Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-99/1811-S		

4. Title and Subtitle	5. Report Date
EVALUATION AND MODIFICATION OF SIGHT DISTANCE CRITERIA USED BY TxDOT	September 1998
	6. Performing Organization Code
7. Author(s) Mark D. Wooldridge, Angelia H. Parham, Kay Fitzpatrick, R. Lewis Nowlin, and Robert E. Brydia	8. Performing Organization Report No. Project Summary Report 1811-S
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project No. 0-1811
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P.O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Project Summary: September 1997 - August 1998 14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

Research Project Title: Develop and Evaluate Sight Distance Criteria at Intersections, Interchanges, and Ramps

16. Abstract

Sight distance is an important consideration in roadway design, affecting many aspects of highway safety and operations. Ramp, interchange, and intersection designs are typically completed in tightly constrained spaces with many structural, earthwork, and roadway features present that may obstruct sight distance. These features are not easily moved; if consideration of sight distance constraints is not given early in the design process, designs may be compromised and a reduced level of safety may be encountered by the public on the completed roadway. After conducting a literature review of design criteria, three case studies of interchange ramps, and a thorough review of the TxDOT *Design Division Operations and Procedures Manual*, the authors recommended revisions for the manual. These revisions include material intended to clarify and extend the consideration of sight distance in roadway design.

17. Key Words	18. Distribution Statement
Ramp Design, Sight Distance Criteria, Stopping Sight Distance, Decision Sight Distance, Intersection Sight Distance	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	50	

EVALUATION AND MODIFICATION OF SIGHT DISTANCE CRITERIA USED BY TxDOT

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Report 1811-S
Project Number 0-1881
Research Project Title: Develop and Evaluate Sight Distance Criteria
at Intersections, Interchanges, and Ramps

Sponsored by the
Texas Department of Transportation
In Cooperation with
U.S. Department of Transportation
Federal Highway Administration

September 1998

TEXAS TRANSPORTATION INSTITUTE
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IMPLEMENTATION RECOMMENDATIONS

1. The report provides proposed revisions to the TxDOT *Design Division Operations and Procedures Manual* (herein referred to as the *Design Manual*). The authors recommend that these revisions be incorporated into the *Design Manual* so that they become effective when the next edition of the *Design Manual* is published.
2. Existing TxDOT training courses may also be used to inform designers of the proposed changes to the *Design Manual.*

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. This report was prepared by Mark D. Wooldridge (TX-65791), Angelia H. Parham (TN-100,307), Kay Fitzpatrick (PA-037730-E), R. Lewis Nowlin, and Robert E. Brydia.

ACKNOWLEDGMENT

The project team recognizes Robert B. Stone, project director; Alvin Krejci, Jr., program coordinator; and project advisors Wesley M. Burford, Robert E. Leahey, and Gus Shanine for their time in providing direction and comments for this study. This study was performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

The authors would also like to recognize the following persons for helping with data collection, data analysis, and report preparation efforts: Abishai Polus, Molly Marshall, Shirley Kalinec, Jon Collins, and Kollan Pillay.

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CHAPTER 1

INTRODUCTION

Providing adequate sight distance on a roadway is one of the central tasks of the designer. Adequate sight distance provides motorists with the opportunity to avoid obstacles on the roadway, to merge smoothly with other traffic, and to traverse intersections safely. Ramp, interchange, and intersection designs are typically completed in tightly constrained spaces with many structural, earthwork, and roadway elements present that may obstruct sight distance. These elements are not easily moved; if consideration to sight distance constraints is not given early in the design process, designs may be compromised and may reduce the level of safety on the completed roadway. To facilitate the completion of satisfactory roadway designs, sight distance criteria must be presented in a clear, comprehensive, and unambiguous manner.

The authors first completed a literature review to examine the development of relevant sight distance criteria. Understanding why various criteria were developed and implemented provided a background necessary for the clear understanding of various sight distance equations and recommendations. The review of actual field locations with poor sight distance problems provided a necessary understanding of challenges encountered in design. The authors completed three case studies in the project, examining available sight distance at three different sites. Finally, they reviewed material currently in TxDOT's *Highway Design Division Operations and Procedures Manual*[1] (herein referred to as the *Design Manual*) and recommended modifications.

The objectives of this project were to evaluate the sight distance guidelines contained in the *Design Manual* and improve or modify those guidelines where necessary. The authors placed an emphasis on ramp design in particular, although they also evaluated other sight distance criteria and recommended modifications.

This report provides a review of stopping sight distance, intersection sight distance, decision sight distance, and ramp merge sight distance. Recommended changes to the *Design Manual* centered around updating design values, including additional references to sight distance, and providing additional design tools to help review available sight distance in the design process.

This report is organized into four chapters. Chapter 1 provides background material for the research, with the literature review presented in Chapter 2. Findings from the three case studies are in Chapter 3, and Chapter 4 presents the recommended changes to the *Design Manual.*

CHAPTER 2

LITERATURE REVIEW

The review of sight distance criteria in the literature focused around three sight distance requirements that frequently apply to various situations encountered in design:

- Stopping sight distance;
- Decision sight distance; and
- Intersection sight distance.

In addition, a fourth category was investigated: ramp merge sight distance. Only a limited amount of literature was available regarding this final topic.

STOPPING SIGHT DISTANCE

According to the American Association of State Highways and Transportation Officials (AASHTO) *A Policy on Geometric Design of Highways and Street*[2] (herein referred to as the *Green Book*), sight distance is the length of roadway ahead that is visible to the driver. The *Green Book* also states that the minimum sight distance at any point on the roadway should be long enough to enable a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path. Although greater length is desirable, sight distance at every point along the highway should be at least that required for a below average driver or vehicle to stop in this distance. The NCHRP (National Cooperative Research Program) recently sponsored a study on stopping sight distance.[3] Most of the following material was obtained from the project's reports.

AASHTO Stopping Sight Distance Model Equations

Stopping sight distances are calculated using basic principles of physics and the relationships between various design parameters. The 1994 *Green Book*[2] defines stopping sight distance as the sum of two components: brake reaction distance (distance traveled from the instant the driver detects an object to the instant the brakes are applied) and the braking distance (distance traveled from the instant the driver applies the brakes to when the vehicle decelerates to a stop).[2] Minimum and desirable stopping sight distances are calculated with the following equation:

$$SSD = BrakeReactionDistance + BrakingDistance \quad \textbf{(2-1)}$$

$$SSD = 0.278Vt + \frac{V^2}{254f} \quad \textbf{(2-2)}$$

where: SSD = stopping sight distance, m;
V = design or initial speed, km/h;
t = driver perception-reaction time, s; and
f = friction between the tires and the pavement surface.

The minimum length of vertical curves is controlled by the required stopping sight distance, driver eye height, and object height. This required length of curve is such that, at a minimum, the stopping sight distance calculated is available at all points along the curve. Where an object off the pavement such as a bridge pier, bridge railing, median barrier, building, cut slope, or natural growth restricts sight distance, the required offset to that obstruction is determined by the stopping sight distance.

Most people agree that the AASHTO stopping sight distance model results in well-designed roads, i.e., roads that are safe, efficient, and economical. If so, why develop a revised model? The need for a revised model has been defined elsewhere[4] as follows:

- The current stopping model was based on common sense, engineering judgment, and the laws of physics; however, the parameters within the model are not representative of the driving environment. Thus, the parameters are difficult to justify, validate, and/or defend.
- It has never been established on the basis of data that the provision of longer stopping sight distance results in fewer accidents. Conversely, it has never been established on the basis of data that at least for marginal reductions, provision of shorter stopping sight distance results in more accidents.

