Design Guidelines for Horizontal Sightline Offsets (2019)

DETAILS

114 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-48054-3 | DOI 10.17226/25537

CONTRIBUTORS

Ingrid B. Potts, Douglas W. Harwood, Daniel J. Cook, Eric T. Donnell, and Bachir Hamadeh; National Cooperative Highway Research Program; National Cooperative Highway Research Program Synthesis Program; Synthesis Program; Transportation Research Board; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine 2019. *Design Guidelines for Horizontal Sightline Offsets*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25537.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 910

Design Guidelines for Horizontal Sightline Offsets

Ingrid B. Potts
Douglas W. Harwood
Daniel J. Cook
MRIGLOBAL
Kansas City, MO

Eric T. Donnell
Bachir Hamadeh
LARSON PENNSYLVANIA TRANSPORTATION INSTITUTE
University Park, PA

Subscriber Categories
Highways • Design • Safety and Human Factors

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

TRB
TRANSPORTATION RESEARCH BOARD

2019

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the National Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the Federal Highway Administration. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

NCHRP RESEARCH REPORT 910

Project 15-59
ISSN 2572-3766 (Print)
ISSN 2572-3774 (Online)
ISBN 978-0-309-48054-3
Library of Congress Control Number 2019943868

NOTICE

The research report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the National Academies of Sciences, Engineering, and Medicine.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board; the National Academies of Sciences, Engineering, and Medicine; or the program sponsors.

The Transportation Research Board; the National Academies of Sciences, Engineering, and Medicine; and the sponsors of the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the report.

Published research reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet by going to

http://www.national-academies.org

and then searching for TRB

Printed in the United States of America

The National Academies of

SCIENCES • ENGINEERING • MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, non-governmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. C. D. Mote, Jr., is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.national-academies.org**.

The **Transportation Research Board** is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to increase the benefits that transportation contributes to society by providing leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied committees, task forces, and panels annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

Learn more about the Transportation Research Board at **www.TRB.org**.

C O O P E R A T I V E   R E S E A R C H   P R O G R A M S

CRP STAFF FOR NCHRP RESEARCH REPORT 910

Christopher J. Hedges, *Director, Cooperative Research Programs*
Lori L. Sundstrom, *Deputy Director, Cooperative Research Programs*
William C. Rogers, *Senior Program Officer*
Jarrel McAfee, *Senior Program Assistant*
Eileen P. Delaney, *Director of Publications*
Natalie Barnes, *Associate Director of Publications*
Margaret B. Hagood, *Editor*

NCHRP PROJECT 15-59 PANEL
Field of Design—Area of General Design

Trinity D. Smith, *Arkansas DOT, Little Rock, AR* (Chair)
Zhongren Wang, *Division of Maintenance, Caltrans, Sacramento, CA*
Andrew Jay Beagle, *City of Olympia, Public Works, Olympia, WA*
Keith R. Damron, *American Engineers, Inc., Louisville, KY*
Sonia Alicia Mercado, *Texas DOT, Austin, TX*
Jason R. Salley, *Illinois DOT, Schaumburg, IL*
Michael Matzke, *FHWA Liaison*
Stephen F. Maher, *TRB Liaison*

FOREWORD

By William C. Rogers
Staff Officer
Transportation Research Board

NCHRP Research Report 910: Design Guidelines for Horizontal Sightline Offsets provides guidance for highway agencies to address the types of sight distance restrictions that are most likely to be encountered on specific roadway types. They identify design situations that address the relative cost of removing the sight restriction and the likely implications for safety of allowing the sight distance restriction to remain. When a decision is reached not to remove a sight restriction, the guidelines include a catalog of mitigation strategies for consideration in specific design situations on specific roadway types.

When the sightlines along horizontal roadway curves are restricted, there are challenges to find acceptable solutions. Designers compensate for the limitations on driver sight distance in various ways, including: accepting shorter sightlines, lowering design speed, increasing shoulder width, or providing additional signage. There are advantages and disadvantages to the trade-offs; as a result, many highway agencies have used the design exception process to address the trade-offs for sight distance in such situations. This project conducted research to evaluate these situations and determine what criteria or mitigation will provide acceptable solutions when impaired horizontal sightline offsets are encountered.

In NCHRP Project 15-59, MRIGlobal, assisted by Larson Pennsylvania Transportation Institute, was asked to: (1) evaluate the safety and operational performance as well as the trade-offs and risks associated with state-of-the-practice mitigation treatments when horizontal sightline offset criteria are not met; and (2) recommend updates to AASHTO's *A Policy on Geometric Design of Highways and Streets* (Green Book) for horizontal sightline offset design criteria, and guidance on curved roadway alignment adjacent to barriers or other types of impediments that may impact the driver's line of sight.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Design Guidelines for Horizontal Sightline Offsets

Design guidelines are presented for providing the horizontal sightline offset needed to provide the design stopping sight distance (DSSD) specified in AASHTO's *A Policy on Geometric Design of Highways and Streets* (known as the Green Book). The guidelines include procedures to assess horizontal curves with sight obstructions on the inside of the curve that limit the horizontal sightline offset.

The distance between the driver's line of sight along the roadway ahead on a horizontal curve and a sight obstruction on the inside of the curve is known as the horizontal sightline offset (HSO). The design criteria for the horizontal component of stopping sight distance (SSD) in the Green Book are based on the maximum sightline offset that may be needed at any point along a curve with a given radius. The Green Book does not fully explain that sightline offset less than the maximum is needed toward the ends of horizontal curves longer than the DSSD and at any point along curves shorter than the DSSD. In addition, the Green Book does not show that some sightline offset is needed even beyond the ends of a horizontal curve.

The relationship between SSD and the frequency and severity of crashes has been difficult to quantify because the role of SSD in reducing crashes is highly situational. A sight-distance-related crash can only occur where a sight distance limitation is present, a vehicle is approaching the sight distance limitation, and an object that the driver of the approaching vehicle needs to see is present in the sight-restricted area. Objects that the approaching driver needs to see are much more likely at some locations than at others.

The crash investigation results indicate that sight-distance-related crashes are so infrequent and so difficult to identify definitively that it is not feasible to develop predictive models for crashes related to SSD or to quantify the crash reduction effectiveness of sight distance improvements. Therefore, several tools, including a reliability analysis approach, are presented here to assist designers in assessing horizontal sight distance issues.

A series of equations is provided to assist planners and designers in identifying the shape and extent of the roadside area that should be clear of sight obstructions so that the applicable DSSD is available. The equations can potentially be used in computer-aided design and drafting (CADD) systems so that the area that should be free of sight obstructions is displayed visually to designers.

A benefit-cost equation allows planners and designers to estimate an upper limit on the project implementation cost that would be justified to remove or mitigate horizontal sight obstructions.

A reliability analysis model was developed to assist designers in assessing existing horizontal curves and horizontal curves under design for new construction to prioritize

the removal or mitigation of horizontal sight obstructions. The reliability analysis model computes the longitudinal distribution or profile of available stopping sight distance (ASSD) along the site and estimates the number and percentage of approaching vehicles per year in each travel lane that may encounter stopped vehicles in the sight-restricted area due to crashes or congestion-related queues. The reliability analysis model has been incorporated in a spreadsheet tool for application by planners and designers.

Procedures for assessing the need for removal or mitigation of horizontal sight obstructions are presented, together with lessons learned from case studies of seven sites with existing horizontal sight restrictions.

Mitigation strategies that may be applied where a decision is reached not to remove a horizontal sight obstruction are presented. The practicality of mitigation strategies depends on the cost of the applicable mitigation strategies and the priority assigned to the site based on the results of the reliability analysis model. The situations in which design exception documentation should be prepared are also identified.

CHAPTER 1

Introduction

1.1 Introduction

SSD is an important geometric design element—one of the FHWA controlling criteria for geometric design—and widely accepted design criteria for SSD are presented in the AASHTO's *A Policy on Geometric Design for Highways and Streets*, commonly known as the Green Book (AASHTO 2011). The vertical component of SSD is fully defined by the vertical profile of the roadway (except on sag vertical curves where an overhead structure may be present). However, the horizontal component of SSD depends on both the vertical and horizontal geometrics of the roadway as well as the varied nature of roadside sight obstructions on the inside of horizontal curves. Sight obstructions can occur on either the right or left side of the roadway, or in a divided highway median. A variety of roadside objects can constitute a horizontal sight obstruction: trees, bushes, utility poles, structures and walls, guardrail, median barrier, rock cuts, or roadside embankments.

Figure 1 illustrates a simplified view of the design situation for HSO to roadside sight obstructions, as presented in the Green Book (AASHTO 2011). The figure illustrates a driver's line of sight to the roadway ahead, which, on a horizontal curve, is a chord of that curve. The dimension labeled HSO in Figure 1, which in terms of analytic geometry is known as the middle ordinate of the curve, is now called the horizontal sightline offset in the Green Book. Any roadside sight obstruction on the inside of the curve whose distance from the centerline of the inside travel lane is less than or equal to HSO may interrupt the driver's view of the road ahead for at least some portion of the curve. As explained in Section 2.3 of this guide, the dimension labeled HSO in Figure 1 actually represents the maximum HSO that can occur at any point on a horizontal curve; the actual HSO needed at some locations on or near the curve will be less than HSO.

The equation for determining HSO for the situation in Figure 1 is:

$$HSO = R\left[1 - \cos\left(\frac{28.65\,S}{R}\right)\right] \tag{1}$$

where

HSO = maximum horizontal sightline offset (ft);
R = radius of curve (ft); and
S = design value of SSD (ft).

The design value of SSD, referred to in the Green Book as S, is known as DSSD when rounded off to a design value.

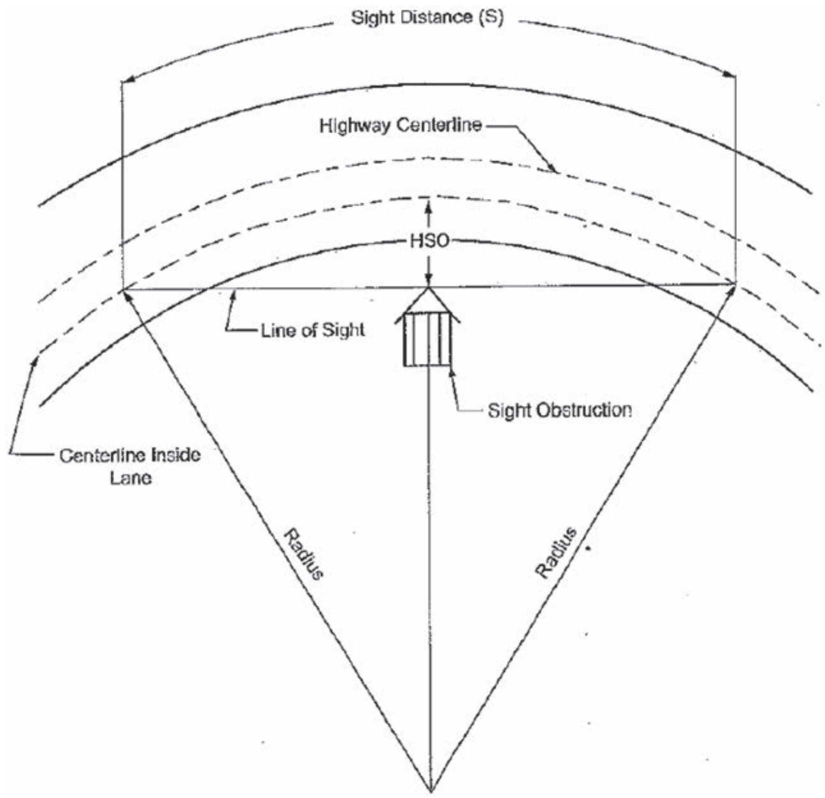

Figure 1. Diagram illustrating components for determining horizontal sight distance (AASHTO 2011).

Generations of highway engineers have been taught that SSD is needed at all points along the roadway alignment. Yet, despite this perceived importance, there are no definitive crash modification factors (CMFs) that quantify the safety effect of SSD either in the *Highway Safety Manual* (AASHTO 2010; AASHTO 2014) or on the FHWA CMF Clearinghouse website (www.cmfclearinghouse.org). The likely reason that the safety effects of SSD have not been successfully quantified is that these effects are highly situational, meaning that limited SSD is far more likely to result in a collision at some locations than at others. Recent research in *NCHRP Report 783: Evaluation of the 13 Controlling Criteria for Geometric Design* (Harwood et al. 2014), found that, at crest vertical curves with limited SSD on rural two-lane highways, crash frequencies were high at locations where intersections, driveways, or horizontal curves were hidden from the approaching driver's view by the sight restriction. However, where no hidden features were present, crash frequency was not elevated, even though the SSD was limited. On other highway types, such as divided highways and freeways, additional types of hidden features, such as ramp terminals or pedestrian crossings, may also be critical if located in a sight-restricted area. On congested highways, there is a possibility of a standing queue being present in a sight-restricted area during specific time periods during a typical day. The research in *NCHRP Report 783* demonstrates for crest vertical curves that correcting or mitigating limited SSD may be much more critical in some highway situations than in others; the same principle is likely to apply to horizontal sight restrictions, as well.

Highway agencies face challenges in assessing horizontal sight restrictions in deciding whether to remove the sight restriction, leave it in place, or incorporate mitigation measures, such as signing or a widened shoulder. The difficulty of such decisions increases with the cost of removing the sight obstructions. For example, for some ramps in complex interchanges, where a traffic barrier or a bridge rail on an elevated structure serves as a horizontal sight obstruction, removing the sight obstruction could cost hundreds of thousands, if not millions, of dollars. Such decisions are complex because some horizontal sight obstructions may be critical to crash reduction, and should therefore be removed; at other locations, leaving the sight obstruction in place may be highly unlikely to lead to collisions and thus may not merit additional large investments. Highway agencies currently lack guidelines and/or analysis tools to distinguish between such situations and, therefore, are limited in their ability to make rational design/investment decisions.

To address horizontal sight restrictions more effectively in the design process, highway agencies need guidance on the types of sight distance restrictions that are most likely to be encountered on specific roadway types. For specific design situations, guidelines have been developed that address the relative cost of removing the sight restriction and the likely implications for safety of allowing the sight distance restriction to remain. Costs of removing sight restrictions should be addressed in general terms because site-specific features naturally influence costs. The decision of whether to remove a specific sight distance restriction should be addressed, where practical, through economic analysis (i.e., comparison of benefits and costs), which considers the tradeoffs between the crash reduction benefits of removing the sight restriction and the costs of doing so. However, in many cases, it may not be possible to quantify crash reduction benefits of removing the sight obstruction, so alternative estimation methods may need to be used. If a decision is reached not to remove a sight restriction, mitigation measures should be considered; the design guidelines include a catalog of mitigation strategies that can be considered in specific design situations on specific roadway types.

Design conventions established many years ago to simplify analyses in the pre-computer era may also oversimplify the analysis of HSOs. For example, SSD is generally analyzed for design purposes along the centerline of the inside lane. Design analyses do not typically develop realistic sightlines taking into account that the driver’s eye is typically located to the left of the vehicle centerline and the vehicle centerline does not necessarily track along the center of the lane. Furthermore, the most critical target that must be seen by a driver to avoid collisions—another vehicle—is not a point on the roadway centerline, but an object approximately 6 to 8.5 ft in width and 4.5 to 13.5 ft in height. In addition, the geometry of the horizontal component of SSD (illustrated in Figure 1 for the situation where both the driver and the target to be seen are on the horizontal curve) and its mathematical derivation become more complex than shown in Equation (1) when the driver is on the tangent and the sight obstruction or the target to be seen by the driver is on the horizontal curve, or vice versa (Raymond, 1972). Three-dimensional (3D) computations can construct realistic sightlines for specific design situations to illustrate whether drivers at particular lateral positions in particular lanes can or cannot see specific targets. Reliability analysis provides a mathematical tool to automate such assessments for realistic ranges of key factors.

Another concern is that the Green Book assumes a single design situation for SSD, with a vehicle traveling at the design speed, a stationary target to be seen, and controlled braking at a specific deceleration rate. In fact, at any given geometric sight restriction, nearly every aspect of a potential emergency braking situation varies, including vehicle speed, vehicle lateral placement, driver’s eye position within the vehicle, driver behavior, tire/pavement conditions, and target location and dimensions. Visibility restrictions (e.g., heavy rain, fog) may also increase the risk of limited SSD by making it more difficult for approaching drivers to see specific targets, even after they come into view. Reliability analysis can also serve as an effective tool to assess the sensitivity of SSD to these factors, based on their likely variations. The purpose of the reliability analysis would be to assess, at specific horizontal curves, whether these factors are more or less critical.

One of the situations with horizontal sight distance restrictions that highway agencies find most difficult and expensive to deal with occurs on a freeway or a ramp curving either to the right or to the left with a barrier on the inside of the curve. In this situation, the barrier itself can become a sight obstruction; the barrier may be very expensive to reposition or remove, and may be critical to roadside safety in its current location. The extent to which a barrier (or retaining wall) is a sight obstruction is a function of the height of the barrier, its offset from the traveled way, and the horizontal and vertical alignment of the roadway. In some scenarios, drivers in the lane closest to the inside of the curve on a roadway or a ramp may have an obstructed view of vehicles ahead; in other scenarios, the driver's view ahead may be only partially obstructed or not obstructed at all, if the barrier is low and the roadway alignment allows the driver to see over the barrier. Other potentially challenging scenarios include locations on structures where the bridge rail becomes a sight obstruction; underpasses; and locations with trees, brush, buildings, retaining walls, or other structures close to the road. High-occupancy vehicle (HOV) facilities often have adjacent barriers or retaining walls. An extreme case for the importance of horizontal sightlines occurs on curved roadways in tunnels.

The design guidelines presented in this document are based on research by Potts et al. (2018).

1.2 Typical Locations with Horizontal Sight Obstructions

This section presents typical locations with horizontal sight obstructions to illustrate the challenges that highway agencies face in making obstruction removal and mitigation decisions.

Figure 2 presents two examples of horizontal curves to the right with sight distance limitations on rural two-lane highways. In both cases, trees located on the inside of a horizontal

(a) (b)

Figure 2. Typical curves with horizontal sight obstructions on rural two-lane highways.

(a) (b)

Figure 3. Typical curves with horizontal sight obstructions on urban mainline freeways.

curve to the right serve as horizontal sight obstructions. And, in both cases, sight distance is also limited for drivers in the opposing direction of travel traversing a curve to the left.

Figure 3 presents two examples of horizontal curves to the left with sight obstructions on urban mainline freeways. In Figure 3(a), sight distance for an approaching driver is limited by a concrete median barrier. In Figure 3(b), sight distance for an approaching driver is limited by a retaining wall in the highway median.

Figure 4 presents a typical rural freeway with a horizontal curve to the left with a concrete median barrier that serves as a sight obstruction.

Figure 5 presents four photographs of interchange ramps with limited horizontal sight distance. Figure 5(a) shows trees and a concrete barrier that serve as sight obstructions on a curve to the right near the gore area of a freeway exit ramp. Figure 5(b) shows a curve to left on a ramp where the median barrier between an exit ramp and the entrance ramp in the opposing direction of travel serves as a sight obstruction. Figure 5(c) shows a retaining wall that serves as a sight obstruction on the inside of a curve to the right. Figure 5(d) shows a curve to the right in the downstream portion a ramp for which a bridge abutment and retaining wall on the inside of the curve serve as a horizontal sight obstruction.

Figure 4. Typical curve with a horizontal sight obstruction on a rural mainline freeway.

(a) (b) (c) (d)

Figure 5. Typical curves with horizontal sight obstructions on interchange ramps.

