Passing Zone (ft)	Minimum Available Sight Distance At Beginning of Zone (ft)	AASHO Passing Sight Distance Design Distance (1) (ft)
	$(d_1 + d_2)$	$(4/3 d_2 + d_3)$	$(d_1 + 2.33d_2 + d_3)$	
50	885	1135	2020	1800
60	1185	1480	2665	2100
65	1335	1655	2990	2300
70	1485	1825	3310	2500
75	1635	2000	3635	2600
80	1785	2170	3955	2700
85	1935	2345	4280	

TABLE 5
 MINIMUM SIGHT DISTANCES
 FOR STRIPING NO-PASSING ZONES

85th Percentile Speed	Distance Based on Field Measurements	1971 MUTCD (2)
30	--	500
40	--	600
50	1135	800
60	1480	1000
70	1825	1200
75	2000	--

TABLE 6

MINIMUM LENGTHS OF PASSING ZONES
 (Minimum Distance Between Successive No-Passing Zones)

1971 MUTCD (2)		Zone Length Based on Integrated Design Concept	
Prevailing Speed (mph)	Length of Passing Zone (ft)	Design Speed (mph)	Length of Passing Zone (ft)
30	400	--	--
40	400	50	885
50	400	60	1185
60	400	70	1485
		80	1785

In applying the concept developed in this research to design, the sight distance and operational distance must be considered as inter-related elements in the total design. Merely providing a specified sight distance at the crest of a vertical curve will not always produce an adequate passing zone. Adequate sight distance to encourage and permit a safe passing maneuver must be provided throughout a distance in which the passing driver can physically perform the maneuver.

Examination of the proposed sight distances in Table 4 reveals several important factors that should be considered in passing sight distance design. For every design speed condition, the passing sight distances at the beginning of the zone exceed the AASHO Policy standards. The available sight distance at the beginning of a zone is determined in a "reverse" order to current design. The terminal end of the passing zone is established by determining the point on the profile where sight distance is limited to $4/3d_2 + d_3$. Then the beginning of the passing zone is located upstream from this point a distance equal to or greater than the minimum passing zone length of $d_1 + d_2$ for the design speed. The sight distance at the beginning of the zone must, therefore, be at least the sum of these two distances, or $d_1 + 2.33d_2 + d_3$.

Under this design concept, a profile that provides a minimum of $4/3d_2 + d_3$ sight distance (for example, 1825 feet for a 70 mph design speed) throughout its entirety would produce continuous passing opportunity.

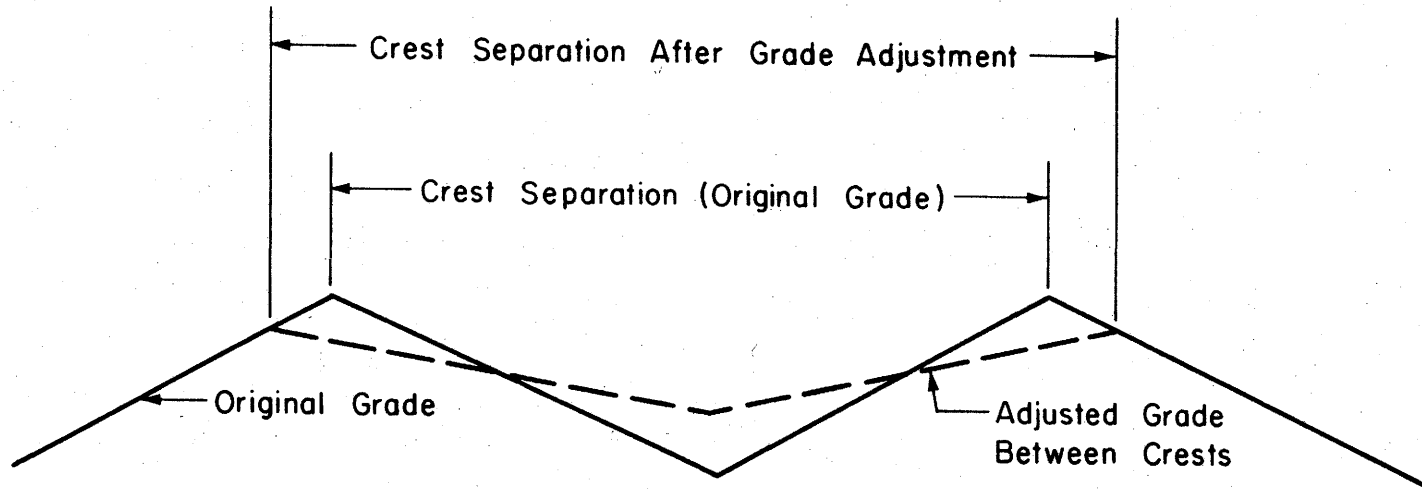
Using the 70-mph design speed to illustrate, another design consideration is revealed in Table 4. If the spacing between successive