As noted, the major criticism of the current model is that its parameters are not representative of the driving environment or safe driving behavior. Thus, although its use results in a good design, it is difficult to justify, validate, and defend as a good model. As a result of these difficulties, a recent NCHRP project recommended a relatively simple driver performance based model[3] as a replacement for the current *Green Book* model.[2] The recommended model is as follows:

$$SSD = 0.278Vt + \frac{0.039V^2}{a} \tag{2-3}$$

where: SSD = stopping sight distance, m;

V = initial speed, km/h;

t = driver perception-brake reaction time, s; and

a = driver deceleration, m/s^2.

An implicit assumption of a driver performance stopping sight distance model is that the tire/pavement friction must meet or exceed the driver's demands for stopping.

For consistency, it was recommended that the parameters within the recommended stopping sight distance model represent common percentile values from the underlying probability distributions. Specifically, 90th (or 10th) percentile values are recommended for design. The resultant values are as follows:

- One design speed and stopping sight distance;
- Perception—brake reaction time—2.5 s;
- Driver deceleration— 3.4 m/s^2;
- Driver eye height—1080 mm; and
- Object height—600 mm.

The new model results in stopping sight distances, sag vertical curve lengths, and lateral clearances between the current minimum and desirable requirements. Crest vertical curve lengths are shorter than current minimum requirements using the new SSD model. (See Figure 2-1 and Table 2-1.)

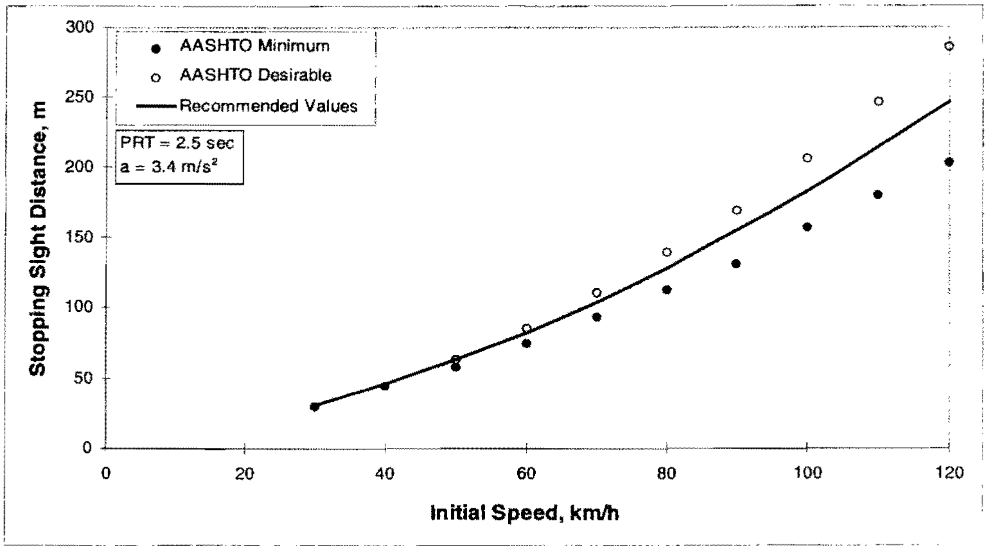

Figure 2-1. Comparison of 1994 AASHTO and Recommended Values for Stopping Sight Distance[3]

Table 2-1. Recommended Stopping Sight Distances for Design[3]

Initial Speed (km/h)	Perception-Brake Reaction		Deceleration (m/s^2)	Braking Distance (m)	Stopping Sight Distance for Design (m)
	Time (s)	Distance (m)			
30	2.5	20.8	3.4	10.2	31.0
40	2.5	27.8	3.4	18.2	45.9
50	2.5	34.7	3.4	28.4	63.1
60	2.5	41.7	3.4	40.8	82.5
70	2.5	48.6	3.4	55.6	104.2
80	2.5	55.6	3.4	72.6	128.2
90	2.5	62.5	3.4	91.9	154.4
100	2.5	69.4	3.4	113.5	182.9
110	2.5	76.4	3.4	137.3	213.7
120	2.5	83.3	3.4	163.4	246.7

Note: Shading represents sight distances that are beyond most drivers' visual capabilities for detecting small and/or low contrast objects.

DECISION SIGHT DISTANCE

The concept of decision sight distance (DSD) was first addressed in a 1966 paper by Gordon.[5] In his paper, Gordon talked about the concept of "perceptual anticipation". The concern was that the existing stopping sight distance values were too short for situations that required high decision complexity. Building on Gordon's argument, Leisch studied this concept further and defined the term "anticipatory sight distance."[6] This distance provides the necessary time for drivers to anticipate changes in design features (such as intersections, interchanges, lane drops, etc.) or a potential hazard in the roadway and perform the necessary maneuvers.

A 1975 study by Alexander and Lunenfeld[7] defined the term "decision sight distance" as follows:

> "..the distance at which drivers can detect a hazard or a signal in a cluttered roadway environment, recognize it or its potential threat, select an appropriate speed and path, and perform the required action safely and efficiently."

A 1978 FHWA study by McGee et al. developed guidelines on DSD values.[8] Recommended values for DSD were developed based on the hazard-avoidance model. Previous research efforts[9,10,11] developed and modified this model which consists of the following six variables:

1. Sighting: Baseline time point at which the hazard is within the driver's sight line;
2. Detection: Time for driver's eyes to fixate on the hazard;
3. Recognition: Time for brain to translate image and recognize hazard;
4. Decision: Time for driver to analyze alternative courses and select one;
5. Response: Time for driver to initiate response; and
6. Maneuver: Time for driver to accomplish a change in path and/or speed.

Adding the above variables determines the total time required from the moment that the hazard is visible to completion of the maneuver. The results from the study by McGee et al. were used to develop recommended DSD values based on the design speed of the roadway. The recommendations were adopted and introduced in the 1984 AASHTO Green Book.[12]

Current Guidelines in *Green Book*

Because the initial guidelines presented in the 1984 *Green Book* were vague and difficult to apply, the guidelines were updated in the 1990 *Green Book*[13] and remained unchanged in the 1994 revision.[2]

In the 1994 *Green Book*,[2] decision sight distance is defined as follows:

> "...distance required for a driver to detect an unexpected or otherwise difficult-to-perceive information source or hazard in a roadway environment that may be visually cluttered, recognize the hazard or its potential threat, select an appropriate speed and path, and initiate and complete the required safety maneuver safely and efficiently."

The *Green Book*[2] recommends that DSD be provided when drivers must make complex or instantaneous decisions, when information is difficult to perceive, or when unexpected or unusual maneuvers are required. Examples of critical locations where DSD should be considered are:

- Interchange and intersection locations where unusual or unexpected maneuvers are required;
- Changes in cross section such as toll plazas and lane drops; and
- Areas of concentrated demand where there is apt to be "visual noise" whenever sources of information such as those from roadway elements, traffic, traffic control devices, and advertising signs compete.

Recommended values for DSD are shown in Table 2-2. These values are substantially greater than stopping sight distance because of the additional time allowed to maneuver a vehicle. The recommendations in Table 2-2 are based on the location of the road (urban, suburban, or rural) and on the type of maneuver required (change speed, path, or direction). As shown in this table, shorter DSD values are required for rural roads and when a stop maneuver is involved.

Table 2-2. Recommended Decision Sight Distance Values in the 1994 *Green Book*[2]

Design Speed (km/h)	Decision Sight Distance for Avoidance Maneuver (m)[1]				
	A	B	C	D	E
50	75	160	145	160	200
60	95	205	175	205	235
70	125	250	200	240	275
80	155	300	230	275	315
90	185	360	275	320	360
100	225	415	315	365	405
110	265	455	335	390	435
120	305	505	375	415	470

[1]A: Stop on rural road
B: Stop on urban road
C: Speed/path/direction change on rural road
D: Speed/path/direction change on suburban road
E: Speed/path/direction change on urban road

INTERSECTION SIGHT DISTANCE

At-grade intersections have long been a focal point for vehicle conflict. Since the first days of geometric design, the crossing of two roadways has necessitated a compromise between mobility and safety. Over time, formal guidelines for establishing clear sight requirements at intersections have evolved. Developed by AASHO (American Association of State Highway Officials) and later AASHTO (American Association of State Highway and Transportation Officials), these guidelines outline the procedures and requirements necessary for the establishment of safe distances that allow vehicles approaching an intersection either to regulate their speeds such that safe passage across the intersection is achieved by both vehicles or to effect regulatory control on the minor roadway by requiring vehicles to stop and proceed when the major roadway is clear.