1.3 Organization of This Guide

This guide presents the results of a literature review and highway agency survey, a set of representative design scenarios faced by highway agencies, the results of data collection and analysis conducted as part of the research, the development of a reliability analysis model for horizontal sight distance, and design guidelines for highway agencies. The remainder of this guideline document is organized as follows:

Chapter 2—Design Criteria for HSOs
Chapter 3—Relationship of Sight Distance to Crash Frequency and Severity
Chapter 4—Benefit-Cost Analysis
Chapter 5—Reliability Analysis Model for Horizontal Curves with Limited SSD
Chapter 6—Assessing Removal or Mitigation of Horizontal Sight Obstructions
Chapter 7—Design Exceptions and Mitigation Strategies
References
Appendix A—Computation of HSOs
Appendix B—Users Guide for Reliability Analysis Tool
Appendix C—Case Studies of Existing Roadways with Sight Obstructions

CHAPTER 2

Design Criteria for HSOs

2.1 Current SSD Design Criteria

This section presents an overview of the current AASHTO SSD design criteria and their application to vertical and horizontal sight restrictions. The review of SSD design criteria presented here is based on the 2011 edition of the Green Book. The forthcoming 2018 edition of the AASHTO Green Book is not expected to include any substantive revisions to the policies on SSD and HSO presented here.

2.1.1 AASHTO SSD Model

Sight distance is the length of the roadway ahead that is visible to a driver at any point on the roadway. Geometric design policies include design criteria for SSD, defined as the minimum length of roadway ahead that a driver needs to be able to see in order to stop before reaching a stationary object in the driver's path. The AASHTO Green Book establishes SSD design criteria based on the following model:

$$S = 1.47\,Vt + 1.075\,\frac{V^2}{a} \qquad (2)$$

where

S = SSD (ft);
V = design speed (mph);
t = brake reaction time (perception-reaction time prior to braking) (sec); and
a = deceleration rate (ft/s^2).

Table 1 presents the current SSD design criteria derived from Equation (2). The rightmost column in Table 1 presents values of DSSD used in designing U.S. roads. Designers seek to provide ASSD at least equal to the DSSD value for the applicable design speed. These Green Book SSD criteria are used by most highway agencies in the United States.

The SSD model in Equation (2) consists of two terms. The first term (1.47 Vt) represents the distance traveled by a vehicle traveling at constant speed equal to the roadway design speed during the driver's perception-reaction time (i.e., the elapsed time from the moment an object in the road ahead comes into the driver's view until the moment the driver begins to apply the vehicle brakes). Perception-reaction time consists of the time needed for the driver to perceive that there is an object ahead (assumed to be 1.5 sec) plus the time needed for the driver to react and begin to apply the brakes (assumed to be 1.0 sec). Thus, the total assumed perception-reaction time is 2.5 sec.

Table 1. Current AASHTO SSD design criteria for level roadways (AASHTO 2011).

Design speed (mph)	Brake reaction distance (ft)	Braking distance on level (ft)	SSD (ft)	
			Calculated (S)	Design (DSSD)
15	55.1	21.6	76.7	80
20	73.5	38.4	111.9	115
25	91.9	60.0	151.9	155
30	110.3	86.4	196.7	200
35	128.6	117.6	246.2	250
40	147.0	153.6	300.6	305
45	165.4	194.4	359.8	360
50	183.8	240.0	423.8	425
55	202.1	290.3	492.4	495
60	220.5	345.5	566.0	570
65	238.9	405.5	644.4	645
70	257.3	470.3	727.6	730
75	275.6	539.9	815.5	820
80	294.0	614.3	908.3	910

The second term in the SSD model ($1.075\ V^2/a$) is the distance needed for the vehicle to come to a stop once the driver begins to apply the brakes. The braking distances are based on braking at a constant deceleration equal to 11.2 ft/s^2, independent of the initial speed at the beginning of the braking maneuver. This deceleration is comfortable to most drivers. Most vehicle braking systems and the tire-pavement friction levels of most roadways are capable of providing this deceleration.

Vehicles need slightly longer braking distances on downgrades and slightly shorter braking distances on upgrades. Thus, on roadways that are not level, the SSD model in Equation (2) changes to:

$$S = 1.47\ Vt + \frac{V^2}{30\left[\left(\frac{a}{32.2}\right) \pm G\right]} \qquad (3)$$

where G is grade expressed as rise/run (ft/ft).

In implementing the Green Book SSD design criteria, highway designers must consider both vertical and horizontal sight distance limitations. Design for each of these types of sight distance limitations is discussed in the following sections.

2.1.2 Design for Vertical Sight Distance Limitations

Vertical sight distance limitations arise mostly from the geometry of the road itself. Crest vertical curves limit the driver's view of the roadway beyond the crest. Sag vertical curves may limit the driver's view of the roadway ahead at night by redirecting the vehicle's headlights away from the roadway ahead. In addition, overpass structures on sag vertical curves may also limit the driver's sight distance.

Figure 6 shows four types of vertical curves found on roadway systems. At crest vertical curves (Types a and b in Figure 2), the roadway profile itself limits SSD.

The Green Book (AASHTO 2011) specifies that crest vertical curves should be designed so that a driver whose eyes are 3.5 ft above the roadway surface should be able to see a 2-ft high object in the road ahead (equivalent to the typical taillight height of passenger vehicles) over

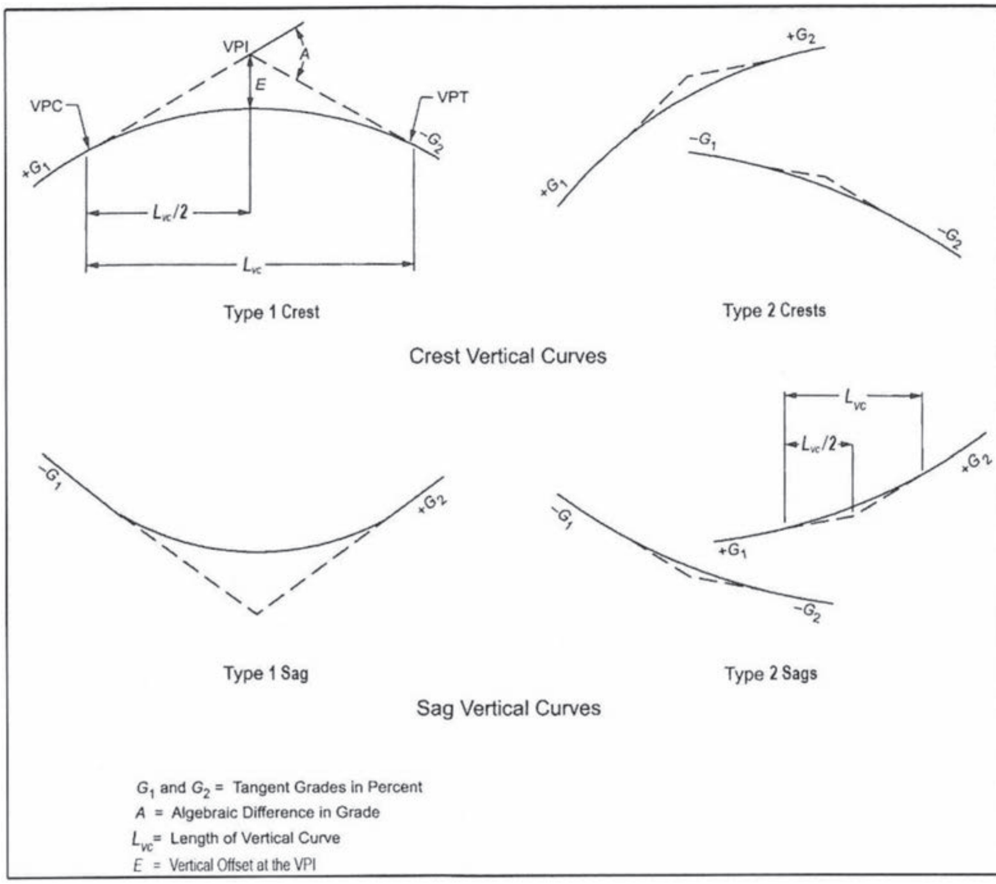

Figure 6. Types of vertical curves [adapted from AASHTO (2011)].

the full distance given by the DSSD criteria presented in Table 1. This requires minimum crest vertical curve length given by:

when DSSD is less than L,

$$L_{VC} = \frac{A(DSSD)^2}{100\left(\sqrt{2h_1} + \sqrt{2h_2}\right)^2} \tag{4}$$

when DSSD is greater than L,

$$L_{VC} = 2\ DSSD - \frac{200\left(\sqrt{h_1} + \sqrt{h_2}\right)}{A} \tag{5}$$

where

L_{VC} = length of vertical curve (ft);
$DSSD$ = design value of stopping sight distance (ft);
A = algebraic difference in grade between entering percent grade (G_1) and departing percent grade (G_2), percent;
h_1 = height of driver's eye above roadway surface (ft); and
h_2 = height of object above roadway surface (ft).

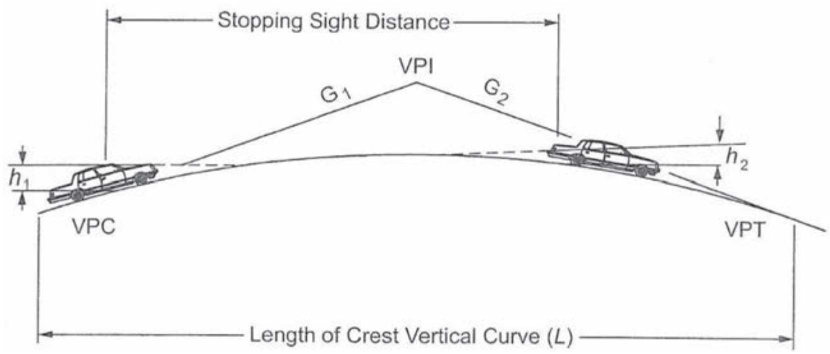

Figure 7. Parameters considered in determining the length of a crest vertical curve to provide SSD (AASHTO 2011).

Figure 7 shows the parameters considered in determining the length of a crest vertical curve to provide SSD.

Figure 8 shows the minimum lengths of crest vertical curves for specific values of algebraic difference in grade (A) to provide the minimum SSD for each design speed. Figure 8 enables users to determine the value of *K*, the length of vertical curve per unit of algebraic difference in grade, needed to provide the minimum SSD. In other words,

$$K = \frac{L_{VC}}{A} \tag{6}$$

where *K* is length of vertical curve per unit of algebraic difference in grade (ft).

The values of *K* for crest vertical curves to provide SSD range from 3 ft per percent difference in grade at 15 mph to 384 ft per percent difference in grade at 80 mph.

Design criteria for length of sag vertical curves (Types 1 and 2 in Figure 6) consider four separate criteria based on headlight sight distance, passenger comfort, drainage control, and general appearance. Of these four criteria, only headlight sight distance is a function of SSD. SSD is not limited on sag vertical curves under daylight conditions (unless an overpass or some other object over the roadway is present), but the shape of a sag vertical curve may limit the distance that headlights illuminate the roadway ahead at night. Headlight sight distance may be less of a concern than commonly supposed because most motorists travel at night at speeds such that their stopping distance is greater than their headlight sight distance, even on level roads where headlight sight distance is not limited by roadway geometry. At design speeds of 55 mph and more, sag vertical curves are generally shorter than comparable crest vertical curves. The values of K for sag vertical curves range from 10 ft per percent difference in grade at 15 mph to 231 ft per percent difference in grade at 80 mph.

2.1.3 Horizontal Sight Distance Obstructions

Horizontal sight distance obstructions are opaque objects that limit the driver's view of the roadway ahead and are located on the inside of horizontal curves. If the inside of a horizontal curve is clear of sight obstructions, the driver of a vehicle will be able to see objects or other vehicles on the roadway ahead by looking along a sight line that traverses a portion of the shoulder and/or the roadside area. However, where sight obstructions such as buildings, rock cuts, retaining walls, roadside barriers, bridge piers and abutments, fences,

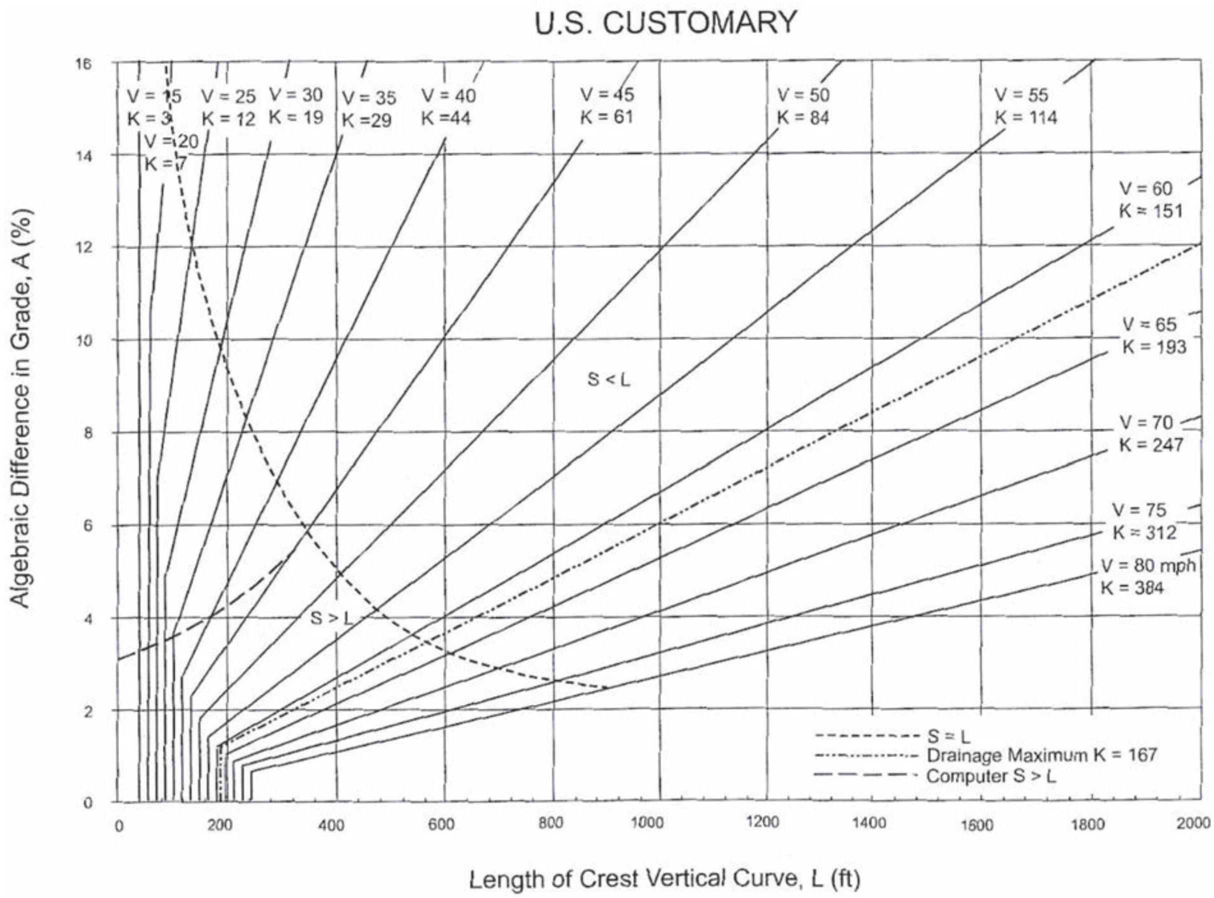

Figure 8. Chart to determine the length of a crest vertical curve needed to provide DSSD (AASHTO 2011).

trees, bushes, crops, or other vegetation are present on the inside of a horizontal curve, a driver's ability to see a sufficient distance ahead may be limited. The smaller the radius of a horizontal curve, the larger the distance from the roadway, or HSO, that should be clear of obstructions for the driver to have available at least the applicable DSSD specified in the Green Book (AASHTO 2011). Because horizontal sight distance limitations are the primary focus of this research, the computation of HSOs is discussed separately in Section 2.3, and more fully in Appendix A.

2.2 Components of AASHTO SSD Criteria

Each component of the AASHTO SSD model is discussed in the following sections.

2.2.1 Design Speed

Design speed is defined as a selected speed used to determine the various geometric design features of the roadway (AASHTO 2011). The design speed selected for a roadway should be logical with respect to the anticipated operating speed, topography, adjacent land use, and functional classification of the roadway. The selection of an appropriate design speed is a decision made by the designer for each individual project. As shown in Table 1, the selected design speed of the roadway directly influences the DSSD that should be provided on horizontal curves.

2.2.2 Initial Speed at Beginning of Braking Maneuver

In deriving SSD values, the first term of Equations (2) and (3) shows that the initial speed of the vehicle at the beginning of a braking maneuver is assumed to be equal to the roadway design speed.

2.2.3 Perception-Reaction Time

Perception-reaction time is the sum of perception time and brake reaction time. Brake reaction time was assumed as 1 sec in the 1940 AASHO sight distance policy (AASHO 1940), and remains at that value today. The assumption concerning perception time was set at 1.5 sec in the 1954 AASHO Blue Book (AASHO 1954), for a total perception-reaction time of 2.5 sec, and remains at that value today. The AASHTO Green Book (AASHTO 2011) cites the 2.5 sec value of perception-reaction time as consistent with the findings of a 1971 study by Johanson and Rumar (1971).

2.2.4 Vehicle Deceleration and Braking Maneuver

The pavement condition and vehicle deceleration/braking maneuver assumed as the basis for SSD design has evolved over the years. AASHTO policy formerly assumed that the braking maneuver was an emergency locked-wheel stop on wet pavement. Research by Fambro et al. (1997) concluded that a locked-wheel stop was not appropriate for SSD design because most drivers who encounter an object in the roadway use controlled braking rather than a locked-wheel braking. Beginning with the 2001 Green Book, the SSD design criteria have been based on controlled braking on a wet pavement surface (AASHTO 2001). The change to controlled braking is especially appropriate today, given that most vehicles are now equipped with anti-lock brakes. The 2001 Green Book, and more recent editions, assume a comfortable, controlled deceleration of 11.2 ft/s^2, or just under 0.35 g.

2.2.5 Driver Eye Height

Driver eye height is based on a combination of vehicle and human characteristics—the vertical position of the driver's seat in the vehicle, which varies between vehicles, and the distance from the driver's seat to the driver's eye, which varies between people. The driver eye heights assumed in SSD design have decreased over the years, from 4.5 ft in 1940 to 3.5 ft today, primarily because of changes in vehicle design.

2.2.6 Object Height

SSD design policy has always recognized that, while maintaining sight distance from the driver's eye to the pavement surface might be desirable, such an approach would not be cost-effective. Research by Fambro et al. (1997) found that most objects struck by vehicles on the roadway were at least 2 ft in height. The object most often struck by a vehicle is another vehicle, and vehicle taillights are typically 2 ft above the roadway surface. Based on the Fambro et al. research, the 2001 Green Book adopted a 2-ft object height for SSD design.

2.3 HSO Design Criteria

HSOs are provided in design so that objects on the inside of horizontal curves do not limit a driver's view of the roadway ahead for at least the established SSD design criteria. As discussed in Section 2.2, the vertical component of SSD is fully defined by the vertical profile of the roadway (except on sag vertical curves where an overhead structure may be present). However, the horizontal component of SSD depends on both the vertical and horizontal geometrics of the roadway as well as the varied nature and height of roadside sight obstructions on the inside of horizontal curves. Sight obstructions can occur on either the right or left side of the roadway, or in a divided highway median. A variety of roadside objects can constitute a horizontal sight obstruction—rock cuts, retaining walls, embankments, median barriers, guardrails, bridge piers and abutments, structures, trees, bushes, and utility poles.