crests is equal to or greater than 3310 feet, adequate sight distance and passing zone length are automatically provided in the sag. If, however, the distance is slightly less than 3310 feet, and neither crest affords 1825 feet of sight distance, an adequate passing zone does not exist. In this case, a passing zone might be provided by minor adjustments to the grade lines, thus increasing the operational efficiency of the facility.

Historically, vertical profiles have been established, or at least greatly influenced, by the economic considerations of earthwork. Although the balance of cut and fill is important in establishing profile, it is possible that a substantial increase in efficiency may be attained by minor adjustments in grade. Flattening grade lines in a sag, in effect, moves both crests outward as illustrated in Figure 20. Also, sight distance over the crest is improved. Long vertical curves are required to provide adequate passing sight distance on crests, especially for the higher design speeds.

From these considerations, proper passing sight distance in rolling terrain is clearly influenced by profile establishment. Computer programs are used widely to establish profile. It is suggested that cost-effectiveness techniques may be incorporated to determine the benefits derived from grade adjustments for reasons other than merely earthwork balance.

Other considerations in passing sight distance design would include determination of the "break-even" length of passing zones for



Effect of grade adjustment on crest separation

Figure 20

particular design speeds. What is the optimum zone length from an operational or utilization aspect? To what degree is efficiency improved by providing a zone length greater than the minimum design? Limited studies (4) have been conducted to investigate the utilization of short passing zones. These studies indicated that utilization increased rapidly for lengths of passing zones greater than about 900 feet for passing zones based on the current MUTCD standard of 1200 feet sight distance.

Obviously, there exists a passing zone length that many drivers will consider inadequate for the performance of a safe passing maneuver. If the acceptable length is greater than the design minimum, there would be little utilization of the zone, and its presence on the facility would be meaningless to operational efficiency. Additional research is obviously warranted to provide the necessary data on which to base cost-effectiveness evaluations.

REFERENCES

1. A Policy on Geometric Design of Rural Highways. American Association of State Highway Officials, 1965.
2. Manual on Uniform Traffic Control Devices For Streets and Highways. U. S. Department of Commerce. Washington, D.C., 1971.
3. Weaver, Graeme D., and Glennon, John C. "The Passing Maneuver As It Relates to Passing Sight Distance Standards." Research Report 134-1. Texas Transportation Institute, August 1969.
4. Jones, J. R. "An Evaluation of the Safety and Utilization of Short Passing Sections." M. S. Thesis, Texas A&M University. December 1970.
5. 1968 Speed Survey. Planning Survey Division, The Texas Highway Department, 1968.
6. Glennon, John C. "The Desirability of Highway Designs For Operating Speeds Above 70 mph." Paper Presented at 40th Annual Meeting, Institute of Traffic Engineers, September 1970.
7. A Policy on Criteria For Marking and Signing No-Passing Zones on Two and Three Lane Roads. American Association of State Highway Officials, 1940.
8. Normann, O. K. "Progress in Study of Motor Vehicle Passing Practices." HRB Proc., Vol. 19, 1939.
9. Prisk, C. W. "Passing Practices on Rural Highways." HRB Proc., Vol. 21, 1941.