The first formal presentation of Intersection Sight Distance (ISD) requirements appeared in the 1940 AASHO publication "A Policy on Intersections at Grade."[14] This initial discussion contained procedures for three general classifications of intersections. Over the next five decades, subsequent publications furthered the concept of intersection sight distance and refined the clear sight requirements. The 1990 *Green Book*[3] included four cases for ISD procedures, and the 1994 *Green Book*[2] added an additional case of vehicles turning left off of the major road onto the minor road for a total of five cases.

The basis of all *Green Book*[2] intersection sight distance requirements is stopping sight distance which was detailed earlier in this report. A vehicle approaching an intersection has the choice of accelerating, slowing, or stopping, depending on the intersection control. The application of intersection sight distance is discussed with regard to a sight triangle, which is a mechanism for applying sight distance along each leg of an intersection. A sight triangle is simply an unobstructed distance along both roadways and across the included corner for a specified distance which should be kept clear of any sight obstructions. A brief discussion of each case in the 1994 policy follows.

Case I

As presented in the original 1940 policy, the concept of a Case I intersection is to allow the drivers of the vehicles to regulate their speeds such that safe passage across the intersection is achieved by both vehicles. That means that the driver of the vehicle has to be able to see an approaching vehicle along the other leg of the sight triangle and moderate his speed accordingly.

Case II

In contrast to Case I, where the concept is to allow vehicle operators to control their speed, Case II is designed to allow the vehicle on the major road to continue at its current speed without stopping. The vehicle on the minor road should regulate its speed and decelerate to a full stop. In order to come to a complete stop, stopping sight distance must be provided along the minor road.

Case III

Case III ISD is applicable when there is a stop sign on the minor road. In this situation the minor road vehicle must be able to see for a sufficient distance along the major roadway for the stopped vehicle to start moving and clear the intersection. The time required to clear the intersection is dependent on the perception time, the time required to engage the vehicle, and the time required to accelerate across the intersection.

Case IV

AASHO publications previous to 1957 did not discuss signalized intersections. The first reference of this situation was acknowledged and then dismissed by stating that normal ISD requirements are not necessary at signalized intersections.

The 1984 *Green Book*[12] gives the first discussion of the Case IV condition by stating that due to the operational considerations inherent at an intersection operated by signalized control, Case III sight distances should be available to the driver. The supporting evidence for this argument is that increased hazards at the intersection warrant this distance, particularly in the event of failure of the signal, violations of the signal, or other possibilities such as right turns on red. Neither the 1990 or 1994 policies furthered the 1984 discussions.

Case V

The 1994 *Green Book*[2] contained the first writeup for vehicles stopped on the major road and turning left onto the minor road. Labeled as Case V, the driver turning left must be able to see a sufficient distance ahead to turn left and clear the opposite lane before a vehicle in that lane reaches the intersection.

Recent Study

In an attempt to answer many of the questions concerning intersection sight distance, such as what are the appropriate methodologies and parameter values, the National Cooperative Highway Research Program (NCHRP) funded a study on ISD which concluded in 1996. The explicit goal of this project was to examine the current AASHTO methodology and recommend new or revised models and/or parameters for Cases I through V. Published in 1996, the final report[17] made the following recommendations:

- Case I rationale should be changed to allow both vehicles the opportunity to stop rather than adjusting speed because adjusting speed requires both drivers to take the correct action. A new model was formulated which accounts for this change.

- Case II recommended ISD values are longer than current AASHTO values to a driver approaching a yield-controlled intersection greater flexibility over a stop-controlled intersection.
- Case III methodology is recommended to use gap acceptance. The standard length of the departure sight triangle along the major road was recommended to be 7.5 seconds for passenger car vehicles, 9.5 seconds for single unit trucks, and 11.5 seconds for combination trucks. The length of the departure sight triangle on the minor road was 4.4 m.
- Case IV sight distance follows the new values and the gap acceptance methodology recommended for Case III. When signals are to be placed on flashing operation for low volume periods, the departure sight triangles for Case III operations should be provided. Where right-turn-on-red operations are allowed, the Case III departure sight triangle for right turns must be provided.
- Case V operations are to be modeled on gap acceptance operations and include adjustments for the number of lanes to be crossed.

RAMP MERGE SIGHT DISTANCE

In a 1960 study, Pinnell[15] reviewed entrance ramp characteristics and investigated sight distance. According to Pinnell, drivers exhibit a more desirable entrance ramp behavior when provided adequate sight distance to the main lanes. When drivers were provided with a view of the main-lane vehicles from 200 feet upstream of the ramp nose, the drivers were able to merge with low relative speed differentials between their vehicles and the vehicles on the main lanes. This view allows the drivers to adjust their speed to provide entry to a suitable gap in the traffic. Another examination of sight distance required on an entrance ramp was completed by Bhise[16] in 1973. Although the study was oriented towards vehicle design and the constraints placed on drivers by roof pillars and other vehicle obstructions, the performance of the test drivers was monitored on a wide variety of ramps. In this study, the search and scan behavior of drivers on on-ramps was monitored with an eye-mark camera system. Drivers on the ramps were observed to be actively searching for main-lane vehicles as much as 10 seconds prior to the ramp nose. A recommendation was made that drivers be able to observe traffic on the main lanes for 10 seconds prior to and after the nose of the ramp. This study was very limited in scope, however, and the findings were based on data from four young male drivers only.

CHAPTER 3
RAMP CASE STUDIES

Sight distance restrictions in freeway interchanges can be problematic because of the likelihood of high traffic volumes and highly restrictive design environments. Ramps geometries are typically at or very near minimum design values because of the high cost of right-of-way (ROW) and the high cost of providing bridge structures. Providing a ramp designed at minimum values is not problematic in and of itself because of the large factors of safety generally present in even a "minimum" level design. Challenges may arise, however, if safety or operational improvements are needed because the same restrictions present in the original design (plus, perhaps, restrictions present as a result of new structures built or proposed for construction subsequently) prevent easy modifications.

To gain additional information regarding "typical" sight distance impediments in the urban environment, the researchers undertook three field investigations. These investigations focused on on-ramps with sight distance limitations.

CASE STUDY A

The first case study was a direct-connect ramp at an urban interchange of two access-controlled freeways. A photograph of the ramp, designed in 1987, is shown in Figure 3-1. The design, constrained by the complex geometry inherent in a multilevel urban interchange, is bordered by a retaining wall on the inside of the curve. Other aspects of the ramp are typical of a high-standard interchange: concrete barriers, metal beam guard fence, and safety end treatments are provided at obstacles and dropoffs; drainage details and cut- and fill-slopes appear to be acceptable; and vertical curvature rates are relatively modest.

The horizontal curve radius and offset distance were reviewed to evaluate available sight distance on the ramp. The applicable sight distance criteria is stopping sight distance (SSD), which should be provided at every point along an alignment. The value of SSD used, however, is contingent on the design speed selected for use by the designer. Three different values for design speed are suggested in the 1994 *Green Book*[2] and the *Design Manual*,[1] representing various percentages of the design speed on the connecting highway. These values are characterized as upper range (85 percent), middle range (70 percent), and lower range (50 percent). Although the exact design speeds actually used by the designers on the connecting highways were not available, desirable (110 km/h) and minimum (80 km/h) design speeds used by TxDOT for controlled access facilities were used for the purposes of this analysis. The minimum and desirable offset distances were calculated using the minimum desirable SSD for the various design speed values.