Figure 1 illustrates the design situation for HSO to roadside sight obstructions on the inside of the curve, as presented in the Green Book (AASHTO 2011). The figure illustrates a driver's line of sight to the roadway ahead which, on a horizontal curve, is a chord of that curve. The dimension labeled HSO in Figure 1, which in terms of analytic geometry is known as the middle ordinate of the curve, is now called the horizontal sightline offset in the Green Book. The HSO, or middle ordinate of the curve, for the situation shown in Figure 1 is determined as shown in Equation (1).

The Green Book (AASHTO 2011) states that horizontal sightlines are assessed along the centerline of the lane closest to the inside of the horizontal curve. Figure 9 presents the design controls from the Green Book for providing SSD on horizontal curves, based on Equation (1). To use Figure 9, plot a horizontal line equivalent to the radius of the horizontal curve (R). Then, identify the point where that horizontal line intersects the curve corresponding to the design speed of the curve. Finally, plot a vertical line through that point of intersection, and the value of HSO where the vertical line intersects the horizontal axis is the horizontal sightline offset shown in Figure 1.

Equation (1) and Figure 9 might be read simplistically to indicate that a horizontal sightline offset equal to HSO is needed throughout each horizontal curve. Thus, casual readers of the Green Book might be under the impression that HSO needs on a horizontal curve are like those shown in Figure 10. However, Figure 10 is purely hypothetical, because Figure 1 illustrates only the simplest case for HSOs since, in Figure 1, both the driver's eye and the object to be seen at a distance of S from the driver's eye are on the horizontal curve. The Green Book notes that the full HSO determined from Equation (1) or Figure 9 is needed only in the middle portion of a horizontal curve, but that the value of HSO shown in Equation (1) or Figure 9 is "approximate" for other locations. However, the Green Book fails to note explicitly that Equation (1) and Figure 9 only apply directly to horizontal curves that are longer than the DSSD, S. If the horizontal curve is shorter than the DSSD, S, the horizontal sightline offset needed is always less than HSO determined with Equation (1) or Figure 9.

Figure 11 shows with shading the extent of the areas that actually need to be clear of roadside sight obstructions. In particular:

- If $L > S$, the area that needs to be clear of sight obstructions is shown in Figure 11(a). The area for which the horizontal sightline offset is equal to HSO in Equation (1) and Figure 9 extends from Station $PC + 0.5S$ to $PT - 0.5S$.
- If $L = S$, the area that needs to be clear of roadside sight obstructions is shown in Figure 11(b). A horizontal sightline offset equal to HSO is needed only at a single point located at the center of the curve, Station $PC + 0.5L$.
- If $L < S$, the area that needs to be clear of roadside sight obstructions is shown in Figure 11(c). At no point does the horizontal sightline offset need to be as great as HSO in Equation (1) and Figure 9.

The vertical dimensions of the cross section of the roadway, including superelevation, do not factor into the dimensions of the shaded areas in Figure 11. Figure 11 is based purely on the plan view of the roadway.

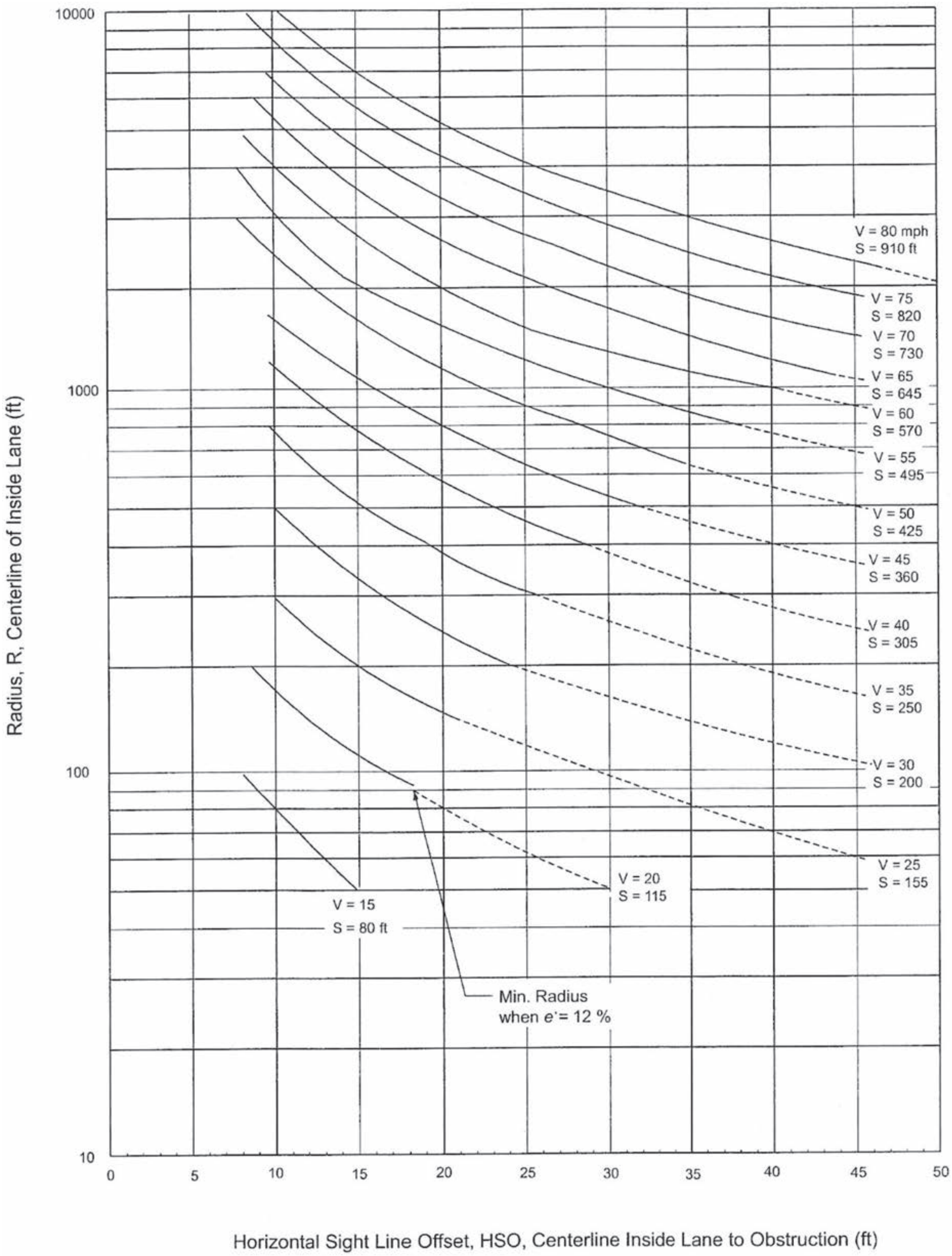

Figure 9. SSD on horizontal curves (AASHTO 2011).

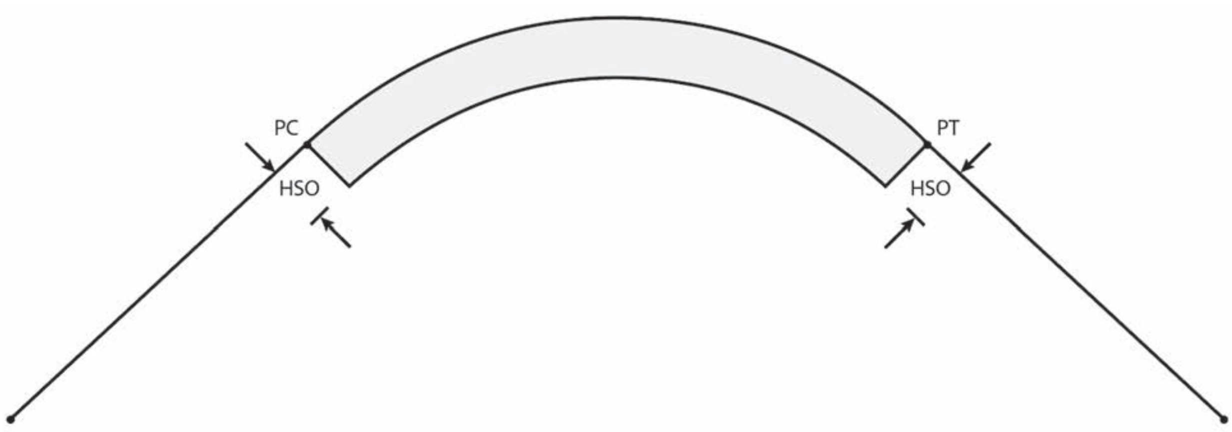

Figure 10. Simplistic view of area that needs to be clear of sight obstructions on the inside of a horizontal curve.

Figure 11 shows that the shaded area that should be clear of sight obstructions extends beyond the ends of the horizontal curve, represented in the figure by the point of curvature (PC) and the point of tangency (PT). The shaded area actually begins at Station PC – S and ends at Station PT + S. It should also be noted that a portion of the shaded area shown in Figure 11 should already be free of sight obstructions. The driver's path from the PC to PT shown in Figure 11 is along the centerline of the lane closest to the inside of the curve. Since HSOs are measured from the centerline of the inside lane and the travel lanes and shoulder are, by definition, clear of sight obstructions (with the possible exception of vehicles

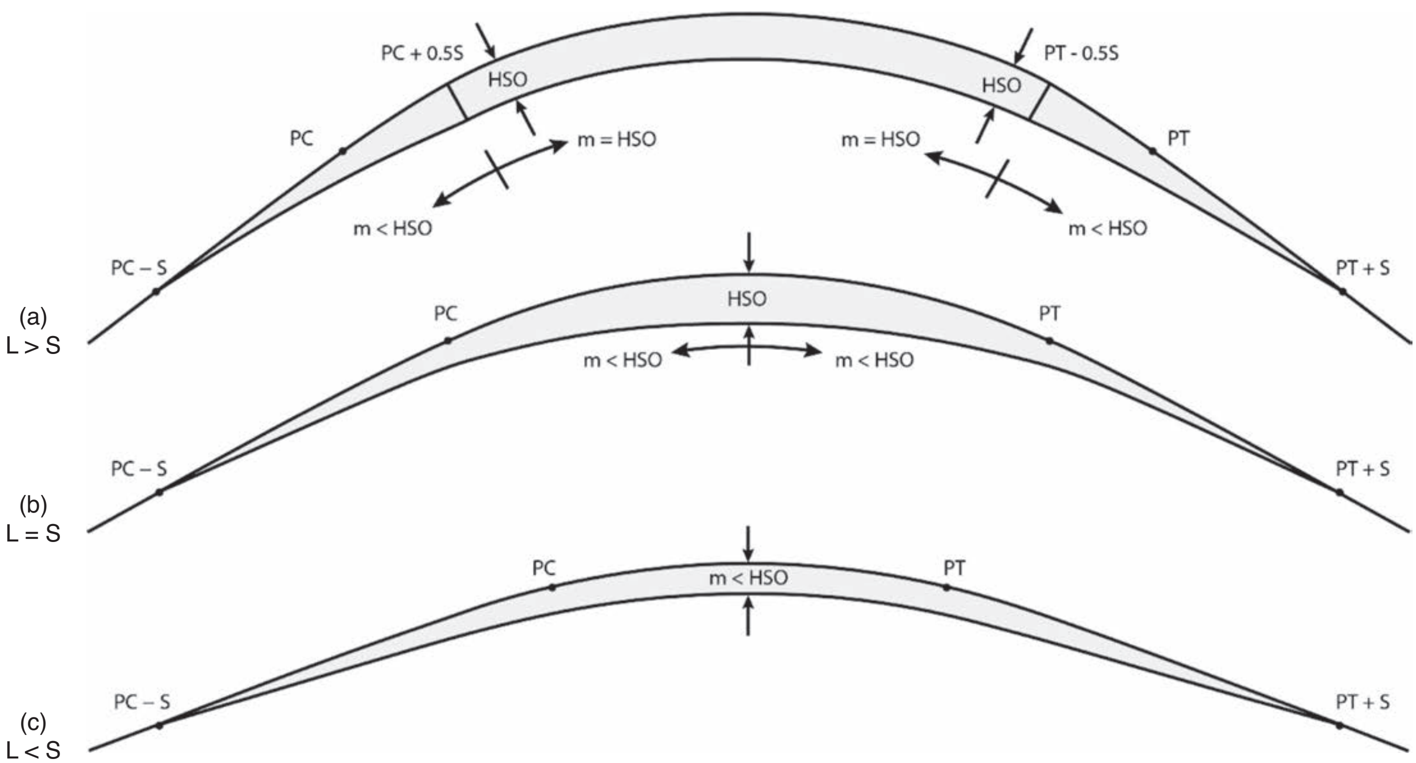

Figure 11. Actual areas that need to be clear of sight obstructions on the inside of a horizontal curve.

stopped temporarily on the shoulder), the value of HSO, m, is only of practical importance to design where:

$$m > \frac{LW}{2} + SW \tag{7}$$

where

m = HSO on the inside of the curve (ft);
LW = lane width for the inside lane on the curve (ft); and
SW = shoulder width (ft).

The width of the roadside area (outside of the shoulder) that should be clear of sight obstructions at any location along the curve is:

$$m_{roadside} = m - \frac{LW}{2} - SW \tag{8}$$

where $m_{roadside}$ is portion of HSO that is on the roadside area outside of the shoulder (ft).

If $m_{roadside}$ is less than or equal to zero, then no portion of the roadside (i.e., outside of the roadway shoulder) needs to be clear of sight obstructions.

There will undoubtedly be design situations in which the variations among the three cases for measurement of HSO shown in Figure 11 have important consequences for design. At some locations (e.g., where a rock cut or retaining wall is present on the roadside), it could be substantially more expensive to assume a roadside clear area like that shown in Figure 10, when one of the cases shown in Figure 11 actually applies. Thus, it appears that the Green Book oversimplifies in stating that HSO is an "approximation" of horizontal sightline offset for those cases shown in Figure 11 in which m is less than HSO. This Green Book discussion of HSOs can be improved to encourage better understanding of the issue of HSOs.

In Figure 11, the variable m is used to represent the value of horizontal sightline offsite that should be provided at any point along a horizontal curve. The value of HSO computed with Equation (1) or Figure 9 represents the maximum value that m can take on any specific horizontal curve; m will reach the value of HSO only if the length of the curve equals or exceeds the DSSD ($L \geq S$). Thus, HSO can also be referred to as m_{max}.

The current Green Book does not address the computation of determining specific dimensions of the shaded areas in Figure 11 that are less than HSO in width. Papers by Mauga (2014, 2015b) present a computational method for determining HSO at any point in the vicinity of a horizontal curve from Station PC − S to Station PC + S. The Mauga method can be applied in new construction to identify roadside areas that should be clear of roadside sight obstructions; the method can also be applied in the assessment of existing roadways. The Mauga method is summarized in Appendix A. The Mauga method may be too complex for manual application, but can readily be incorporated in CADD systems to show the designer the area that needs to be clear of horizontal sight obstructions.

Raymond (1972) presents graphs for determining HSO, and the roadside area that should be clear of sight obstructions is influenced by the presence of spiral curve transitions with increasing HSOs needed as the length of spiral increases (see Figure 1).

An analysis by Easa (1991, 1993) developed a sight distance model and concluded that HSOs needed on compound curves analyzed together may exceed those for the individual curves analyzed separately. Mauga (2015a) also examined HSOs for compound curves.

Liu and Wang (2012) and Liu (2013) provide a 3D analysis methodology, based on vector algebra, for determining sight distance on combined horizontal curves and crest vertical curves.

The design criteria in the Green Book and its predecessors were developed prior to the computer era, at a time when the conservative "approximation" discussed earlier may have been necessary. Today, given that virtually all design is done with CADD systems, more exact methods of analysis can be implemented. It is likely that the complete computational method is too complex to be incorporated in the Green Book, but its value for CADD systems is evident.

2.4 Alternative Assumptions for Measuring Horizontal Sight Distance

This section presents assumptions that may be considered for measuring horizontal sight distance in design analyses as alternatives to the traditional AASHTO (Green Book) assumptions. Three issues are addressed: lateral position of the driver's eye, the height of the driver's eye, and the height of the object to be seen.

2.4.1 Lateral Position of Driver's Eye

The AASHTO Green Book assumes that horizontal sight distance should be measured along the centerline of the inside travel lane on the horizontal curve. Since the driver sits on the left side of the vehicle, it may be more realistic to consider an off-center position for the driver's eye. The reliability analysis model presented in Chapter 5 and Appendix B allows the designer to consider the effect on ASSD of the lateral placement of the driver's eye anywhere within the travel lane. A suggested value for the distance from the left edge of the travel lane to the driver's eye is one-quarter of the lane width. This positioning assumption provides an advantage in sight distance for curves to the right, but a disadvantage in sight distance for curves to the left.

2.4.2 Height of Driver's Eye

The AASHTO Green Book assumes that the driver's eye is positioned 3.5 ft above the roadway. This is an appropriate assumption for a typical driver in a typical passenger car. The reliability analysis model presented in Chapter 5 and Appendix B allows the designer to consider the effect on ASSD of positioning the driver's eye lower or higher than the AASHTO value. For example, a driver eye height of 3.0 ft might be used as representation of a low-profile vehicle such as a sports car, while a driver eye height of 8.0 ft might be used as representative of a truck.

2.4.3 Height of Object to Be Seen

The AASHTO Green Book assumes that the object to be seen is 2.0 ft above the roadway, equivalent to the taillight height of a typical passenger car. As a result there are horizontal curve locations appearing not to provide sufficient SSD when assessed with AASHTO criteria, but at which the driver can see stopped vehicles ahead in the travel lane over the sight obstruction. For example, the upper portion of passenger vehicles is often visible ahead over roadside or median barriers. The reliability analysis model presented in Chapter 5 and Appendix B allows the designer to consider the effect on ASSD of modifying the height of the object to be seen. For example, if the object height is set at 3.5 or 4.0 ft, it may still be possible for approaching drivers to see the upper portion of a 4.5-ft passenger car ahead on the roadway.

CHAPTER 3

Relationship of Sight Distance to Crash Frequency and Severity

Only limited research has examined the relationship of sight distance to crash frequency and severity and no studies have developed any generally applicable CMFs.

Glennon (1987) reviewed seven published studies in which SSD was considered one of several factors that might affect crash rates. These studies included work by Cirillo et al. (1969), Foody and Long (1974), Gupta and Jain (1973), Hills (1977), Raff (1953), Schoppert (1957), and Sparks (1968). Each of these studies used some form of either multivariate analysis or a sufficiency rating scheme to address SSD effects. Glennon concluded that none of these studies provided any reliable method of determining the effects of SSD on crashes.

Olson et al. (1984) evaluated the crash history of 10 pairs of crest vertical curve sites. One site of each pair was a crest vertical curve with limited SSD (118 to 308 ft), while the other was a similar nearby crest with adequate SSD (greater than 700 ft). Olson et al. (1984) found that in seven of the 10 pairs, the limited SSD site had more crashes than the adequate SSD site. In one of the pairs, the adequate SSD site had more crashes. For two of the 10 pairs of sites, there was no difference in crashes between the paired sites. For the 10 sites as a whole, the sites with limited SSD experienced 50 percent more crashes than the sites with adequate SSD. This study provides some evidence for an effect of SSD on crashes, but the study has flaws that limit its applicability. The Olson et al. (1984) crash study did not compensate for regression-to-the-mean bias and did not document what roadway features, if any, were hidden by the sight distance limitation.

Limited research has also addressed crash relationships for sight distance types other than SSD. For example, recent research by Himes et al. (2016) has established that intersections with greater intersection sight distance (ISD) have fewer crashes, including fewer fatal-and-injury crashes, than intersections with less ISD. Results from Himes et al. (2016) indicate that ISD has a greater effect on crash frequency at higher traffic volumes than at lower traffic volumes.