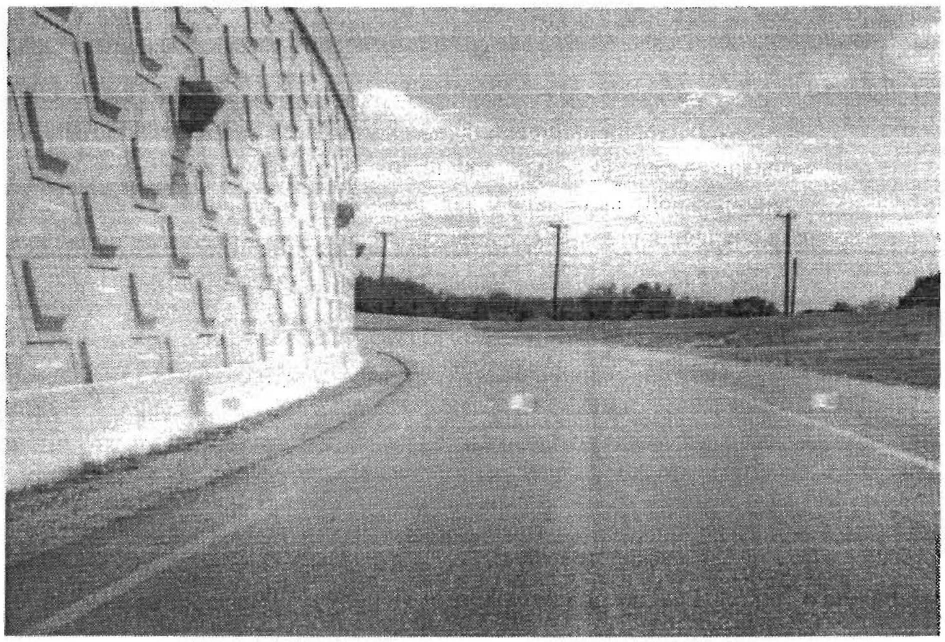

Figure 3-1. Case Study A: Direct Connect Ramp

Comparing the measured offset to calculated offset distances that represent a range of design speeds, researchers found that the site provided sight distance adequate for a design speed of 60 km/h. This design speed, however, met the "middle range" requirement when the minimum main-lane design speed (80 km/h) was used as a basis for the ramp design speed, and it met the "lower range" requirement when the desirable main-lane design speed (110 km/h) was used as the basis for the ramp design speed.

Although design speed and the appropriateness of the design criteria shown in the 1994 *Green Book*[2] and the *Design Manual*[1] are outside the bounds of this study, it appears that the use of the lower range design speed would be questionable in this case. If this lower range design speed were used for design purposes, however, the available sight distance on the ramp provided by the offset (7.62 m) would exceed the offsets calculated using both minimum and desirable SSD requirements (3.69 and 4.78 m, respectively). To provide a frame of reference for the ramp, a spot speed study was conducted to determine the operating speed on the ramp. Speeds of free-flow vehicles were measured in approximately the middle of the ramp. The measured offset distance corresponds to a design speed of 60 km/h which was roughly the 3rd percentile operating speed on the facility.

The middle range design speed based on a design speed of 110 km/h on the main lanes corresponded to approximately the 85th percentile speed. This speed appears to represent a more realistic design condition in this case. For example, an offset calculated using desirable SSD requirements would exceed that value available by 5.26 m; however, calculated using minimum SSD requirements, the offset would exceed that width available by only by 0.85 m.

Ramp and direct connection shoulder width design values used by TxDOT[1] provide a total shoulder width of 2.4 to 3.6 m, allowing motorists to bypass stalled vehicles on one-lane ramps. An alternative design solution to this existing ramp could be to provide a narrower outside shoulder and correspondingly wider inside shoulder, providing the additional 0.85 m offset. This would provide greater sight distance and still permit bypassing stalled vehicles on the ramp.

CASE STUDY B

The second case study examined the on-ramp shown in Figures 3-2 and 3-3. The ramp connects the local street network to a limited access freeway. The ramp design was complicated by two factors: an historic structure limiting the availability of right-of-way and a harbor bridge that provides clearance for large ocean-going ships. Both the horizontal and vertical curvature limited the available sight distance on the ramp. The concrete parapet at the top of the retaining wall created the small offset distance available on the inside of the horizontal curve on the ramp; the retaining wall was necessary to prevent encroachment on the historic structure. The sharp vertical curvature was dictated by the large grade difference and short horizontal distance between the surface street network and the approach to the harbor bridge.

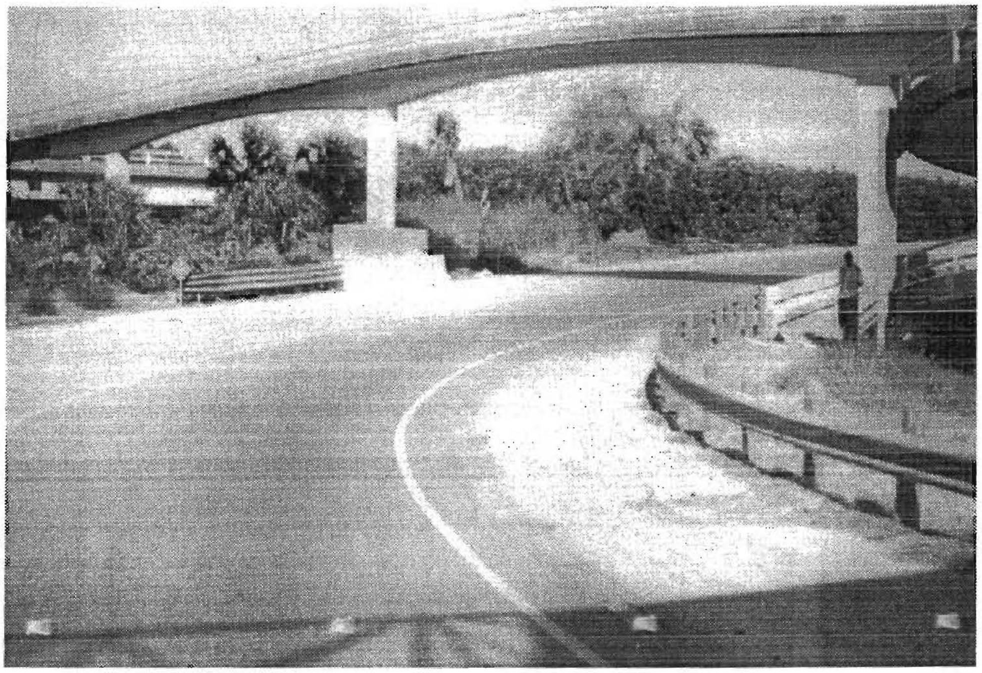

Figure 3-2. Case Study B: Horizontal Curvature

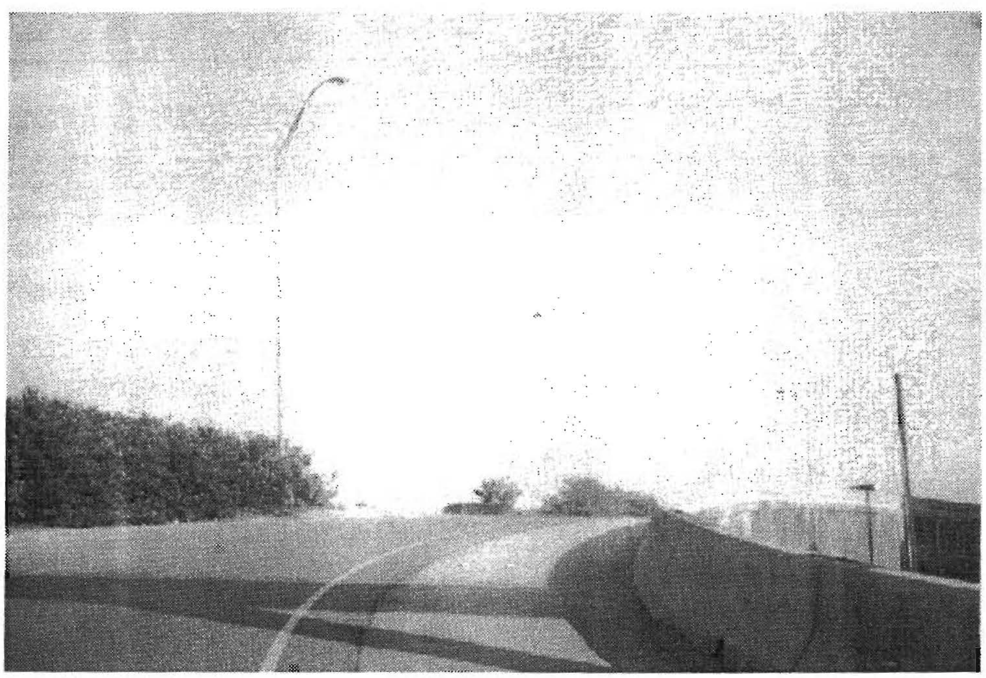

Figure 3-3. Case Study B: Vertical Curvature

Horizontal Curvature

Similarly to case study A, alternative design speeds were examined to compare resulting offset distances to those actually provided for the on-ramp. These design speeds (based again on assumed 110 km/h and 80 km/h main-lane design speeds) ranged from 40 to 100 km/h; the 85th percentile speed was approximately 50 km/h. The existing offset for the horizontal curve at the study site (5.82 m) exceeded the value calculated (5.12 m) using the lower range design speed of 40 km/h (based on a main-lane design speed of 80 km/h). This offset corresponded to the 32nd percentile operating speed. Meeting the minimum calculated offset for the 85th percentile operating speed would require an additional 2.63 m, while meeting the desirable calculated offset would require an additional 4.24 m.

Widening the inside shoulder would partially alleviate the sight distance constraints imposed by the concrete parapet on the retaining wall, allowing the site to meet the 85th percentile operating speed minimum offsets. Because the site has a larger than required shoulder on both the inside and outside of the curve, this width increase could be accomplished without moving the retaining wall. Meeting either the middle range or upper range criteria would require moving the retaining wall or changing the typical section to eliminate the concrete barrier. Either modification would be extremely costly and politically difficult to accomplish.

Vertical Curvature

The vertical curvature used in the design at case study B site constrained sight distance. The crest vertical curve used at the apex of the ramp did not meet SSD requirements for the design speeds reviewed. The curve length provided was 7 m shorter than required for the lowest design speed, 40 km/h.

Solutions to the concerns with the site's vertical alignment are difficult to derive. A longer vertical curve would overlap with the sag curve prior to the crest curve and prevent attaining a tie-in with the grades on the freeway. Raising the grade on the local street network would require rebuilding a number of at-grade intersections and streets and would reduce the clearance at one of the freeway structures, while lowering the grade on the freeway would reduce clearance for the harbor bridge (unacceptable) and also reduce clearance over the local street network.

CASE STUDY C

Case study C reviewed the design of an on-ramp connecting a frontage road to an exit ramp from a freeway. The relatively unusual ramp location resulted from the stage construction of the multiple freeways in the immediate vicinity, with the ramp providing needed access that has since become redundant. The ramp, now permanently closed, provided problematic operation and an unacceptably high accident rate while it was in operation.

Reviewing sight distance restrictions at the site, attention focused on the vertical alignment. A crest and a sag vertical curve are present on the ramp which descends from the frontage road to merge with the exit ramp (see Figures 3-4 and 3-5). An examination revealed that the design for each curve met lower range ramp design speed desirable length criteria for both 80 and 110 km/h main-lane design speeds. Comparisons regarding the 85th percentile operating speed were not available because of the ramp's closure.

Sight distance on the vertical curves present at the site appeared to be relatively good, although it would have been desirable to compare operating speeds on the ramp with the design speeds presented. Reasons for the poor performance of the ramp could be charged to several issues (and have indeed been the subject of an extensive investigation). Modifications to the vertical alignment of the ramp to improve available sight distance would be possible, although relatively expensive due to the rolling terrain. The improvement might have improved the performance of the facility, although the efficacy of such measures appears doubtful given the relatively good design standard already in place.

CONCLUSIONS

The case studies revealed that appropriate design criteria are somewhat difficult to discern in advance of the construction of a facility. Care must be taken to select appropriate design speeds that yield acceptable designs. Design speeds that, although acceptable according to guidelines, only accommodate a small percentage of drivers are problematic and inappropriate. Of course, the difficulty lies in accurately predicting which design speeds *are* appropriate.

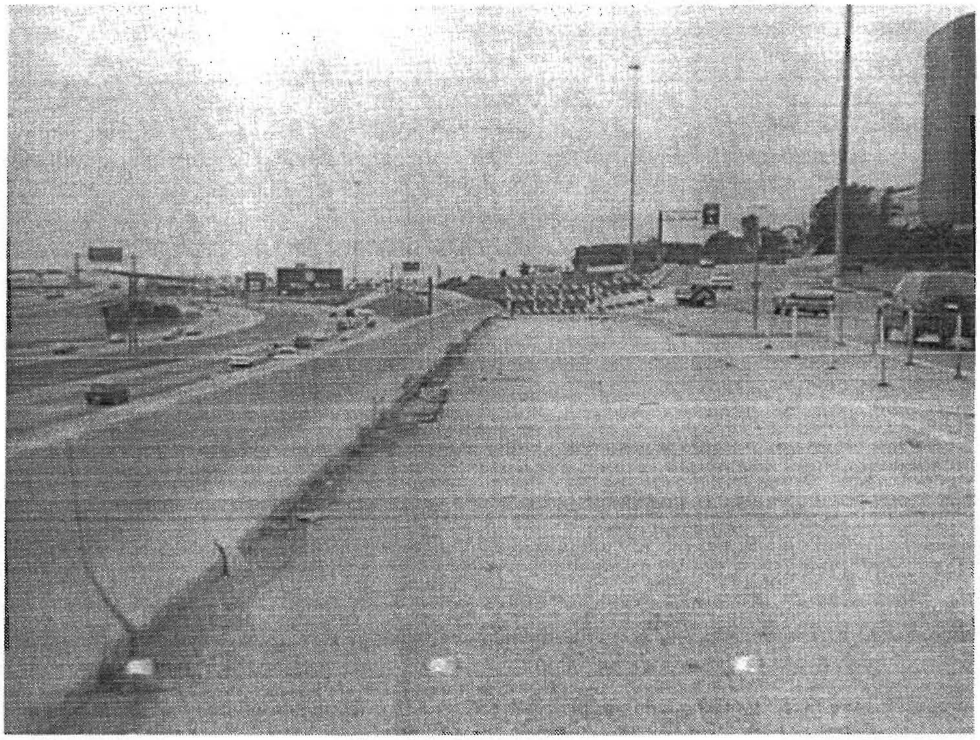

Figure 3-4. Case Study C: Crest Vertical Curve

Figure 3-5. Case Study C: Sag Vertical Curve

Critiquing a design from the viewpoint of information not available to the designer at the time the design was completed (i.e., using a spot speed study to calculate an 85th percentile speed) is somewhat unrealistic and limited in application. It does, however, lead to the desire to have additional guidance about the selection of ramp design speed in general. Reasonably accurate predictions about operating speeds and design conditions on ramps would be helpful to the designer as ramp curvature and sight distance requirements are selected for use in the design of an interchange. However, ramp design speed lies outside the bounds of this study and is currently the subject of other TxDOT research.