The lack of crash reduction effectiveness measures for SSD is puzzling, given the emphasis placed on SSD in design. Generations of highway engineers have been taught that SSD must be provided at all points along the roadway alignment. Yet, despite this perceived importance, there are no definitive CMFs that quantify the effect of SSD on crashes in either the AASHTO *Highway Safety Manual* (AASHTO 2010; AASHTO 2014) or on the FHWA CMF Clearinghouse website (www.cmfclearinghouse.org). The likely reason that the safety effects of SSD have not been successfully quantified is that these effects are highly situational, meaning that limited SSD is far more likely to result in a collision at some locations than at others. Recent research in *NCHRP Report 783* (Harwood et al. 2014) found that, at crest vertical curves with limited SSD on rural two-lane highways, crash frequencies were high at locations where intersections, driveways, or horizontal curves were hidden from the approaching driver's view by the sight restriction. However, where no hidden features were present, there was much lower crash experience, even though the SSD was limited. On other highway types, such as divided highways, freeways, or urban arterials, a variety of additional hidden features, such as ramp terminals or pedestrian crossings, may also be critical if located in a sight-restricted area. And, on congested highways, there is a possibility of a standing queue being present in a sight-restricted area during specific time periods. This research demonstrates for crest vertical curves that correcting or mitigating limited SSD may be much more critical in some highway situations than in others; the same principle is likely to apply to horizontal sight restrictions. Considering the findings of *NCHRP Report 783*, it is reasonable that Himes at al. (2016) found an effect of ISD on crashes—since an intersection is present by definition at locations where ISD is limited—while previous research on sites with limited SSD, but not necessarily with critical features present in the sight-limited area, found no effects or inconsistent effects.

Research by Potts et al. (2018) studied curves with limited horizontal sight distance and found that sight-distance-related crashes were difficult to identify explicitly from either electronic crash data or hard-copy police crash reports. However, it was evident that sight-distance-related crashes are rare events. Sight-distance-related crashes were found to be so infrequent that there was not sufficient data to develop formal CMFs for removal of horizontal sight obstructions. In fact, given the varying criticality of SSD, depending on the presence or absence of hidden features in the sight-restricted area, it is unlikely that generally applicable CMFs for SSD improvements can be developed.

Given the lack of CMFs for sight distance improvements, alternative approaches are needed to prioritize locations for improvement. This guide presents two tools that can assist highway agencies in analyzing and setting priorities for horizontal sight distance improvements:

- A benefit-cost analysis procedure that uses a user-supplied estimate of the maximum crash reduction likely to result from a project to estimate the maximum implementation cost that should be invested in such a project (see Chapter 4).
- A reliability analysis model and accompanying spreadsheet-based tool that can quantify the extent of a horizontal sight distance restriction and can estimate the number of approaching vehicles per year on a particular curve that are likely to encounter a stopped vehicle in the sight-restricted area (see Chapter 5).

Chapter 6 presents a step-by-step procedure for using these tools to assess whether horizontal sight restrictions on particular horizontal curves should be removed or mitigated. Available mitigation strategies are reviewed in Chapter 7.

CHAPTER 4

Benefit-Cost Analysis

Benefit-cost analysis is an economic analysis approach that can be used to assess whether any proposed highway improvement is cost-effective (i.e., whether the benefits from implementation of the improvement exceed its costs). A limitation in the application of benefit-cost analysis to horizontal sight obstructions is that quantitative estimates for both the benefits and costs of the improvement must be available for the analysis to be performed.

The costs of removing horizontal sight obstructions are difficult to generalize, because the costs can vary substantially from site to site. However, for any specific site, an estimate of the cost to remove the horizontal sight obstruction can be developed.

The crash reduction benefits of removing a horizontal sight obstruction are much more difficult to quantify than the costs. There are no CMFs that represent the crash reduction effectiveness of removing a sight obstruction. CMFs for removal of horizontal sight obstructions have not been developed because:

- Horizontal sight obstructions have seldom been removed in a project with no other changes, so the number of projects that could be used in before-after evaluations is limited; and
- The frequency of sight-distance-related crashes is small and is difficult to quantify; as shown in Potts et al. (2018), sight-distance-related crashes cannot generally be distinguished from other crashes in electronic crash data and are difficult to distinguish reliably from other crashes even when hard-copy police crash reports are available.

Thus, no exact benefit-cost analysis can be performed for removal or mitigation of horizontal sight obstructions. However, as explained below, benefit-cost analysis can be used to approximate the maximum amount that a highway agency should consider spending to remove or mitigate a particular horizontal sight obstruction.

The basic equation used for benefit-cost analysis of any proposed highway improvement based on the potential crash reduction of the improvement is:

$$B/C = \left[\sum\nolimits_k CRF_{jk} \mathrm{N}_{\mathrm{ik}} \mathrm{C}_{\mathrm{k}} \left(P/A, \mathrm{i}\%, n\right)\right] / \mathrm{IC}_{ij} \tag{9}$$

where

B/C = benefit-cost ratio;
CRF_{jk} = crash reduction effectiveness (percentage reduction in crashes) for crash severity level k from implementing improvement j;
N_{ik} = expected annual crash frequency for crash severity level k at site i prior to improvement;
C_{k} = benefit ($) per crash reduced for crash severity level k;

IC_{ij} = implementation cost ($) for improvement *j* at site *i*;
$(P/A, i\%, n)$ = uniform series present worth factor;
i = discount rate or minimum attractive rate of return (percent); and
n = improvement service life (years).

Each specific element of the benefit-cost analysis in Equation (9) is reviewed in the following sections.

4.1 Crash Reduction for Sight Distance Improvements

The CRF_{jk} term in Equation (9) represents the proportional reduction in crash frequency for a particular severity level due to a sight distance improvement. This crash reduction effectiveness, or percent reduction in crashes, is expected to be highly situational. In other words, the percent reduction in crashes might be substantial at some types of sites (i.e., with critical downstream roadway elements limited from the driver's view) and zero or near-zero at other locations.

4.2 Expected Annual Crash Frequency

The expected annual crash frequency for a site prior to improvement can be estimated either from site-specific crash history data or from the crash prediction methods of the *Highway Safety Manual* (AASHTO 2010; AASHTO 2014).

4.3 Benefit per Crash Reduced

The benefit per crash reduced represents the societal costs of crashes by severity level. The crash costs currently in use in Safety Analyst (www.safetyanalyst.org), shown in Table 2, are typical of current highway agency practice.

4.4 Improvement Service Life

The service life for physical changes to the roadway to increase horizontal sight distance should be 20 years or more. Improving sight distance by clearing brush or other vegetation should be assigned a shorter service life (e.g., 5 years) if the brush or vegetation could grow back. Some mitigation measures, such as signing or marking, would typically have a substantially shorter service life than 20 years.

4.5 Discount Rate or Minimum Attractive Rate of Return

A discount rate or minimum attractive rate of return of 7 percent has typically been used in benefit-cost analysis, in accordance with current federal guidelines.

Table 2. Recommended value of crash costs or crash reduction benefits by crash severity level.

Crash Severity Level	Comprehensive Societal Crash Costs
Fatal (K)	$5,722,300
Disabling Injury (A)	302,900
Evident Injury (B)	110,700
Possible Injury (C)	62,400
Property Damage Only (O)	10,120

SOURCE: **www.safetyanalyst.org**

4.6 Uniform Series Present Worth Factor

The annual crash cost savings should be reduced to their present worth by multiplying by the uniform series present worth factor, computed as follows:

$$(\mathrm{P/A}, i\%, n) = \frac{\left(1+\frac{i}{100}\right)^n - 1}{(i/100)\left(1+\frac{i}{100}\right)^n} \tag{10}$$

where

$(P/A, i\%, n)$ = uniform series present worth factor;
i = discount rate or minimum attractive rate of return (percent); and
n = improvement service life (years).

4.7 Project Implementation Cost

Project costs or improvement costs are referred to here as project implementation costs, rather than construction costs, since they include not only the estimated construction cost, but also the cost for additional right-of-way that may be needed. The project implementation cost is likely to vary from site to site, even for nominally similar horizontal sight obstructions, so site-specific cost estimates should be developed for each potential project.

4.8 Cost-Effectiveness Analysis

The site-specific project crash reduction benefits are difficult to quantify, but it may be feasible to estimate the maximum crash reduction that could potentially occur from a given project and use that value to quantify the maximum project implementation cost that should be considered for horizontal sight obstruction removal or mitigation. The maximum potential crash reduction can be estimated by:

- Reviewing electronic crash history data to estimate the average annual number of crashes for the following crash types for all lanes in the primary direction of travel: rear-end, same-direction sideswipe, and run-off-road; such crashes may possibly be related to sight distance, but are known to be an overestimate of sight-distance-related crashes;
- Using the *Highway Safety Manual* (AASHTO 2010; AASHTO 2014) procedures to estimate the average annual number of crashes for those three possibly related crash types in the primary direction of travel (i.e., for two-way roadways, divide the two-way crash frequency estimate in half); or
- Reviewing hard-copy police crash reports and identifying the average annual number of crashes that are potentially sight distance related.

A review of hard-copy police crash reports by Potts et al. (2018) suggests that the results of a hard-copy review will likely identify as potentially sight-distance-related only about 5 percent of the crashes for the three possibly related crash types. Even the estimate based on hard-copy police crash reports will likely include some crashes that are not, in fact, sight-distance-related. To be conservative, it is suggested that the estimate of the maximum likely crash reduction benefit from implementation of a sight distance improvement, $maxN_{ik}$ in Equation (11), be estimated as follows:

- Multiply the total number of rear-end, same-direction sideswipe, and run-off-road crashes from electronic crash data by 0.05; or
- Use the number of probable sight-distance-related crashes obtained from review of hard-copy police crash reports unchanged.

Equation (9) can be transformed as follows to estimate the maximum implementation cost that could be incurred while still achieving a benefit-cost ratio equal to 1.0:

$$maxIC_{ij} = \left[\sum_{k} maxN_{ik} C_{k} \left(P/A, i\%, n\right)\right] \tag{11}$$

where

$maxIC_{ij}$ = estimate of the maximum implementation cost ($) for a cost-effective improvement j at site i; and

$maxN_{ik}$ = estimated maximum annual crash frequency for crash severity level k at site i prior to improvement.

The computed value of $maxIC_{ij}$ can then be compared to the improvement cost level estimated by the highway agency to decide whether the improvement is likely to be cost-effective. For example, if the improvement cost level estimated by the highway agency is low and the value of IC_{ij} determined with Equation (11) is high, then a horizontal sight distance improvement would very likely be cost-effective. If, on the other hand, the improvement cost estimated by the highway agency is high and the value of IC_{ij} is low, then a horizontal sight distance improvement would very likely not be cost-effective.

A key challenge in applying benefit-cost analysis of this type is that the value of $maxN_{ik}$ will likely always be an uncertain estimate. This challenge should be addressed by using the available crash data to make a conservative estimate. At sites with no history of crashes that could possibly be sight-distance-related, the best available estimate of $maxN_{ik}$ may be zero. In such cases, substantial investments to remove sight distance obstructions are likely not justified, but consideration should be given to lower cost mitigation strategies (see Section 7.2).

4.9 Computational Example

A computational example of the application of Equation (11) is presented here. This example addresses a particular horizontal curve on a rural two-lane highway with trees and vegetation located on the inside of the horizontal curve. The designer responsible for a planned project that includes the horizontal curve in question reviews the crash history of the curve and concludes that there have been at most three sight-distance-related crashes at the curve site in the past 5 years, and there may have been as few as one sight-distance-related crash. To be conservative, the designer decides to use the estimate of three sight-distance-related crashes in 5 years. Using the typical crash severity distribution for the site, the designer concludes that the maximum annual crash reduction likely to result from removing the trees and vegetation on the inside of the curve would be:

- No fatalities;
- 0.05 disabling injuries (A injuries) per year;
- 0.10 evident injuries (B injuries) per year;
- 0.15 possible injuries (C injuries) per year; or
- 0.30 property-damage-only injuries per year,

Assuming a project service life of 20 years and a discount rate of 7 percent, Equation (10) is applied to determine the uniform series present worth factor as follows:

$$\left(\frac{P}{A}, i\%, n\right) = \frac{\left(1+\frac{7}{100}\right)^{20} - 1}{\left(\frac{7}{100}\right)\left(1+\frac{7}{100}\right)^{20}} = 10.59 \tag{12}$$

Then, using the crash cost estimates in Table 2, Equation (11) is applied to estimate the maximum implementation cost as follows:

$$\begin{aligned} \text{maxIC}_{ij} &= (5722300 + 0.05 \times 302{,}900 + 0.1 \times 110700 \times 0.15 \times 62400 + 0.3 \times 10120) \times 10.59 \\ &= \$408{,}891 \end{aligned} \tag{13}$$

This computation indicates that if the trees and vegetation on the inside of the horizontal curve that constitute the horizontal sight obstruction can be removed for a cost of $408,891 or less, this could be a cost-effective improvement project. Because of the uncertainty in the crash reduction estimate, the designer treats the value of $408,891 as a potential upper limit on project cost and not as a firm decision-making criterion. However, if the removal of the trees and vegetation, including any right-of-way or site easement needed would cost more than $408,891, the designer considers that the project would not be considered cost effective.

CHAPTER 5

Reliability Analysis Model for Horizontal Curves with Limited SSD

This chapter presents a reliability analysis model for horizontal curves with limited SSD due to sight obstructions on the inside of the curve. Any horizontal curve is likely to experience more crashes than a tangent roadway section simply because of the presence of the curve (AASHTO 2010; AASHTO 2014) even in the absence of any sight distance limitation.

The reliability analysis model developed in this research can determine the sight distance profile on any horizontal curve with a specific sight obstruction on the inside of the curve and can estimate the opportunities for crashes to occur due to limited SSD. The measure of opportunities for crashes to occur is the number of events during a 1-year time period in which there is increased likelihood that a crash will occur in a portion of the roadway with limited SSD where there would be no increased likelihood of a crash if the horizontal sight obstruction were not present. The reliability model is applicable to the direction of travel closest to the inside of the horizontal curve. While the likelihood of sight-distance-related collisions in a particular direction of travel is greatest in the travel lane closest to the inside of the curve in that direction of travel, the model addresses the opportunities for sight-distance-related crashes in all travel lanes for a specific direction of travel.

If the minimum ASSD is never less than the applicable DSSD at any point approaching or on the horizontal curve in question, then the opportunity for sight-distance-related crashes is zero. If the minimum ASSD is less than the applicable DSSD at any point approaching or on the horizontal curve, then the opportunity for sight-distance-related crashes is greater than zero. Most situations in which sight-distance-related crashes could occur do not result in crashes. Many factors make crashes unlikely even when the opportunity for a crash exists. For example, drivers may avoid crashes by decelerating more rapidly than assumed in design criteria or by making avoidance maneuvers, such as changing lanes or using the shoulder (if available). Also, the opportunity for a sight-distance-related crash may not persist for as long as assumed in the model. The model is purposely conservative in overestimating the opportunities for sight-distance-related crashes. Thus, the model estimates do not predict the number of crashes that will occur where a horizontal sight obstruction is present, but may be useful in estimating the relative frequency of opportunities for crashes at specific sites. At some sites, the opportunity for sight-distance-related crashes, even though nonzero, may be very small and may justify only low-cost mitigation measures. At other sites, the opportunity for sight-distance-related crashes may be substantially higher and may justify higher cost mitigation measures.

The reliability analysis model considers two alternatives for measuring ASSD. The basic method incorporates the sight distance measurement assumptions used in the AASHTO Green Book (2011), including an assumed height of 2.0 ft (equivalent to vehicle taillight height) for the object to be seen and the assumption that sight distance is measured along the center of a given travel lane. The alternative method allows the user of the reliability model to specify an increased height for the object to be seen. For example, if the object to be seen is another vehicle, a more realistic assumption for the height of the object to be seen would be 3.5 ft, which is used as the assumed object height in passing sight distance design. In addition, the alternative method assumes that the lateral position of the driver's eye within a given travel lane on a horizontal curve is at 75 percent of the distance from the inside to the outside edge of the travel lane on a curve to the right and at 25 percent of the distance from the inside to the outside edge of the travel lane on a curve to the left. These assumptions for the lateral position of the driver's eye appear more realistic than the assumption that the driver's eye is in the center of the lane.

The reliability analysis model assumes that vehicles ahead on the roadway are visible to an approaching driver only when there is a direct line of sight from the driver's eye to the other vehicle. This assumption represents daylight conditions. At night, atmospheric diffusion of light from the headlights or taillights of a vehicle ahead may make the presence of a vehicle apparent even when there is no direct line of sight from the driver's eye to the other vehicle. Thus, the reliability analysis addresses the most critical condition.

The input data, output results, and the reliability model logic are explained in this section. A spreadsheet tool has been developed to apply the reliability model. A users guide to this spreadsheet tool is presented in Appendix B with more details concerning both the input data and the output results.

5.1 Input Data for the Reliability Analysis Model

The reliability analysis model is applied to a specific curve that has a potential horizontal sight obstruction and whose annual average daily traffic (AADT) and traffic volume are known. Input data for the reliability analysis model apply to the primary direction of travel (i.e., the direction of travel in which the horizontal sight obstruction is on the inside of the curve) and include:

- Roadway type (freeway, ramp, rural multilane divided highway, rural multilane undivided highway, rural two-lane highway);
- Number of travel lanes in primary direction of travel;
- Average lane width (ft);
- Design speed or operating speed (mph);
- Direction of curve (right or left);
- Radius of curve (ft);
- Length of curve (mi);
- Type of vertical geometry (straight grade/vertical curve);
- Percent grade for straight grades;
- Approach percent grade and departure percent grade for vertical curves;
- Length of vertical curve (mi);
- Distance to the sight obstruction from the inside edge of the traveled way (ft);
- Type of sight obstruction (point obstruction, continuous obstruction);
- Distance from the PC to the beginning of the sight obstruction (mi);
- Distance from the PC to the end of the sight obstruction (mi);
- AADT (veh/day) for the primary direction of travel;
- Proportion of traffic in each lane for the primary direction of travel; and
- Proportion of traffic in the peak hour (k).

The reliability analysis model includes built-in tables of default values for the typical percentage of traffic in each of the 24 hours of a typical day, as a function of the proportion of traffic in the peak hour (k). These default values can be replaced by the program user with agency-specific or site-specific values for the percentage of traffic in each of the 24 hours of a typical day.

Figure 12 shows the main data entry screen for the reliability tool, illustrating the input data.

INPUT DATA

Facility Type	
Urban one-lane exit ramp	
Number of lanes in analysis direction	1
Average lane width (ft)	12.0
AADT (one direction, veh/d)	14572

- ○ Point obstruction
- ○ Continuous obstruction, straight grade
- ◉ Continuous obstruction, vertical curve present

Direction of Curve
To the left

Horizontal Curve and Obstruction Data Input	
Curve Radius, R (ft)	1432.0
Curve Length, L (mi)	0.330
Design or Operating Speed (mi/h)	55
Longitudinal distance from PC to beginning of continuous obstruction, B1 (mi)	-0.100
Longitudinal distance from PC to end of continuous obstruction, B2 (mi)	0.430
Offset from edge of traveled way to sight obstruction, m (ft)	4.0
Height of obstruction above edge of traveled way (ft)	4.5

Vertical Curve Data	
Approach grade (%)	0.00
Departure grade (%)	2.00
Distance from PC to PVC (mi)	-0.033
Vertical curve length (mi)	0.050

Figure 12. Example of input data entry screen in the reliability analysis spreadsheet tool.

5.2 Output Data from the Reliability Analysis Model

The outputs provided by the reliability model include:

- Minimum ASSD at any point in each travel lane for the primary direction of travel;
- Length of the sight-restricted area;
- A color-coded indication whether the minimum ASSD for each travel lane is less than or greater than or equal to the AASHTO value of DSSD for the applicable design or operating speed;
- An estimate of the total number of vehicles per year potentially affected by any sight distance restriction that is present, for each travel lane and for all lanes combined;
- Total number of vehicles passing through the horizontal curve site in a year, for comparison to the previous measure; and
- An estimate of the percentage of the total number of vehicles per year potentially affected by any sight distance restriction that is present, for each travel lane and for all lanes combined.