Clearly, the central issue remains that designers and planners must recognize at an early point in the design of a facility that sight distance is of great importance in the operation of that facility. Both vertical and horizontal curvature must be examined with regard to their impacts on sight distance. Although some modifications can be made to improve available sight distance at a given location, frequently those modifications are either extremely expensive or virtually impossible to effect once the facility is in place.

CHAPTER 4

RECOMMENDATIONS FOR IMPLEMENTATION

This chapter provides proposed revisions to the *Design Manual.*[1] It is recommended that these revisions be incorporated into the current rewrite of the *Design Manual* so that they become effective when the *Design Manual* is republished. Existing TxDOT training courses may also be used to inform designers of the proposed changes to the *Design Manual.*

The *Design Manual* communicates recommended design practices, procedures, and criteria to highway designers and engineers. Although other references and design materials are frequently and necessarily used by designers and engineers at TxDOT, this manual provides guidance regarding geometric design.

The *Design Manual* has a number of references to sight distance in various sections, but substantive guidance is provided only with regard to stopping sight distance and passing sight distance. Material related to intersection sight distance is scant, and decision sight distance is not mentioned in the manual.

Stopping sight distance criteria are provided in the section on Basic Design Criteria. In this section, a table presents minimum and desirable stopping sight distance values for design speeds from 30 to 120 km/h. The minimum and desirable values reflect the range of stopping sight distance values given in the 1994 *Green Book.*[2] The values in the *Design Manual*, however, are rounded up to the nearest value of 10. In some instances, this results in a recommended value 9 m higher than what is recommended in the *Green Book.*

Stopping sight distance is also addressed in the section on freeways in the discussion of sight distance on ramps. In this section, the manual maintains that stopping sight distance is provided along ramps from the terminal junctions along the freeway.

Intersection sight distance is mentioned very briefly in the discussions on intersections in each of the following sections of the manual: Urban Streets, Multilane Rural Highways, and Two-Lane Rural Highways. In these sections, general statements are provided regarding intersection sight distance and directing the reader to relevant sections of the manual.

Specific recommended changes to the text of the *Design Manual* follow. A brief discussion of the reason for the changes is included with suggested wording for the recommended modifications. Figure and table numbers within the material quoted from the *Design Manual* refer to the figures and tables as numbered within the *Design Manual.* Figures and tables are provided only where proposed for modification (i.e., figures or tables extraneous to any proposed modifications are not included).

BASIC DESIGN CRITERIA, DESIGN ELEMENTS, Sight Distance

In this section of the manual, sight distance is introduced with a brief rationale for its importance. The only two types of sight distance previously mentioned, however, are stopping sight distance and passing sight distance. Therefore, decision sight distance and intersection sight distance are added to the discussion.

> Of utmost importance in highway design is the arrangement of geometric elements so that there is adequate sight distance for safe and efficient traffic operation assuming adequate light, clear atmospheric conditions, and drivers' visual acuity. For design, ~~two types of sight distance are considered: that for overtaking vehicles, and that required for stopping. Passing sight distance is applicable only in the design of two-lane rural highways and therefore is presented in Paragraph 4-502(D)~~ four types of sight distance are considered:
>
> - Stopping sight distance;
> - Decision sight distance;
> - Passing sight distance; and
> - Intersection sight distance.

BASIC DESIGN CRITERIA, DESIGN ELEMENTS, Sight Distance, Stopping Sight Distance

This section defines stopping sight distance and includes the criteria for its application. Table 4-1 [*Design Manual* Figure 4-3] provides distances to be used for various design speeds. Previously, a very conservative hard conversion from English to metric units was used, providing up to an 11 percent increase in required sight distance. Because the values provided meet current design criteria and are already quite conservative, it is recommended that values are rounded to the nearest meter rather than to the nearest ten meters.

> Minimum stopping sight distance is the length of roadway required to enable a vehicle traveling at or near design speed to safely stop before reaching an object in its path. Minimum stopping sight distance values for various design speeds are tabulated in Figure 4-3 [research report Table 4-1]. These values are based on driver's eye height of 1,070 mm and object height of 150 mm as recommended by AASHTO. After selection of design speed, stopping sight distance values become a controlling element for several basic design features such as roadway alignment and non-signalized intersection design. Greater than minimum stopping sight distances should normally be used, and minimum values should be used only in select instances where economic or other restrictive conditions dictate (see Minimum Standards).

Table 4-1. Recommended Changes to *Design Manual* Figure 4-3

Figure 4-3. Stopping Sight Distance Values (Wet Pavements).		
Design Speed (km/h)	Stopping Sight Distance (m)	
	Minimum	Desirable
30	30	30
40	~~50~~ 45	~~50~~ 45
50	~~60~~ 58	~~70~~ 63
60	~~80~~ 75	~~90~~ 85
70	~~100~~ 95	~~120~~ 111
80	~~120~~ 113	140
90	~~140~~ 132	~~170~~ 169
100	~~160~~ 157	~~210~~ 205
110	180	~~250~~ 247
120	~~210~~ 203	~~290~~ 286

BASIC DESIGN CRITERIA, DESIGN ELEMENTS, Sight Distance, Decision Sight Distance

It is recommended that a section defining decision sight distance be provided to designers. Criteria for its use should also be included.

Decision sight distance is the distance required for a driver to detect an unexpected or otherwise difficult-to-perceive information source, recognize the source, select an appropriate speed and path, and initiate and complete the required maneuver safely and efficiently. Because decision sight distance gives drivers additional margin for error and affords them sufficient length to maneuver their vehicles at the same or reduced speed rather than to just stop, its values are substantially greater than stopping sight distance. Table 4-2 [research report Figure 4-2] shows recommended decision sight distance values for various avoidance maneuvers.

Examples of situations in which decision sight distance is preferred include the following:

- Interchange and intersection locations where unusual or unexpected maneuvers are required (such as exit ramp gore areas and left-hand exits);
- Changes in cross section such as toll plazas and lane drops; and
- Areas of concentrated demand where there is apt to be "visual noise" whenever sources of information compete, as those from roadway elements, traffic, traffic control devices, and advertising signs.

Table 4-2. Recommended New Table

Table. Recommended Decision Sight Distance Values					
Design Speed (km/h)	Decision Sight Distance (m)				
	Avoidance Maneuver [1]				
	A	B	C	D	E
50	75	160	145	160	200
60	95	205	175	205	235
70	125	250	200	240	275
80	155	300	230	275	315
90	185	360	275	320	360
100	225	415	315	365	405
110	265	455	335	390	435
120	305	505	375	415	470

[1] A: Stop on rural road.
B: Stop on urban road.
C: Speed/path/direction change on rural road.
D: Speed/path/direction change on suburban road.
E: Speed/path/direction change on urban road.

BASIC DESIGN CRITERIA, DESIGN ELEMENTS, Sight Distance, Intersection Sight Distance

A section defining intersection sight distance and the rationale for its use is recommended for inclusion in the manual. Full development of all of the AASHTO[2] models within the TxDOT manual was judged to be unnecessary because no changes from AASHTO guidelines were envisioned as necessary. Accordingly, designers are made aware of intersection sight distance and referred to AASHTO's *A Policy on Geometric Design of Highways and Streets*.

The operator of a vehicle approaching an intersection at grade should have an unobstructed view of the entire intersection and an adequate view of the intersecting highway to permit control of the vehicle to avoid a collision. When designing an intersection, the following factors should be taken into consideration:

- Adequate sight distance should be provided along both highway approaches and across corners.
- Gradients of intersecting highways should be as flat as practical on sections that are to be used for storage of stopped vehicles.
- Combination of vertical and horizontal curvature should allow adequate sight distance of the intersection.
- Traffic lanes should be clearly visible at all times.
- Lane markings and signs should be clearly visible and understandable from a desired distance.
- Intersections should be free from the sudden appearance of potential conflicts.

For selecting appropriate intersection sight distance, refer to ***A Policy on Geometric Design for Streets and Highways***, AASHTO. Sight distance criteria are provided for the following five types of intersection controls:

1. No control, but allowing vehicles to adjust speed;
2. Yield control on minor roads;
3. Stop control on minor roads;
4. Signal control; and
5. Stopped vehicle turning left from major highway.

BASIC DESIGN CRITERIA, DESIGN ELEMENTS, Sight Distance, Sight Distance on Horizontal Curves

In this section, material has been added to include an equation developed by P. L. Olson, et al. This equation conservatively approximates the required offset for sight obstructions on horizontal curves. Additional material has been provided directing readers to AASHTO's section on measuring sight distance graphically. Although numerous equations have been developed to calculate sight distance for a wide variety of conditions, graphical methods can in most cases more readily accommodate the needs of the designer where sight obstructions are near the ends of horizontal curves or where unusual combinations of curves are encountered. Finally, the figure providing offset requirements for cases where sight distance is less than the length of horizontal curve was updated to conform with the text of the manual.

> Where an object off the pavement, such as bridge pier, bridge railing, median barrier, building, cut slope, or natural growth restricts sight distance, the minimum radius of curvature is determined by the stopping sight distance.
>
> Stopping sight distance on horizontal curves is obtained from <u>the following equations:</u>
>
> $$S<L: \qquad M = R\left[1 - Cos\frac{28.65S}{R}\right]$$
>
> ______________________________
>
> <u>where: *L*</u> = <u>Curve length</u>
> <u>M</u> = <u>Middle ordinate</u>
> <u>*S*</u> = <u>Stopping sight distance</u>
> <u>*R*</u> = <u>Radius</u>

For S>L (from P. L. Olson et al., NCHRP Report 270, Parameters Affecting Stopping Sight Distance, Transportation Research Board, Washington, DC, June 1984):

$$S>L: \qquad M = \frac{L(2S-L)}{8R}$$

where: L	=	Curve length
M	=	Middle ordinate
S	=	Stopping sight distance
R	=	Radius

Figure 4-12 [research report Figure 4-1] provides a graph illustrating the required offset where stopping sight distance is less than the length of curve (S<L).

Figure 4-12 [research report Figure 4-1] may be used in either case but may be overly conservative for curves with small deflection angles. In cases where complex geometries or discontinuous objects cause sight obstructions, graphical methods may be useful in determining available sight distance and associated offset requirements.

It is assumed that the driver's eye is 1,070 mm above the center of the inside lane (inside with respect to curve) and the object is 150 mm high. The line-of-sight is assumed to intercept the view obstruction at the midpoint of the sight line and 600 mm above the center of the inside lane. The clear distance is measured from the center of the inside lane to the obstruction.

To check horizontal sight distance on the inside of a curve graphically, sight lines equal to the required sight distance on horizontal curves should be reviewed to ensure that obstructions such as buildings, hedges, barrier railing, high ground, etc., do not restrict sight below that required in either direction. See **AASHTO**'s Chapter III section on measuring and recording sight distance on plans in Chapter 3 for further information.

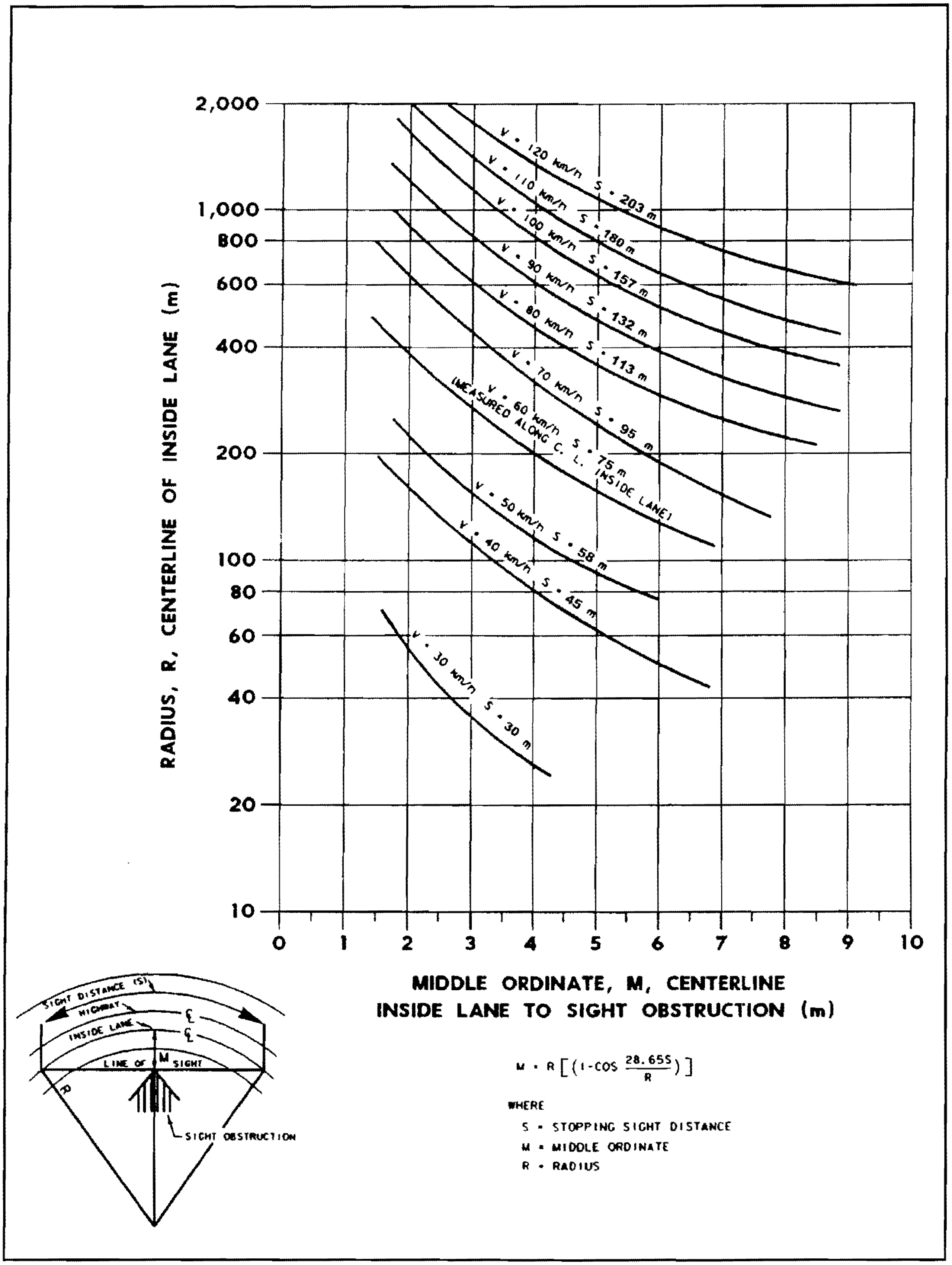

Figure 4-1. Revisions to *Design Manual* Figure 4-12. Stopping Sight Distance on Horizontal Curves

(Updated to conform with SSD values used in text)

NEW LOCATION AND RECONSTRUCTION (4R) DESIGN CRITERIA, URBAN STREETS, Intersections

A brief mention of intersection sight distance is provided to direct the designer to the appropriate section of the manual.