Figure 13 illustrates the display of these results in the output spreadsheet tool.

RESULTS		Lane 1				Total
Minimum available sight distance (ft)		338.7				
Total Number of affected vehicles per year		59.45				59.45
Total number of vehicles passing site per year		1,595,634				1,595,634
Percent affected		0.004%				0.004%
Time and date of last analysis	3/30/2018 12:10		AASHTO design stopping sight distance (ft)			495

Figure 13. Example of output results display in the reliability analysis spreadsheet tool.

In addition, the model output includes the values of ASSD along the road from Station PC – S to PC + S, so that the point of minimum ASSD can be located and so that the designer can assess the distance over which the ASSD remains at a low level. Figure 14 shows an example of a sight distance profile plotted from the ASSD data in the model output.

The number and percentage of vehicles potentially affected by the sight distance restrictions are measures of the opportunity for drivers to encounter a crash- or congestion-generated queue of vehicles in the sight-restricted area. The model assesses the probability that each driver approaching the horizontal sight obstruction over the course of a year will encounter a queue of stopped vehicles on a portion of the roadway which the horizontal sight obstruction restricts the driver from seeing. If the number or percentage of potentially affected drivers is small, the likelihood of crashes resulting is small. If the number or percentage of potentially affected drivers is large, the risk of collision is high. Thus, the reliability model provides a quantitative estimate of the opportunity for crashes to occur. Only a very small percentage of the potentially affected drivers may actually encounter crashes.

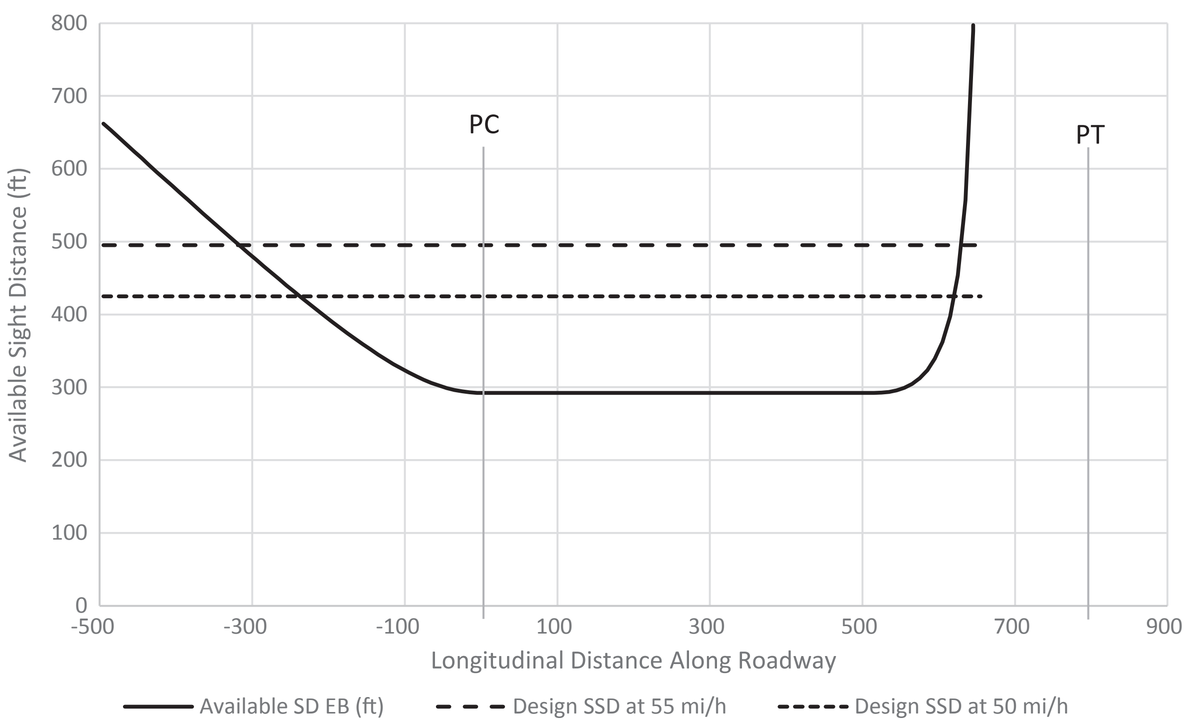

Figure 14. Example of sight distance profile from model output.

The reliability model can provide output for two different sets of assumptions concerning sight distance measurement. The first option uses the sight distance measurement assumptions exactly as presented in the AASHTO Green Book (AASHTO 2011). The assumptions are:

- Sight distance is measured along the centerline of a travel lane;
- The driver's eye is located 3.5 ft above the roadway surface; and
- The object ahead which the driver is expected to see has a height of 2 ft, equivalent to the taillight height of a typical passenger car.

The model is also capable of providing output results for an alternative user-specified set of sight distance assumptions. Suggested values for those alternative assumptions are discussed here, but the model will permit the user to enter values for whatever set of alternative assumptions the user wishes:

- The user may specify that sight distance be measured along a line other than the centerline of the travel lane. The alternative value entered for this option is the distance from the left edge of the travel lane to the driver's eye location. The capability to consider noncenterline locations makes sense, because the driver's eye location is unlikely to be in the center of the lane. The user may enter whatever driver's eye location they wish, but the suggested value for the distance from the left edge of the travel lane to the driver's eye is 25 percent of the lane width. These alternative assumptions are more realistic concerning the actual positioning of the vehicle within a lane and provide a sight distance advantage for the driver on curves to the right and a sight distance disadvantage to the driver on curves to the left, as compared to the Green Book assumptions.
- The user may also specify an alternative value of driver eye height. The AASHTO value of 3.5 ft as a typical driver eye height for passenger cars is well established, and there is little need to vary this value for passenger cars unless an explicit study of lower height vehicles (e.g., sports cars) is being conducted. However, capability for changing the assumed driver eye height can be used to analyze SSD for trucks. The AASHTO Green Book recommends a value of 8.0 ft as the driver eye height for a truck.
- The assumed object height of 2.0 ft used in the Green Book was based on research by Fambro et al. (1997). Fambro et al. found that very few collisions on the roadway involved objects less than 2.0 ft in height. Many, but not all, of the objects that vehicles collided with were other vehicles. The value of 2.0 ft for object height has been accepted because this corresponds to the typical taillight height for passenger cars, and seeing the taillights of vehicles ahead is certainly a desirable SSD criterion. Nevertheless, there are many horizontal curves, both to the right and to the left, where a roadside barrier constitutes a horizontal sight obstruction if sight distance is measured with the Green Book criteria, but the upper portion of each vehicle ahead is still visible above the barrier. Where this occurs, a highway agency may decide that removal or mitigation of the sight obstruction is not needed. The reliability model can identify this situation by assessing ASSD for an alternative value of object height, such as 3.5 ft, which allows the upper portion of a passenger car, from the driver's eye to the roofline, to be seen.

The structure of the reliability model and the logic employed in each component module of the reliability analysis model is presented in Sections 5.3 through 5.5.

5.3 Structure of Reliability Analysis Model

The computations within the reliability analysis model are organized into two distinct modules: an ASSD module and a reliability analysis module. The available stopping sight distance module computes, for each travel lane, ASSD at a series of points along the roadway, determines the minimum value of ASSD, compares that minimum value of ASSD to the DSSD for the applicable design or operating speed, and determines whether there is a horizontal sight distance restriction. The reliability analysis model estimates the number and percentage of vehicles per year potentially affected by any sight distance restriction present. Aspects of the reliability analysis computation include:

- Crash-generated queues in the sight-restricted area;
- Congestion-generated queues in the sight-restricted area; and
- Computation of potentially affected vehicles.

Each module of the reliability analysis model is discussed in the following sections.

5.4 Available SSD Module

The first module of the reliability model is the calculation of the ASSD along the curve where a horizontal sightline obstruction is present. The sightline obstruction either can be a point obstruction or a longitudinal obstruction. The tool calculates the minimum ASSD for each lane as well as the length of downstream roadway in which the ASSD is less than the AASHTO DSSD specified in the Green Book. Figure 15 shows how the sight-restricted area is determined. The beginning of the sight-restricted area is shown in Figure 15(a), where the ASSD begins to be less than the DSSD. The end of the sight-restricted area is shown in Figure 15(b), where the ASSD begins to be greater than the DSSD. The resulting length of downstream roadway in which the ASSD is less than the DSSD is shown in Figure 15(c).

5.4.1 Horizontal Sight Obstruction

A horizontal sight obstruction can be defined as either a point obstruction or a longitudinal obstruction that extends along the roadside for a specified distance. For a point obstruction, the calculations are simply done in the x-y plane, because point obstructions are assumed to have a very tall height (such as a single tree or a corner of a building). If a point obstruction that is not very high needs to be evaluated, it can be treated as a very short longitudinal obstruction. For a longitudinal obstruction, the height of the obstruction is used in the calculation. The location of the obstruction relative to the roadway is treated as a fixed offset distance from the inside edge of the traveled way to the sight obstruction.

5.4.2 Roadway Alignment and Cross Section

It is assumed that all horizontal curves are circular curves with no spiral transitions. In the case of longitudinal sight obstructions, the roadway profile is considered in the calculation of ASSD. The roadway profile can either consist of a straight grade or a vertical curve with specified approach and departure grades. The model is capable of considering a single horizontal curve, with the option of including a single vertical curve as well. The model does not address multiple horizontal curves or multiple vertical curves.

The model assesses the ASSD separately for each travel lane, working in sequence from the inside lane to the outside lane on the curve. In the computation of ASSD for each successive travel lane, the distance to the horizontal sight obstruction and the radius of the horizontal curve are each increased by one lane width. The lane width considered is the average lane width; the model does not have the capability to consider different widths for each lane.

5.4.3 Procedure for ASSD Calculation

ASSD cannot be determined with a single equation. ASSD as a function of the driver's position on the roadway is not continuous from a point on the tangent upstream of the PC of a horizontal

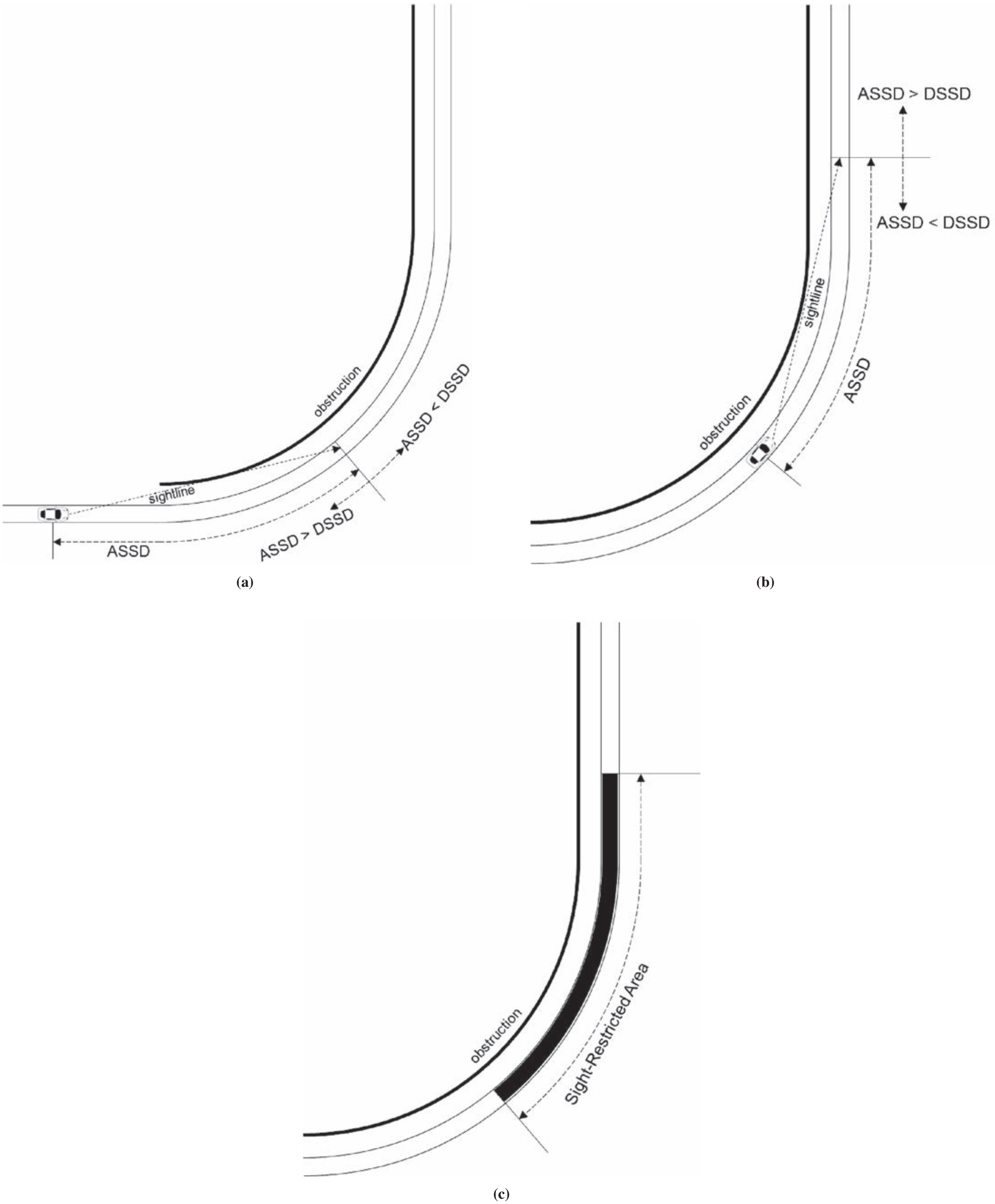

Figure 15. Determination of the sight-restricted area.

curve to a point where ASSD is no longer limited by the sight obstruction. Rather, ASSD as a function of the driver's position on the roadway must be analyzed with a set of equations for a specific scenario applicable to that position on the roadway. The scenarios that must be addressed separately in the computations include each unique combination of the following factors:

- The driver's eye location either before or after the PC of the horizontal curve;
- The driver's eye location either before the vertical point of curvature (VPC), between the VPC and vertical point of tangency (VPT), or after the VPT of the vertical curve (applicable only if a vertical curve is present);
- The location of the point along the sight obstruction to which the driver's sightline is tangent (applicable only to longitudinal obstructions); and
- The location of the point where the sightline intersects the downstream roadway, either before or after the PT of the horizontal curve.

The equations used to compute ASSD for each scenario and an explanation of how the equations are used are presented in Potts et al. (2018).

5.5 Reliability Module

The computations in the reliability module are explained in the following sections.

5.5.1 Estimating the Number of Vehicles That May Encounter a Queue in a Sight-Restricted Area If a Stopped Vehicle Is Present

The reliability module estimates the total number of vehicles in a year that may potentially encounter a queue present in the sight-limited area. The queue of concern occurs on the roadway where the obstruction limits the view of the stopped vehicles such that the ASSD is less than the DSSD. The reliability module considers two events that may generate queues behind a stopped vehicle: crashes and congestion. Later sections deal with the probability of a stopped vehicle due to a crash or congestion under the flow conditions present during a particular hour of the day. This discussion addresses the maximum number of drivers that may approach a stopped vehicle from the rear and not be able to see the stopped vehicle or the queue that has formed behind it. The model logic assumes that the crash- or congestion-generated queue will not be cleared until after the queue has spilled back out of the site-restricted area.

The number of vehicles that may potentially be affected when a queue occurs is dependent on the length of roadway that falls within the sight-restricted area as well as the hourly flow rate. Where multiple lanes are present, these factors vary depending on which lane is being analyzed. The sight-restricted area is divided for computational purposes into 25-ft segments, where 25 ft represents the length of a passenger car, plus a typical spacing between stopped vehicles. Let j_y represent the number of 25-ft segments in the sight-restricted area in lane y. Figure 16 shows a lane in which the sight-restricted area is divided into 25-ft segments. If a stopped car is present in Segment 1, then a vehicle traveling toward the stopped vehicle will not be able to see the stopped vehicle with an ASSD greater than or equal to DSSD. However, the second vehicle traveling toward the stopped vehicle will be able to see the first vehicle that is stopped behind the stopped vehicle with an ASSD greater than or equal to DSSD. In Figure 16, a vehicle is stopped in Segment 4. The first three approaching vehicles will occupy Segments 1 through 3 after they encounter the first vehicle and are forced to stop. The fourth vehicle will be the last vehicle whose driver will experience ASSD less than DSSD. The driver of any fifth or subsequent vehicle approaching the queue would be able to see the queue without any sight distance limitation. Thus, a maximum of four vehicles would encounter the stopped

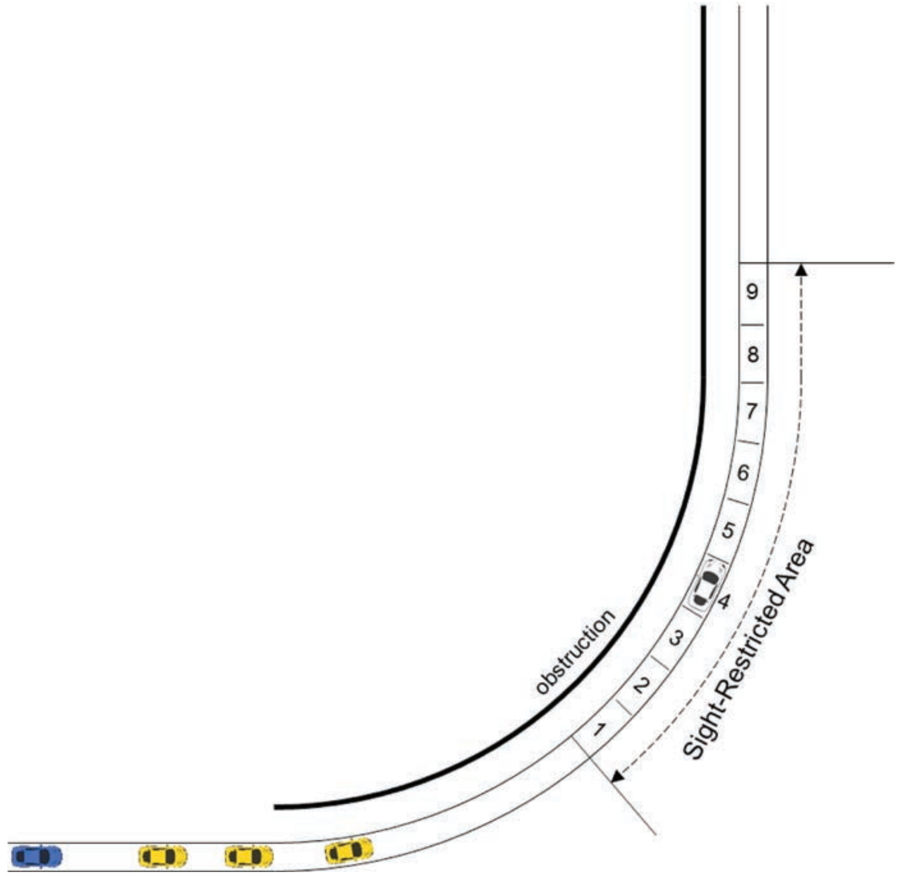

Figure 16. Example of stopped vehicle in the sight-restricted area.

vehicle with the ASSD less than DSSD so that their drivers could not see the queue with the full DSSD available.