> The number, design, and spacing of intersections influence the capacity, speed, and safety on urban streets. Capacity analysis of signalized intersections is one of the most important considerations in intersection design. Dimensional layout or geometric design considerations are closely influenced by traffic volumes and operational characteristics and the type of traffic control measures used.
>
> Because of the space limitations and lower operating speeds on urban streets, curve radii for turning movements are less than for rural highway intersections. Curb radii of 4.5 m to 7.5 m permit passenger cars to negotiate right turns with little or no encroachment on other lanes. Where heavy volumes of trucks or buses are present, increased curb radii of 9 m to 15 m expedite turns to and from through lanes. Where combination tractor-trailer units are anticipated in significant volume, reference should be made to the material in section, MINIMUM DESIGNS FOR TRUCK AND BUS TURNS.

In general, intersection design should be rather simple, and free of complicated channelization, to minimize driver confusion. Sight distance is an important consideration even in the design of signalized intersections since, during the low volume hours, flashing operation may be used. <u>For more information on sight distance as part of intersection design, see Intersection Sight Distance Design, Chapter II.</u>

NEW LOCATION AND RECONSTRUCTION (4R) DESIGN CRITERIA, TWO-LANE RURAL HIGHWAYS, Intersections

Text is added to this section recommending general design practices to be followed in the vicinity of intersections, together with references to material on intersection sight distance.

The provision of adequate sight distance is of utmost importance in the design of intersections along two-lane rural highways. At intersections, consideration should be given to avoiding steep profile grades and locating intersections on or near a short crest vertical curve or a sharp horizontal curve. These locations could result in poor operations and/or inadequate sight distance at the intersection. Where necessary, backslopes should be flattened and horizontal and vertical curves lengthened to provide additional sight distance. For more information on intersection sight distance, see **Intersection Sight Distance**, Chapter II.

Desirably, the roadways should cross at approximately right angles. Where crossroad skew is flatter than 60 degrees to the highway, the crossroad should be re-aligned to provide for a near perpendicular crossing. The higher the functional classification, the closer to right angle the crossroad intersection should be.

Section 4-710 provides information regarding the accommodation of various types of truck class vehicles in intersection design. Further information on intersection design may also be found in AASHTO's **A Policy on Geometric Design of Highways and Streets.**

NEW LOCATION AND RECONSTRUCTION (4R) DESIGN CRITERIA, MULTILANE RURAL HIGHWAYS, INTERSECTIONS

Reference is made to sight distance sections in appropriate locations. Further recommendations are made for modifications at median openings to improve operations at those points.

In the design of intersections, careful consideration should be given to the appearance of the intersection from the driver's perspective. In this regard, design should be rather simple to avoid driver confusion. In addition, adequate sight distance should be provided throughout, especially in maneuver or conflict areas. See section on **Sight Distance** in Chapter II for further information regarding sight distance.

Right-angle crossings are preferred to skewed crossings, and where skew angles exceed 60 degrees, alignment modifications are generally necessary. Speed change lanes may be provided in accordance with the previous discussion in the section on **Speed Change Lanes**.

Section 4-710 provides information regarding the accommodation of various types of truck class vehicles in intersection design. AASHTO's **A Policy on Geometric Design of Highways and Streets** should be consulted for further information on intersection design and intersection sight distance.

Intersections formed at bypass and existing route junctions should be designed so as not to mislead drivers as typified in **Figure 4-35**.

For intersections with a narrow, depressed median section, it may be necessary to have superelevation across the entire cross section to provide for safer operation at the median openings.

For more information on intersection design, see **Intersection Design**, Chapter II.

NEW LOCATION AND RECONSTRUCTION (4R) DESIGN CRITERIA, FREEWAYS

Modified text is provided to allow reversing the inside and outside shoulder width recommendations for bridges if sight distance requirements may be met in this manner. Providing a larger inside shoulder will in some cases provide improved sight distance without moving the structures. The combination of the inside and outside shoulder widths would still permit passing a stalled vehicle. Table 4-3 contains the recommended revisions to the *Design Manual*'s Figure 4-51.

Table 4-3. Revisions to Figure 4-51 in the *Design Manual*

Figure 4-51. Roadway and Structure Widths for Controlled Access Facilities.

Type of Roadway	Inside Shoulder Width (m)		Outside Shoulder Width[1] (m)		Traffic Lanes (m)	Structure Width (m)	
Mainlanes:							
4-Lane Divided	1.2		3.0		7.2	11.4 Min.	
6-Lane Divided	3.0[1]		3.0		10.8	16.8 Min.[2]	
8 Lanes or More	3.0		3.0		14.4[3]	20.4 Min.[3]	
1-Lane Direct Conn.[7]	0.6 Rdwy. 1.2 Str.	See Note 4	2.4		4.2	7.8 Min.	
2-Lane Direct Conn.	0.6 Rdwy. 1.2 Str.	See Note 4	2.4		7.2	10.8 Min.	
Ramps[7]	0.6 Rdwy.	See	Min.	Des.		Min.	Des.
	1.2 Str.	Note 4	1.8	2.4[5]	4.2	7.2	7.8[5]
Median Width	Urban		7.2[6] (usual)	--		--	--
	Rural		14.4	22.5		--	--

[1] Minimum 3.0 m inside shoulders are usually provided on urban freeways with flush medians and six or more lanes. For urban freeway rehabilitation and expansion, the provision of wide inside shoulders may not be feasible. Under these circumstances documentation for narrower shoulders should be submitted and a design exception requested. Six-lane freeways with depressed median may include 1.2 m shoulders with 15.0 m minimum structure width.

2 For auxiliary (speed change) lanes, see Main Lanes, **Shoulders** for outside shoulder width.

3 For more than eight lanes, add 3.6 m width per lane.

4 Minimum inside shoulder width is 0.6 m on uncurbed roadway sections and 1.2 m on bridges and curbed roadways. All longitudinal traffic barriers, including bridge rail, wall, and guard fence, should be located a minimum of 1.2 m from the travel lane edge.

5 Desirable values should be used where there are sufficient combination type vehicles to govern design. Where ramp ADT includes greater than 10 percent trucks, desirable values are appropriate for use.

6 Applicable to urban freeways with flush medians and six or more mainlanes.

7 If sight distance restrictions are present due to horizontal curvature, the shoulder width on the inside of the curve may be increased and the shoulder width on the outside of the curve decreased to 0.6 m (Rdwy) or 1.2 m (Str).

NEW LOCATION AND RECONSTRUCTION (4R) DESIGN CRITERIA, FREEWAYS, Sight Distance

Text is provided to indicate the need for increased sight distance on a freeway prior to an exit ramp. Decision sight distance or, alternatively, a 25 percent increase in stopping sight distance, is recommended to the designer for this situation.

> On all ramps and direct connections, the combination of grade, vertical curves, alignments, and clearance of lateral and corner obstructions to vision shall be such as to provide sight distance along such ramps and connections from terminal junctions along the freeway, consistent with the probable speeds of vehicle operation. **Figure 4-55** shows recommended minimum and desirable stopping sight distances for ramps and direct connections.
>
> The sight distance on a freeway preceding the approach nose of an exit ramp should exceed the minimum stopping sight distance for the freeway design speed, preferably by 25 percent or more. Decision sight distance, as discussed in Chapter II, **Decision Sight Distance**, is a desirable goal.

LONGITUDINAL BARRIERS, CONCRETE BARRIERS, LOCATION

Text is provided to indicate to the designer that the provision of concrete barriers may impede sight distance on horizontal curves.

> On controlled access highways, concrete barriers will generally be provided in medians of 9.0 m or less. On non-controlled access highways, concrete barriers may be used on medians of 9.0 m or less; however, care should be exercised in their use in order to avoid the creation of an obstacle or restriction in sight distance at median openings or on horizontal curves. Generally, the use of concrete barriers on non-controlled access facilities should be restricted to areas with potential safety concerns such as railroad separations or through areas where median constriction occurs.

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