If a stopped vehicle should be present in Segment 2, then the first two vehicles traveling toward the stopped vehicle will be in a situation with ASSD less than DSSD. This trend continues all the way until a stopped vehicle is present in the last segment of the sight-restricted area, Segment 9. The sum of all these scenarios can be expressed as:

$$\text{Sum of potentially affected vehicles due to stopped vehicle in sight-restricted area} = \sum_{n=1}^{j_q} n \qquad (14)$$

where

j_y = number of 25-ft segments in sight-restricted area in lane y;
q_{iy} = flow rate (veh/hr/lane) during i in lane y;
j_q = smaller of j_y and q_{iy}; and
n = index variable defined as increasing from 1 to j_y.

An additional situation to consider is that a stopped vehicle downstream of the sight-restricted area may generate a queue that spills back into the sight-restricted area. In this situation, the number of affected vehicles would be the total number of vehicles within the sight-restricted area, which is equal to j_y, as illustrated in Figure 17. The vehicle that stops in Segment 9 is the last vehicle that cannot be seen by an approaching driver with ASSD greater than DSSD. The drivers of the next nine approaching vehicles experience ASSD less than the DSSD.

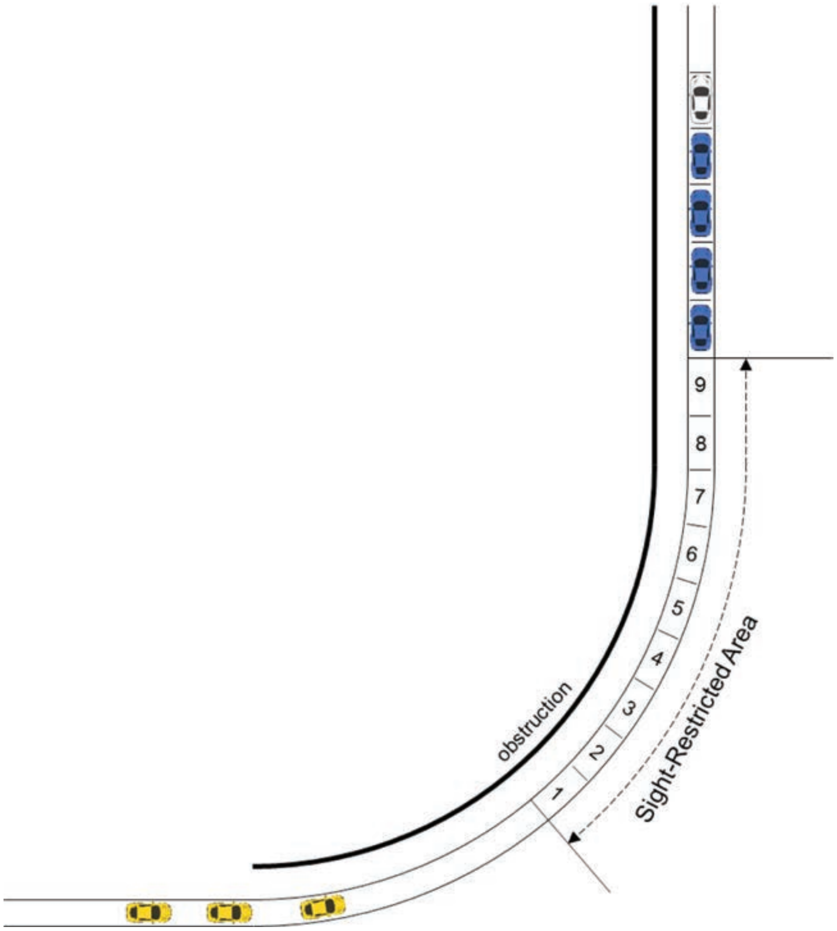

Figure 17. Vehicles experiencing ASSD less than DSSD due to a queue backing into the sight-restricted area.

The furthest downstream a stopped vehicle can queue back into the sight-restricted area during hour i is dependent on the flow rate, q_{iy}, in lane y during hour i. Let this distance be expressed by x_{iy}, the number of 25-ft segments downstream of the sight-limited area in lane y in which a crash could occur that would produce a queue long enough to enter the sight-limited area in hour i, determined as:

$$x_{iy} = q_{iy} - j_y \quad (15)$$

where x_{iy} is the number of 25-ft segments downstream of the sight-limited area in lane y in which a crash could occur that would produce a queue long enough to enter the sight-limited area in hour i.

A stopped vehicle in any 25-ft segment beyond the sight-restricted area will affect j_y vehicles. The sum of all vehicles affected by a stopped vehicle in any of these downstream segments is computed as:

$$\text{Sum of potentially affected vehicles due to stopped vehicle downstream of sight-restricted area} = j_y x_{pos} \quad (16)$$

where x_{pos} is the larger of x_{iy} and zero.

The estimated number of vehicles potentially affected when a stopped vehicle is present during hour i in lane y, V_{iy}, is the sum of Equations (11) and (13) divided by the total number of 25-ft segments where a vehicle could be stopped. This estimated number of vehicles potentially affected is computed as:

$$V_{iy} = \frac{\sum_{1}^{n=j_q} n + j_y x_{pos}}{j_y + (q_{iy} - j_y)} = \frac{0.5 j_q (1 + j_y) + j_y x_{pos}}{q_{iy}} \tag{17}$$

where V_{iy} is average number of vehicles affected when a stopped vehicle is present during hour i in lane y.

5.5.2 Frequency of Crash-Generated Queues

Crashes are one of the two types of events considered in the model that may generate queues of stopped vehicles in a sight-restricted area. Using safety performance functions (SPFs) from the *Highway Safety Manual* (AASHTO 2010; AASHTO 2014), the predicted average annual crash frequency, N_{25}, can be estimated for a 25-ft section of roadway. Since the SPFs from the *Highway Safety Manual* estimate crash frequencies for two-way roadways, it is assumed that the crash frequency for a 25-ft section of roadway in the direction of travel being evaluated is half of the predicted value from the SPF. The predicted average annual crash frequency for the 25-ft interval, N_{25}, can be multiplied by the k-factor for hour i, k_i, and the percentage of traffic in lane y, U_y, to estimate the number of average annual crashes in hour i in lane y, $N_{iy,25}$, as follows:

$$N_{iy,25} = N_{25} k_i U_y \tag{18}$$

where

$N_{iy,25}$ = predicted number of annual crashes during hour i in lane y;
N_{25} = predicted annual crash frequency for a 25-ft segment in the analysis direction of travel;
k_i = percentage of AADT during hour i; and
U_y = percentage of vehicles using lane y in analysis direction.

The predicted average annual crash frequency during hour i in lane y along the entire length of roadway in which a stopped vehicle will have an impact in the sight-limited area can be estimated as:

$$N_{iy} = N_{iy,25} q_{iy} \tag{19}$$

where N_{iy} is predicted average annual crash frequency during hour i in lane y along the entire length of roadway in which a stopped vehicle will have an impact in the sight-limited area.

5.5.3 Frequency of Congestion-Generated Queues

Congestion is the second type of event considered in the model that may generate queues of stopped vehicles in a sight-restricted area. Queues can form on roadways where volumes are near capacity. The cumulative distribution function of the shifted lognormal distribution with a mean value of 1.1609 and a standard deviation of 0.4906 was used to determine the probability of a breakdown in traffic flow based on average headway. These values for the log normal distribution are those recommended by Jia et al. (2010) for a similar application. It was assumed that the queueing dynamics were the same for all facilities. The cumulative distribution function is shifted, however, based on the capacity of the facility. The probability of a breakdown in flow resulting in a congestion-related queue during any particular hour with a specified flow rate is computed as:

$$P_{congestion,iy} = \int_{-\infty}^{x} \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}} \quad (20)$$

$$x = \frac{3600}{q_{iy}} - shift \quad (21)$$

$$shift = \frac{3600}{c} \quad (22)$$

where:

$P_{congestion,iy}$ = probability of a queue forming due to congestion;
x = shifted average headway (sec/veh/lane);
σ = standard deviation of lognormal distribution, 0.4906;
μ = mean of lognormal distribution, 1.1609; and
c = capacity (veh/hr/lane).

5.5.4 Total Potentially Affected Vehicles

As stated in the previous discussions, two events that can lead to a stopped vehicle and queueing in a particular travel lane are crashes and congestion (flow rates nearing capacity). During an hour of a given day, it is assumed that if a crash occurs, then queueing due to congestion is not going to occur. This is because the crash in the traveled way has already produced a queue. A second, independent queueing event is unlikely during that same hour. The total number of vehicles potentially affected per year on a curve with a horizontal sight obstruction is determined by multiplying the average number of vehicles affected when a queueing event occurs by the probable annual number of queueing events summed over all 24 hours of the day and all lanes of the roadway, as follows:

$$\text{Total number of affected vehicles per year} = \sum_{y=1}^{L}\sum_{i=1}^{24}\left[V_{iy}\left[N_{iy} + (365 - N_{iy})P_{congestion,iy}\right]\right] \quad (23)$$

where

L = total number of lane in analysis direction;
y = lane number; and
i = hour of the day.

5.6 Application of Reliability Analysis to Curves with Horizontal Sight Obstructions

Since the crash frequency estimates to support benefit-cost analysis are so uncertain, an alternative approach to assessment of horizontal sight obstructions that is not dependent on crash history data is needed. The reliability analysis model described earlier can be used for this purpose. The model considers the stream of vehicles approaching a horizontal curve with a sight obstruction on the inside of the curve and assesses the average number and percentage of vehicles per year that will potentially encounter a stopped vehicle or a queue of stopped vehicles, due to a crash or due to flow in excess of capacity, in the sight-restricted area. Approaching vehicles are treated as potentially affected by the sight distance limitation only if the crash-involved vehicle or the stopped vehicle at the rear of the queue is not visible to the approaching driver over a distance greater than or equal to the applicable value of DSSD.

The measures provided by the reliability analysis model that can assist designers in assessing the priority of removing or mitigating a particular sight obstruction include:

- Minimum ASSD in any point in each travel lane for the primary direction of travel;
- A color-coded indication whether the minimum ASSD for each travel lane is less than or greater than or equal to the AASHTO value of DSSD for the applicable design or operating speed;
- ASSD values at user-specified intervals from Station PC – S to Station PT + S;
- The total length of the sight-restricted area for which ASSD is less than DSSD;
- An estimate of the total number of vehicles per year potentially affected by any sight distance restriction that is present, for each travel lane and for all lanes combined;
- Total number of vehicles passing through the horizontal curve site in a year, for comparison to the previous measure; and
- An estimate of the percentage of the total number of vehicles per year potentially affected by any sight distance restriction that is present, for each travel lane and for all lanes combined.

The reliability analysis model has been incorporated in a spreadsheet tool for application by designers to assess horizontal sight obstructions. A users guide to the spreadsheet tool is presented in Appendix B.

The reliability analysis model was used to perform a sensitivity analysis of three key measures—minimum ASSD, number of potentially affected vehicles per year, and percentage of potentially affected vehicles per year. This sensitivity analysis considered:

- Five design scenarios (rural two-lane highway curve to the right/rural two-lane highway curve to the left/urban six-lane freeway curve to the right/rural four-lane freeway curve to the right/urban one-lane exit ramp curve to the right);
- Six representative curve radii, curve length, and design speed combinations for each design scenario;
- Nine representative AADT levels for each design scenario; and
- Six representative offset distances from the obstruction to the inside edge of the traveled way.

The results address three additional design scenarios because, for urban freeways, rural freeways, and ramps, the sensitivity analysis results for curves to the left would be identical to those for curves to the right.

Rather than presenting the results of all the sensitivity analyses that were performed, Table 3 shows the results for just the smallest curve radius considered for each design scenario. The smallest curve radius was selected for presentation in the table, because it results in the largest values for the number and percentage of potentially affected vehicles. The smallest radius curves are generally below the Green Book minimum radii for the applicable design speed.

The sensitivity analysis results for rural two-lane highways show very little likelihood of approaching vehicles encountering crash-involved vehicles or queues of stopped vehicles in the sight-restricted area. For a curve to the right on a two-lane highway with the largest AADT considered (10,000 veh/day/lane or 20,000 veh/day in both directions combined), the maximum number of potentially affected vehicles is 412 vehicles per year or 0.011 percent of the total yearly flow. For the curve to the left in the opposing direction of travel on such a road, the maximum number of potentially affected vehicles is 387 vehicles per year, also equivalent to

Table 3. Results of sensitivity analysis with the reliability analysis model for key design scenarios (Potts et al. 2018).

Rural two-lane highway curve to the right, 250-ft radius, 0.20-mi curve length, 60-mph design speed																		
AADT per lane (veh/day)	Offset of obstruction from inside edge of traveled way (ft)																	
	Minimum ASSD (ft)						Number of potentially affected vehicles						Percentage of total vehicles that are potentially affected					
	0	2	5	10	15	20	0	2	5	10	15	20	0	2	5	10	15	20
500	110	127	149	180	206	230	1	1	1	1	1	0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
1,000	110	127	149	180	206	230	2	2	2	2	2	2	0.001%	0.001%	0.001%	0.001%	0.001%	0.001%
1,500	110	127	149	180	206	230	7	6	6	6	6	6	0.001%	0.001%	0.001%	0.001%	0.001%	0.001%
2,000	110	127	149	180	206	230	13	13	13	13	12	12	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%
2,500	110	127	149	180	206	230	22	21	21	21	20	20	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%
4,000	110	127	149	180	206	230	61	60	59	58	56	55	0.004%	0.004%	0.004%	0.004%	0.004%	0.004%
5,000	110	127	149	180	206	230	97	96	95	93	90	89	0.005%	0.005%	0.005%	0.005%	0.005%	0.005%
7,500	110	127	149	180	206	230	228	224	221	217	210	207	0.008%	0.008%	0.008%	0.008%	0.008%	0.008%
10,000	110	127	149	180	206	230	412	406	400	393	380	374	0.011%	0.011%	0.011%	0.011%	0.010%	0.010%

Rural two-lane highway curve to the left, 250-ft radius, 0.20-mi curve length, 60-mph design speed																		
AADT per lane (veh/day)	Offset of obstruction from inside edge of traveled way (ft)																	
	Minimum ASSD (ft)						Number of potentially affected vehicles						Percentage of total vehicles that are potentially affected					
	0	2	5	10	15	20	0	2	5	10	15	20	0	2	5	10	15	20
500	195	206	221	244	266	286	1	1	1	0	0	0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
1,000	195	206	221	244	266	286	2	2	2	2	2	2	0.001%	0.001%	0.001%	0.001%	0.001%	0.001%
1,500	195	206	221	244	266	286	6	6	6	6	6	6	0.001%	0.001%	0.001%	0.001%	0.001%	0.001%
2,000	195	206	221	244	266	286	12	12	12	12	12	12	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%
2,500	195	206	221	244	266	286	21	20	20	20	19	19	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%
4,000	195	206	221	244	266	286	57	56	56	55	54	53	0.004%	0.004%	0.004%	0.004%	0.004%	0.004%
5,000	195	206	221	244	266	286	92	90	90	87	86	84	0.005%	0.005%	0.005%	0.005%	0.005%	0.005%
7,500	195	206	221	244	266	286	214	210	210	203	200	196	0.008%	0.008%	0.008%	0.007%	0.007%	0.007%
10,000	195	206	221	244	266	286	387	380	380	367	361	355	0.011%	0.010%	0.010%	0.010%	0.010%	0.010%

Urban six-lane freeway curve to the right, 750-ft radius, 0.20-mi curve length, 60-mph design speed																		
AADT right lane (veh/day)	Offset of obstruction from inside edge of traveled way (ft)																	
	Minimum ASSD, Right Lane (ft)						Number of potentially affected vehicles, right lane						Percentage of total vehicles that are potentially affected, right lane					
	0	2	5	10	15	20	0	2	5	10	15	20	0	2	5	10	15	20
6,800	190	219	257	310	356	396	99	97	94	89	84	79	0.004%	0.004%	0.004%	0.004%	0.003%	0.003%
8,500	190	219	257	310	356	396	163	160	155	147	138	130	0.005%	0.005%	0.005%	0.005%	0.004%	0.004%
10,200	190	219	257	310	356	396	247	243	235	222	210	197	0.007%	0.007%	0.006%	0.006%	0.006%	0.005%
11,900	190	219	257	310	356	396	354	348	336	318	300	282	0.008%	0.008%	0.008%	0.007%	0.007%	0.006%
13,600	190	219	257	310	356	396	489	481	465	440	415	390	0.010%	0.010%	0.009%	0.009%	0.008%	0.008%
17,000	190	219	257	310	356	396	960	943	911	861	812	762	0.015%	0.015%	0.015%	0.014%	0.013%	0.012%
20,400	190	219	257	310	356	396	2,938	2,888	2,787	2,635	2,483	2,331	0.039%	0.039%	0.037%	0.035%	0.033%	0.031%
25,500	190	219	257	310	356	396	27,579	27,103	26,149	24,717	23,282	21,845	0.296%	0.291%	0.281%	0.266%	0.250%	0.235%
30,600	190	219	257	310	356	396	94,588	92,951	89,675	84,754	79,826	74,891	0.847%	0.832%	0.803%	0.759%	0.715%	0.671%

(continued on next page)

Table 3. (Continued).

Rural four-lane freeway curve to the right, 1000-ft radius, 0.20-mi curve length, 75-mph design speed																		
AADT right lane (veh/day)	Offset of obstruction from inside edge of traveled way (ft)																	
	Minimum ASSD, Right Lane (ft)						Number of potentially affected vehicles, right lane						Percentage of total vehicles that are potentially affected, right lane					
	0	2	5	10	15	20	0	2	5	10	15	20	0	2	5	10	15	20
2,500	219	253	297	358	411	457	11	11	11	11	10	10	0.001%	0.001%	0.001%	0.001%	0.001%	0.001%
5,000	219	253	297	358	411	457	51	49	48	46	44	42	0.003%	0.003%	0.003%	0.003%	0.002%	0.002%
7,500	219	253	297	358	411	457	120	117	113	108	103	100	0.004%	0.004%	0.004%	0.004%	0.004%	0.004%
10,000	219	253	297	358	411	457	224	218	211	202	192	186	0.006%	0.006%	0.006%	0.006%	0.005%	0.005%
12,500	219	253	297	358	411	457	368	358	347	331	315	304	0.008%	0.008%	0.008%	0.007%	0.007%	0.007%
15,000	219	253	297	358	411	457	574	557	541	516	490	473	0.010%	0.010%	0.010%	0.009%	0.009%	0.009%
20,000	219	253	297	358	411	457	2,228	2,163	2,097	1,998	1,899	1,832	0.031%	0.030%	0.029%	0.027%	0.026%	0.025%
25,000	219	253	297	358	411	457	20,116	19,518	18,918	18,018	17,117	16,515	0.220%	0.214%	0.207%	0.197%	0.188%	0.181%
30,000	219	253	297	358	411	457	74,337	72,121	69,902	66,569	63,232	61,004	0.679%	0.659%	0.638%	0.608%	0.577%	0.557%

Urban one-lane exit ramp curve to the right, 250-ft radius, 0.20-mi curve length, 60-mph design speed																		
AADT (veh/day)	Offset of obstruction from inside edge of traveled way (ft)																	
	Minimum ASSD (ft)						Number of potentially affected vehicles						Percentage of total vehicles that are potentially affected					
	0	2	5	10	15	20	0	2	5	10	15	20	0	2	5	10	15	20
2,000	110	127	149	180	206	230	16	16	16	16	15	15	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%
4,000	110	127	149	180	206	230	63	62	61	60	58	57	0.004%	0.004%	0.004%	0.004%	0.004%	0.004%
6,000	110	127	149	180	206	230	133	131	129	127	123	121	0.006%	0.006%	0.006%	0.006%	0.006%	0.006%
8,000	110	127	149	180	206	230	225	221	218	214	208	204	0.008%	0.008%	0.007%	0.007%	0.007%	0.007%
10,000	110	127	149	180	206	230	337	331	326	321	311	305	0.009%	0.009%	0.009%	0.009%	0.009%	0.008%
12,500	110	127	149	180	206	230	507	499	491	483	467	459	0.011%	0.011%	0.011%	0.011%	0.010%	0.010%
15,000	110	127	149	180	206	230	746	734	722	710	687	675	0.014%	0.013%	0.013%	0.013%	0.013%	0.012%
20,000	110	127	149	180	206	230	4,161	4,094	4,027	3,960	3,827	3,760	0.057%	0.056%	0.055%	0.054%	0.052%	0.052%
25,000	110	127	149	180	206	230	44,892	44,168	43,444	42,720	41,270	40,544	0.492%	0.484%	0.476%	0.468%	0.452%	0.444%
NOTE: Table addresses the smallest radius horizontal curve considered for each design scenario; assumed lane width = 12 ft; ASSD measured with Green Book assumptions																		

0.011 percent of the total yearly flow. These results indicate that sight-distance-related crashes are highly unlikely on rural two-lane highways, as only a small fraction of the potentially affected vehicles would likely become involved in a crash.

The sensitivity analysis results for six-lane urban freeways show that the number of potentially affected vehicles is 79 per year (0.003 percent of the total yearly flow) for the smallest AADT and the largest offset to obstruction considered. For the largest AADT and smallest obstruction to offset considered, the number of potentially affected vehicles increases to 94,588 per year (0.847 percent of the total yearly flow). Thus, the number of vehicles that may potentially encounter a crash-involved or stopped vehicle in the sight-restricted area increases by a factor of approximately 1,200 with changes in AADT and offset to obstruction.

Similarly, the sensitivity analysis results for four-lane rural freeways show that the number of potentially affected vehicles is 10 per year (0.001 percent of the total yearly flow) for the smallest AADT and the largest offset to obstruction considered. For the largest AADT and smallest obstruction to offset considered, the number of potentially affected vehicles increases to 74,337 per year (0.679 percent of the total yearly flow). Thus, the number of vehicles that may potentially encounter a crash-involved or stopped vehicle in the sight-restricted area increases by a factor of approximately 7,400 with changes in AADT and offset to obstruction.

The sensitivity analysis results for one-lane urban exit ramps show that the number of potentially affected vehicles is 15 per year (0.002 percent of the total yearly flow) for the smallest AADT and the largest offset to obstruction considered. For the largest AADT and smallest obstruction to offset considered, the number of potentially affected vehicles increases to 44,892 per year (0.492 percent of the total yearly flow). Thus, the number of vehicles that may potentially encounter a crash-involved or stopped vehicle in the sight-restricted area increases by a factor of approximately 3,000 with changes in AADT and offset to obstruction.

These results show that the reliability analysis model can be useful in quantifying the potential opportunities for crashes at horizontal curves with sight restrictions on the inside of the curve. The percentage of vehicles that may encounter a crash-involved vehicle or a queue of stopped vehicles over the course of a year can range from essentially zero to a value approaching 1 percent of the total yearly flow. The number of crashes that will actually occur will be substantially smaller than the number of potentially affected vehicles, but this number and percentage of potentially affected vehicles provide a relative measure that can be used to prioritize sites for improvement.

The reliability analysis model is a flexible tool that can be used by planners and designers to compare, in a relative sense, the need for sight distance improvements on specific horizontal curves. A key strength of the model is its ability to consider roadway alignment in three dimensions (i.e., horizontal and vertical alignment in combination). Limitations of the model include:

- The model can access a site with at most one horizontal and one vertical curve; compound curves are not considered.
- The model provides a conservative estimate of the number and percentage of vehicles potentially affected by a particular sight distance limitation and, thus, estimates a maximum value rather than an average value of these measures.
- The number of crashes related to a particular sight distance limitation will likely be much smaller than the number of potentially affected vehicles.
- The model does not quantify the increased number of vehicles potentially affected by a sight distance limitation if an intersection, driveway, ramp terminal, pedestrian crossing, or subsequent horizontal curve is located within the sight-restricted area.

CHAPTER 6

Assessing Removal or Mitigation of Horizontal Sight Obstructions

This chapter presents recommended procedures to assess removal or mitigation of horizontal sight obstructions. The primary procedure is for application to existing sight obstructions. The chapter then discusses adaptation of the procedure to projects under design for new construction.

6.1 Step-by-Step Procedure for Assessing Whether to Remove or Mitigate Existing Horizontal Sight Obstructions

This section presents a step-by-step procedure to review and analyze existing horizontal curves with roadside sight obstructions on the inside of the curve. The procedure assumes the site being studied has at most one horizontal and one vertical curve. If this is the case, the site may be evaluated with the spreadsheet tool described in Chapter 5 and Appendix B. If there is more than one horizontal curve or more than one vertical curve present, the spreadsheet tool is not applicable. In that case, perform a comparable review to that described here using a CADD system or another 3D tool. The steps in the analysis process presented here are suggestions. Any step may be skipped if the planner or designer concludes that it would not be productive or that the likely finding is evident from the information already gathered.

1. Locations to be reviewed for potential horizontal sight distance limitations may be identified by many methods including:
   - Sites that are noted in the planning or design process for a particular project
   - Sites noted in a field review or a review of street level photography
   - Sites reported by motorists
   - Sites identified through network screening to identify high-crash locations
   - Sites of potential interest identified by any other method
2. Data should be assembled on each identified location including:
   - Roadway type, number of lanes, and other roadway characteristics
   - Horizontal curve radius and length
   - Direction of curve (right/left)
   - Vertical alignment (percent grade or, if a vertical curve is present, approach grade, departure grade, vertical curve length and location relative to the horizontal curve)
   - Type of horizontal sight obstruction
   - Location of sight obstruction relative to the horizontal curve
   - Height of sight obstruction above the inside edge of the traveled way (ft)
   - Distance to sight obstruction from the inside edge of the traveled way (ft)
   - Directional traffic volume (veh/day)

- Design speed of horizontal curve from as-built plans (mph), if available and if still applicable to current conditions
- Posted speed limit (mph) upstream of the horizontal curve (in the case of exit ramps, use the posted speed on the mainline roadway)
- Signed advisory speed (mph), if any
- Average lane width (ft)

3. Apply the spreadsheet tool described in Chapter 5 and Appendix B to generate the ASSD profile for the site and compare the minimum ASSD to the DSSD for applicable speed(s), including the design speed and/or posted speed limit for the roadway upstream of the horizontal curve and the signed advisory speed, if any. If there is more than one applicable speed to consider, the spreadsheet tool should be applied for each applicable speed, keeping all input data except the speed unchanged. The same ASSD profile will be generated for each application of the tool, but the minimum ASSD will be compared in each run to a different DSSD value.
4. For each applicable speed, consider not only the default sight distance measurement rules based on AASHTO Green Book criteria, but also appropriate variations in the sight distance measurement rules. These might include:
   - Consideration of an alternative object height of 3.5 or 4.0 ft if it appears likely that an approaching driver could see over the horizontal sight obstruction.
   - Consideration of an alternative placement of the vehicle within its lane with the driver's eye 3 ft from the left edge of the curve.
   - Consideration of an alternative driver eye height of 8.0 ft if there is a substantial volume of large trucks at the site.
5. Review the sight distance profile(s) to determine whether the minimum ASSD is less than the DSSD for any of the applicable speed(s). If the minimum ASSD is greater than the DSSD for all speeds of interest, there is no horizontal sight restriction at the site and there is no need to continue the investigation further. Any crash patterns or other concerns at the site likely have a cause other than lack of horizontal sight distance and other appropriate engineering studies should be conducted.
6. Determine the location and length of the sight-restricted area for each applicable speed. The length of the sight-restricted area is given in the output results portion of the spreadsheet. The location of the sight-restricted area can be determined by noting all ASSD values in each sight distance profile that are less than the applicable DSSD value.
7. If the minimum ASSD value is less than the applicable DSSD value for some applicable speeds but not for others, conduct a further investigation of actual operating speeds at the site. The 85th percentile speed of traffic is typically used as a representative value. Either make an estimate of operating speed or conduct a speed study at the site. If there is a signed advisory speed on the curve, do not assume that the operating speed is equal to the signed advisory speed unless field observation or field studies indicate that this is the case.
8. Determine whether critical roadway features are located in or near the sight-restricted area. Critical roadway features could include at-grade intersections, driveways, additional horizontal curves, ramp terminals, or pedestrian crossings. In the case where an intersection or a stop- or signal-controlled ramp terminal is present, check whether the Green Book design value for ISD, which is greater than DSSD, is available. If a free-flow ramp terminal or a midblock pedestrian crossing is present, check whether the Green Book design value for decision sight distance, which is also greater than DSSD, is available.
9. Review the crash history of the site, focusing on crashes in or near the sight-restricted area. Identify crashes of types that may *possibly* be related to limited sight distance including rear-end, same-direction sideswipe, and run-off-road crashes. Where practical, review hard-copy police crash reports and note crashes for which there is no evident explanation of

the causation of the crash other than limited sight distance. Crashes of the types considered possibly related to sight distance should be eliminated from consideration if:

- The crash location was misreported, and the crash did not occur at the site in question.
- The crash occurred in a lane, which the spreadsheet tool indicates does not have a sight distance limitation.
- The crash can be verified as occurring at a location not within or immediately adjacent to the sight-restricted area.
- The crash was clearly caused by other factors such as mechanical failure of the at-fault vehicle, loss of control due to a wet or snow-and-ice-covered roadway, limited visibility due to weather, or an animal entering the roadway.
- The at-fault driver stated explicitly that the crash was caused by their inattention to the driving task.

The remaining crashes not eliminated by the above criteria are considered *potentially*, but not definitely, related to limited sight distance. If the hard-copy police crash report states explicitly that the crash was caused by limited sight distance, which is rare because law enforcement officers are not trained to use engineering terms, the crash should not be eliminated from consideration, even if one of the listed factors is present. Considering the crashes not eliminated in this step, determine whether there is a pattern of crashes potentially related to sight distance. The definition of a crash pattern is left to each individual agency to determine based on traffic volumes and other factors, but clearly a pattern consists of multiple crashes.

10. In the results from the spreadsheet tool analysis, note the number and percentage of approaching vehicles per year potentially affected by the sight distance restriction. If the number of vehicles potentially affected is high, this may indicate that removing or mitigating the sight distance restriction may be desirable. If the percentage of approach vehicles potentially affected by the sight distance restriction is also high (e.g., 0.5 percent or more), removing or mitigating the sight distance restriction may be desirable.
11. If it appears that removing or mitigating the sight distance restriction would be desirable, estimate the cost to remove the sight obstruction(s). First, identify whether all obstacles present on the inside of the curve are, in fact, obstructions that may need to be removed. The procedures developed by Mauga (2014, 2015b) and presented in Appendix A can be used to define the area that should be clear of sight obstructions. The reliability analysis model, presented in Chapter 5, and the spreadsheet tool to implement the reliability analysis model, presented in Appendix B, can be used to determine whether the driver will be able to see over an obstruction.
12. Perform an economic analysis to determine whether it is likely to be cost effective to remove the sight obstruction. Use Equation (11) to determine the maximum implementation cost that would be cost effective. To be conservative, the benefit should be the average number of crashes per year found to be potentially related to sight distance in Step 9 or an alternative estimate that the planner or designer considers more realistic. If the cost to remove the sight obstruction is less than the maximum implementation cost that would be cost-effective [$maxIC_{ij}$ in Equation (11)], this indicates that removal of the sight obstruction is an economically viable alternative.
13. Considering all of the data and findings assembled in Steps 2 through 12, develop a recommendation as to whether the sight obstruction should be removed. Removal of the sight obstruction is indicated if ASSD is less than the applicable value of DSSD for the speed determined in Step 7, if removal of the sight obstruction was found to be cost-effective in Step 12, if the funds to remove the sight obstruction are available and are approved by agency management, and if one or more of the following were also found:
    - There are critical features such as intersections, driveways, additional horizontal curves, ramp terminals, or pedestrian crossings, located in or near the sight-restricted area. Where applicable, as explained in Step 8, consider ISD or decision sight distance.

- There is a documented pattern of crashes *potentially* related to sight distance, as defined in Step 9.
- The values from the spreadsheet tool for both the number and percentage of approaching vehicles potentially affected by the sight distance restriction are relatively high, as discussed in Step 10.

14. If the recommendation reached in Step 13 was not to remove the sight obstruction, consider whether specific mitigation strategies should be implemented. Review the table in Section 7.2 and identify candidate mitigation strategies to determine which strategies can be implemented for less than the maximum implementation cost determined in Step 12. For each of the candidate strategies identified, review the description of the strategy in Section 7.2 to assess its appropriateness for the site in question. Develop a recommendation as to which candidate strategy (or strategies), if any, should be implemented.

6.2 Assessment of Horizontal Sight Obstructions Under Design for New Construction

The step-by-step procedure for existing sight obstructions presented in Section 6.1 can be adapted to consider sight obstructions under design for new construction. The procedure should be adapted as follows:

- In Step 1, the only method to identify horizontal sight limitations of interest may be from project planners and designers.
- There will be no crash history to review in Step 9.
- No economic analysis can be performed in Step 12 unless the designer is able to estimate potential future crash reduction benefits of removing a sight obstruction using some method other than crash history review. Alternative methods might include past experience with similar sites.

Many potential horizontal sight obstructions may be less expensive to remove at the design stage than on an existing roadway. However, where the horizontal sight obstruction is created by a bridge structure or retaining wall, removal of the horizontal sight obstruction may be very expensive, even at the design stage, and consideration of mitigation measures may be more appropriate.

6.3 Case Studies of Existing Roadways with Horizontal Sight Obstructions

Appendix C presents seven case studies for existing roadways with horizontal sight obstructions. The seven horizontal curve sites are located in the states of Illinois, Kansas, Pennsylvania, and Washington, and were selected from among 263 horizontal curve sites reviewed in research by Potts et al. (2018). The case studies include two rural two-lane highway sites, two urban mainline freeway sites, one rural mainline freeway site, and two interchange ramp sites. The lessons learned from the case studies include:

- Where crash experience is limited, high-cost sight distance improvements are not likely to be practical.
- In many cases, only the inside lane on a horizontal curve will experience a horizontal sight distance limitation.
- On some curves, a sight obstruction on the inside of a horizontal curve may limit the ASSD in both directions of travel. The ASSD for traffic in the direction of travel on the outside of the curve is likely to be only slightly limited unless the curve radius is very small and/or the sight obstruction on the inside of the curve is very close to the traveled way.

- Depending on the location and offset of the horizontal sight obstructions, sight distance limitations may extend upstream of a horizontal curve and may end before the PT of the curve is reached.
- Advisory speed signing is useful for warning drivers of the need to slow down, but does not necessarily result in drivers traveling at or below the advisory speed.
- Where multiple horizontal sight obstructions are present, removing even one of those sight obstructions may substantially reduce the resulting sight distance restriction, without the need to remove both sight obstructions. This approach may be desirable where the sight distance with the greater height is less expensive to remove (e.g., trees or bushes behind a roadway structure or roadside barrier).
- Even where the conditions for sight-distance-related collisions appear to exist, crashes will not necessarily occur. Drivers are often very effective at adapting to conditions they encounter in the field.
- More realistic positioning for the driver's eye closer to the outside of the travel lane, rather than along the centerline of the lane, on a horizontal curve to the right will increase the sight distance for that direction of travel. However, the opposite is true for the curve to the left, where the available sight distance may decrease if measured with more realistic positioning of the driver's eye.
- Where the upper portion of vehicles can be seen over a barrier on the inside of a horizontal curve, the sight distance on the curve may be effectively adequate, even where sight distance measures using AASHTO criteria appears limited.

CHAPTER 7

Design Exceptions and Mitigation Strategies

This chapter explains the situations in which design exceptions for horizontal sight distance should be prepared and the mitigation strategies that may be considered where a horizontal sight obstruction is not removed.

7.1 Design Exceptions

FHWA has established 10 controlling criteria for geometric design that must be met on projects on the National Highway System (NHS) or a design exception document must be prepared. Two of the 10 controlling criteria, structural loading capacity and design speed, apply to all NHS roads and streets. The remaining eight controlling criteria, including SSD, apply only to NHS roads that are Interstate highways, other freeways, and roads with design speeds of 50 mph or greater. Any project on these facility types containing a horizontal curve for which the ASSD is less than the applicable value of DSSD for which the sight restriction is to remain in place would require a design exception to be prepared and approved. Internal policies of individual highway agencies may require design exceptions for other design situations, as well. A design exception document typically describes the project site, the geometric design element that does not meet design criteria and is to remain in place, the traffic operational and safety performance of the site, and the mitigation strategies (if any) that will be implemented.

7.2 Potential Mitigation Strategies for Limited Horizontal Sight Distance

Where horizontal sight obstructions are identified on the inside of horizontal curves, their removal should be considered. A highway agency may conclude that it is impractical to remove some horizontal sight obstructions where the cost to do so would be high. In such cases potential mitigation strategies should be considered. The costs of the mitigation strategies themselves range from low to very high, and their practicality also needs to be assessed.

Table 4 summarizes the potential mitigation strategies that may be considered by highway agencies once a decision has been reached that it is impractical to remove a sight obstruction on the inside of a specific horizontal curve. The table identifies each potential mitigation strategy and presents the location type(s) to which the strategy is applicable, the relative mitigation cost for new construction projects and projects on existing roads, and comments on implementation of the strategy. The mitigation strategies presented here were identified from the FHWA publication, *Mitigation Strategies for Design Exceptions* (Stein and Neuman 2007), and from the research by Potts et al. (2018).

Table 4. Summary of potential mitigation strategies for horizontal sight obstructions (Potts et al. 2018).

Mitigation strategy	Applicable location type(s)	Relative mitigation cost		Comments
		New construction projects	Projects on existing roads	
Remove a portion of the sight obstruction	All	Low to very high	Low to very high	Cost is potentially lower than removing the entire sight obstruction.
Reduce the height of the sight obstruction	All	Low to very high	Low to very high	An example would be using a concrete barrier with reduced height.
Widen inside shoulder adjacent to sight obstruction	All	Medium to high	Medium to very high	For projects on existing roads, this strategy may involve narrowing the travel lanes or realigning the entire roadway.
Widen inside shoulder in the sight-restricted area	All	Medium to high	Medium to very high	Provides an improved primary recovery area on the portion of the roadway where the driver may encounter an unexpected condition.
Switch inside and outside shoulder widths so that the wider shoulder is on the inside of the horizontal curve	Ramps	Low	Low to very high	Very little cost at the design stage in new construction; on existing roads, involves restriping only if the shoulders have been designed to accommodate traffic loads.
Realign roadway	All	Medium to very high	High to very high	Realignment of the roadway may cost as much or more than removing the sight obstruction.
Widen median	Divided highways	High to very high	High to very high	Widening a median may make it possible to remove a barrier or locate the barrier further from the traveled way, but will likely also involve realignment of one or both roadways.
Install advance curve warning signs	All	Low	Low	Particularly desirable where the presence of the curve is not apparent to approaching drivers.
Install advance curve warning signs with advisory speed plates	All	Low	Low	Desirable where drivers need to reduce speed on particular curves.
Install advance warning signs for geometric features in the sight-restricted area	All	Low	Low	Desirable where conflict or decision points, such as intersections, driveways, ramp junctions, or a subsequent curve is located in the sight-restricted area.
Relocate existing signs to better positions	All	N/A	Low to medium	Locate signs in highly visible positions, sufficiently far in advance of the horizontal curve or sight-restricted area.
Install dynamic signing with flashing beacons triggered by vehicles exceeding the speed limit or advisory speed	All	Low to medium	Low to medium	May be appropriate at mainline locations and isolated ramp curves; not desirable for curves adjacent to decision points, such as the diverge point on an off-ramp.
Improve delineation	All	Low	Low	Improve the visibility of the horizontal curve to approaching drivers by improving centerline, lane line, and edgeline markings on the curve or installing chevron warnings on the outside of the curve.
Remove conflict or decision points from sight-restricted area	All	Medium to high	Medium to very high	Costs to remove intersections, driveways, off-ramps, or subsequent curves from the sight-restricted area may range from medium (for driveways) to high or very high (for other features).
Provide lighting for intersections or other features in the sight-restricted area	All	Medium to high	Medium to high	Lighting may assist drivers in identifying potential conflicts at intersections or decision points to which sight distance may be limited.
Provide real-time warning of crashes or queues ahead	Urban freeways	Medium to high	Medium to high	Real-time warnings are likely to be practical only on managed freeways.

The relative costs for implementation of mitigation strategies range from low to very high, and the cost for any given strategy can vary widely based on site conditions. Mitigation costs are likely to be low for strategies that involve signing or other traffic control devices, but can be high to very high for strategies at sites where implementation of the strategy would involve structures, earthwork, roadway reconstruction, or right-of-way acquisition.

There are no direct CMFs or measures of effectiveness for mitigation of limited horizontal sight distance. Research in *NCHRP Report 783* (Harwood et al. 2014) found that, at crest vertical curves with limited SSD on rural two-lane highways, crash frequencies were high at locations where intersections, driveways, or horizontal curves were hidden from the approaching driver's view by the sight restriction. However, where no hidden features were present, crash frequency was not elevated, even though the SSD was limited. This general principle may apply to other situations, such as horizontal sight distance limitations, but no quantitative results can be derived because *NCHRP Report 783* addressed only crest vertical curves.

Each of the mitigation strategies is discussed in the following sections. The previous section discusses the decision-making process for implementing mitigation strategies.

7.2.1 Remove a Portion of the Sight Obstruction

Even when it is impractical to remove all of the horizontal sight obstruction, it may be practical to remove a portion of the sight obstruction. For example, where trees and a concrete barrier create sight obstructions, it may substantially improve the available sight distance if the trees were removed, even with the concrete barrier being retained. This would avoid the high cost of realignment and retain the advantages of the barrier, which may be needed as a roadside safety device for other reasons.

7.2.2 Reduce the Height of the Sight Obstruction

It may be feasible to reduce the height of a roadside sight obstruction even where it would be undesirable to remove it completely. For example, while many concrete traffic barriers are 4 to 4.5 ft in height, there are approved concrete barriers that are 2.4 to 2.7 ft in height which may be suitable in some locations (Stein and Neuman 2007).

7.2.3 Widen Inside Shoulder Adjacent to Sight Obstruction

At some locations, it may be possible to increase horizontal sight distance by increasing the distance between the sight obstruction and the inside edge of the traveled way by widening the inside shoulder of the roadway. This would typically involve either narrowing the travel lanes or realigning the roadway.

7.2.4 Widen Inside Shoulder in the Sight-Restricted Area

Where it is not feasible to widen the inside shoulder adjacent to the sight obstruction, it may be feasible to widen the inside shoulder downstream of the sight obstruction within the sight-restricted area. This would provide an improved primary recovery area for drivers trying to avoid a collision in the sight-restricted area.

7.2.5 Switch Inside and Outside Shoulder Widths

The AASHTO Green Book recommends that one-way interchange ramps should have 2 to 4 ft paved shoulders on the left side of the ramp and 8 to 10 ft paved shoulders on the right of the ramp, with a total combined shoulder width of 10 to 12 ft. The unequal shoulder width provides an opportunity, where a ramp has a horizontal sight obstruction on the inside of a curve to the left, to switch the left and right shoulder widths so that the wider shoulder is on the left side of the ramp and the narrower shoulder is on the right side of the ramp. This moves the vehicles further from the inside of the curve and increases the available sight distance on the ramp. This strategy can be implemented at low cost in the design stage of a newly constructed ramp. For an existing ramp, the only implementation cost may involve restriping the edgelines, as long as the paved area onto which traffic is moved is suitable for traffic loads. This strategy is particularly desirable for ramps on structures where any other method of increasing the available sight distance may have a very high cost.

7.2.6 Realign Roadway

Realigning roadway(s) to move traffic further from a horizontal sight obstruction and thereby increase sight distance is typically very expensive. If a horizontal sight obstruction that would be impractical to move is recognized early in the design process for a new construction project, the increased cost of realigning a roadway may, in some cases, be modest, but in most situations realigning a roadway is likely to involve high to very high cost. Roadway realignment may cost as much, or more, than removing the sight obstruction would cost.

7.2.7 Widen Median

For many curves to the left on divided highways, a continuous median barrier may constitute a horizontal sight obstruction. The only feasible method to eliminate the barrier as a sight obstruction may be to widen the median sufficiently that the barrier can be moved further from the traveled way or sufficiently that the barrier is no longer needed. Widening the median may involve very high cost because one or both roadways may need to be realigned and additional right-of-way may need to be acquired.

7.2.8 Install Advance Curve Warning Signs

Installation of an advance curve warning sign is desirable in advance of any horizontal curve with limited sight distance. Advance curve warning signs are intended primarily for use where the presence of the curve is not apparent to approaching drivers. However, if drivers are alerted to the presence of the curve by the advance warning sign, they may be better prepared to deal with any potential conflicts they encounter in a sight-restricted area at or beyond the curve. Figure 18 shows a typical advance warning sign for a horizontal curve.

At some sites, Pennsylvania has supplemented advance curve warning signs with pavement markings in the travel lane showing the word SLOW and a curve arrow to the left or right, as appropriate.

7.2.9 Install Advance Curve Warning Signs with Advisory Speed Plates

Advance curve warning signs may be supplemented with advisory speed plates indicating the appropriate speed at which drivers should traverse the curve. Advisory speeds are typically chosen based on the side friction demands in traversing the curve, which can be measured with a ball-bank indicator. However, the ASSD for the curve may also be useful in determining an appropriate advisory speed. Figure 19 shows two examples of typical advance warning signs for horizontal curves with advisory speed plates.

Figure 18. Typical advance warning sign for a horizontal curve.

Figure 19. Typical advance warning signs for horizontal curves with advisory speed plates.

Figure 20. Typical advance warning signs for intersections and driveways located in sight-restricted areas.

7.2.10 Install Advance Warning Signs for Geometric Features in the Sight-Restricted Area

Where horizontal sight obstructions are present on a curve, it is highly desirable to provide signing to warn drivers in advance of any conflict or decision points that may be present in the sight-restricted area, including intersections, driveways, pedestrian crossings, ramp junctions, and subsequent horizontal curves. Figure 20 shows typical advance warning signs for intersections and driveways located in sight-restricted areas.

7.2.11 Relocate Existing Signs to Better Positions

Warning signs provided in advance of the horizontal curve, whether warning of the curve itself or of other conflict or decision points, should be placed, following criteria in the *Manual on Uniform Traffic Control Devices for Streets and Highways* (FHWA 2009), in a position that will be visible to the driver and sufficiently far in advance of the feature addressed on the warning sign. It is also desirable to avoid sign clutter, placing warning signs where they are not immediately adjacent to other signs and other demands on the driver's attention.

7.2.12 Install Dynamic Signing With Flashing Beacons

Dynamic signing with flashing beacons triggered by vehicles exceeding the speed limit or the applicable advisory speed are desirable to provide a highly visible warning to drivers. Their use in advance of horizontal curves with limited sight distance should be considered in main-line locations on freeways and other highways or in isolated locations on ramps. The use of dynamic signing may not be desirable on curves located at decision points, such as adjacent to

Figure 21. Typical horizontal curve with chevron markers for added delineation.

an off-ramp gore area; dynamic signs addressing one decision may not be desirable at a location where multiple decisions must be made by the driver.

7.2.13 Improve Delineation

Delineation may be used to improve visibility of a horizontal curve to approaching drivers. Appropriate delineation includes improved centerline, lane, and edgeline markings, and placement of chevron markers on the outside of the curve. Improved delineation will not inform drivers of the sight restriction, but may assist drivers in choosing an appropriate speed for the curve geometrics. Figure 21 shows a typical horizontal curve with chevron markers for added delineation.

7.2.14 Remove Conflict or Decision Point in the Sight-Restricted Area

Conflict or decision points, such as intersections, driveways, ramp junctions, and subsequent curves are undesirable with the sight-restricted area downstream of a horizontal curve with a horizontal sight obstruction. Removal of such conflict or decision points is desirable, but may be impractical because of high cost.

7.2.15 Provide Lighting at Intersections and Other Features in the Sight-Restricted Area

Lighting of intersections or other features in the sight-restricted area may assist drivers in choosing an appropriate path and speed through those features at night, even with the presence of the sight restriction.

7.2.16 Provide Real-Time Warning of Crashes or Queues Ahead

Real-time warnings to drivers of crashes or queues ahead, particularly crashes or queues within a sight-restricted area, are desirable. However, providing real-time warnings may only be practical on managed facilities, such as urban freeways, where the infrastructure to provide such warning messages is already in place.

References

American Association of State Highway Officials (AASHO), *A Policy on Sight Distance for Highways*, Washington, DC, 1940.

American Association of State Highway Officials (AASHO), *A Policy on Geometric Design of Rural Highways*, Washington, DC, 1954.

American Association of State Highway and Transportation Officials (AASHTO), *A Policy on Geometric Design of Highways and Streets*, Washington, DC, 2001.

American Association of State Highway and Transportation Officials (AASHTO), *Highway Safety Manual*, Washington, DC, 2010.

American Association of State Highway and Transportation Officials (AASHTO), *A Policy on Geometric Design of Highways and Streets*, Washington, DC, 2011.

American Association of State Highway and Transportation Officials (AASHTO), *Highway Safety Manual, 2014 Supplement*, Washington, DC, 2014.

Cirillo J. A., S. K. Dietz, and R. L. Beatty. Analysis and Modeling of Relationships Between Accidents and the Geometric and Traffic Characteristics of the Interstate System. *Bureau of Public Roads*, 1969.

Easa, S. M. Lateral Clearance to Vision Obstacles on Horizontal Curves. *Transportation Research Record*, No. 1303, 1991, pp. 22–32.

Easa, S. M. Lateral Clearance Needs On Compound Horizontal Curves. *Journal of Transportation Engineering*, American Society of Civil Engineers, Vol. 119, No. 1, 1993.

Fambro, D. B., K. Fitzpatrick, and R. J. Koppa. *NCHRP Report 44: Determination of Stopping Sight Distances.* TRB, National Research Council, Washington, DC, 1997.

Federal Highway Administration. *Manual on Uniform Traffic Control Devices*, Washington, DC, 2009.

Foody, T. J. and M. D. Long. *The Identification of Relationships Between Safety and Roadway Obstructions*, Ohio Department of Transportation, 1974.

Glennon, J. C. Effect of Sight Distance on Highway Safety. *TRB State-of-the-Art Report No. 6*, Transportation Research Board, Washington, DC, 1987.

Gupta, R. C. and R. Jain. *Effect of Certain Geometric Design Characteristics of Highways on Accident Rates for Two-Lane Roads in Connecticut*. Civil Engineering Department, School of Engineering, University of Connecticut, 1973.

Harwood, D. W., J. M. Hutton, C. Fees, K. M. Bauer, A. Glen, and H. Ouren. *NCHRP Report 783: Evaluation of the 13 Controlling Criteria for Geometric Design*. Transportation Research Board of the National Academies, Washington, DC, 2014.

Hills, B. L. Hillcrests: Problems of Vertical Line of Sight and Visibility. *Proceedings, Geometric and Design Standards*. Paris: OECD, 1977.

Himes, S., K. A. Eccles, K. Peach, C. M. Monsere, and T. Gates. "Estimating the Safety Effects of Intersection Sight Distance at Unsignalized Intersections," presented at the 95th annual meeting of the Transportation Research Board, January 2016.

Jia, A., B. Williams, and N. Rouphail. Identification and Calibration of Site-Specific Stochastic Freeway Breakdown and Queue Discharge. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2188, 2010.

Johansson, G. and K. Rumar. Driver's Brake Reaction Times. *Human Factors*, 13 (1), Human Factors Society, Santa Monica, CA. 1971.

Liu, C. and Z. Wang, Determination of Sight Distance on a Combined Crest and Circular Curve in a Three Dimensional Space. *International Journal of Transportation Science and Technology*, Vol. 1, No. 2, 2012.

Liu, C. Exact Sight Distance Determination on Compound Vertical and Horizontal Curves in the Presence of Road Barriers. *International Journal of Transportation Science and Technology*, Vol. 2, No. 2, 2013.

Mauga, T. Horizontal Clearance Offsets to Objects Higher Than Sight Lines. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2436, 2014.

Mauga, T. New Spiral Curves for Appropriate Transition of Minimum Roadside Clearance on Simple Curves. Journal of Transportation Technologies, No. 5, 2015a.

Mauga, T. "Horizontal Clearance Offsets to Objects on Insides of Reverse Curves," presented at the 94th annual meeting of the Transportation Research Board, January 2015b.

Olson, P. L., D. E. Cleveland, P. S. Fancher, L. P. Kostyniuk, and L. W. Scheider. *NCHRP Report 270: Parameters Affecting Stopping Sight Distance*. TRB, National Research Council, Washington, DC, 1984.

Potts, I. B., D. W. Harwood, D. J. Cook, J. M. Hutton, E. T. Donnell, M. T. Pietrucha, J. S. Wood, and L. Li. *Horizontal Sightline Offset Design Criteria, Exceptions, and Mitigation Strategies*, final report of NCHRP Project 15–59, MRIGlobal, 2018.

Raymond, W. L. Offsets to Sight Obstructions Near the Ends of Horizontal Curves. *ASCE Journal of Civil Engineering*, 42, 1972.

Raff, M. S. Interstate Highway Accident Study. *Highway Research Board Bulletin 74*, Washington, DC, 1953.

Schoppert, D. W. Predicting Traffic Accidents from Roadway Elements of Rural Two-Lane Highways with Gravel Shoulders. *Highway Research Board Bulletin 158*, Washington, DC, 1957.

Sparks, J. W. The Influence of Highway Characteristics on Accident Rates. *Public Works, Vol. 120*, 1968.

Stein, W. J., and T. R. Neuman. Mitigation Strategies for Design Exceptions. Report No. FHWA-SA-07-011, Federal Highway Administration Office of Safety, Washington, DC, 2007.

Waissi, G. R. and D. E. Cleveland. Sight Distance Relationships Involving Horizontal Curves. *Transportation Research Record*, No. 1122, Washington, DC, 1987.

APPENDIX A

Computation of HSOs

This appendix addresses the computation of horizontal sightline offsets.

A.1 Presentation of HSOs in the AASHTO Green Book

The Green Book (AASHTO 2011) presents the fundamental equation for the distance from the driver's eye to a roadside object that should be provided so that the roadside object does not become a horizontal sight obstruction. This distance is known to surveyors as the middle ordinate of a horizontal curve, typically designated as m or m_{max}. This distance was designated as m in the Green Book through 2001, but since the 2004 edition of the Green Book it has been designated as the HSO. The HSO is illustrated in Figure A-1 (based on Green Book Figure 3-23) and its value is determined in Green Book Equation (3-36) as:

$$HSO = R\left[1 - \cos\left(\frac{28.65\,S}{R}\right)\right] \quad \text{(A-1)}$$

where

HSO = horizontal sightline offset (ft);
S = design stopping sight distance (ft); and
R = radius of horizontal curve measured along the centerline of the inside lane (ft).

The Green Book states that Equation (A-1) is exact only when both the vehicle and the object are located within the limits of a simple horizontal curve. The Green Book states that when the vehicle or the sight obstruction is situated beyond the limits of the simple curve (or if both are within the limits of a spiral curve or compound curve), the value obtained from Equation (A-1) is only approximate. In fact, the value provided by Equation (A-1) represents the maximum value of horizontal sightline offset that can occur at any point along a simple curve, and this maximum value applies only in the middle portion of curves whose length exceeds the design stopping sight distance (L > S). The HSO will be smaller than HSO in Equation (A-1) toward the ends of a simple curve. Furthermore, the Green Book does not state, but should, that where the length of a horizontal curve is less than the design stopping sight distance (L < S), the HSO that is needed will be less than the maximum value indicated by HSO in Equation (A-1) throughout the entire curve.

The Green Book suggests two approaches to estimating actual HSO values less than the maximum indicated in Equation (A-1). These are use of graphical procedures and computational methods. Both of these approaches are discussed here.

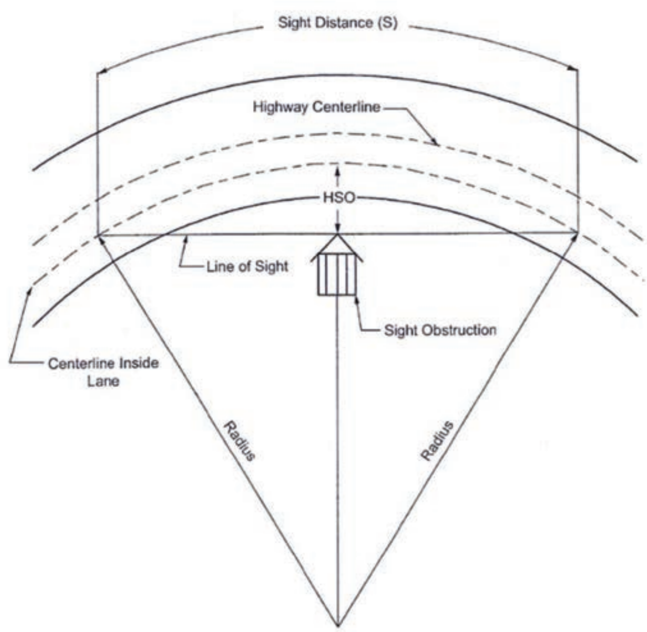

Figure A-1. Diagram illustrating components for determining horizontal sight distance (AASHTO 2011)

Determination of the actual horizontal sightline offset needed at a specific point on a horizontal curve, rather than the maximum needed anywhere within a curve, is potentially valuable to highway agencies because such knowledge can avoid unnecessary construction or right-of-way costs that might be incurred in providing the maximum HSO along the entire curve. In some cases, such as in rock cuts or along retaining walls, determination of the actual HSO needed could substantially reduce costs and might indicate situations where no design exception is needed because the planned or existing design already provides the design stopping sight distance along the entire curve. A computational method would be preferable to an approximate graphical method, because a computational method could be incorporated in CADD systems so that the actual area on the inside of a horizontal curve that should be free of sight obstructions can be displayed to the designer.

A.2 Early Studies

Raymond (1972) used an unspecified computational method for determining offset ratios for specified points along a horizontal curve. The offset ratio (OR) is a dimensionless quantity defined as:

$$OR = \frac{m}{HSO} \tag{A-2}$$

Thus, the offset ratio is the horizontal sightline offset actually needed at any given point on a horizontal curve divided by the maximum horizontal sightline offset determined with Equation (A-1). Figure A-2 presents the chart developed by Raymond. In this chart, the horizontal and vertical axes and the multiple curves are labeled with three ratios:

- The distance from the spiral-to-curve (SC) point or the PC to the sight obstruction measured along the curve divided by the design stopping sight distance;
- The length of the spiral curve divided by the design sight distance, or L_s/S; and

- The offset to the horizontal sight obstruction that is needed to provide the design stopping sight distance divided by the maximum offset determined with Equation (A-2), or m/M.

This chart has been reviewed by Mauga (2015), who found it to be suitable for sites with spiraled horizontal curves and for simple curves whose length exceeds the design stopping sight distance ($L \geq S$). Raymond's work does not address curves whose length is shorter than the design stopping sight distance ($L < S$).

Raymond's work also developed a correction factor (CF) that should be added to the computed value of OR computed with Equation (A-2) for small values of the ratio of curve radius to stopping sight distance, R/S. The correction factor is determined as shown in Figure A-3. The correction factor is determined with two ratios: the Z/S ratio used in Figure A-2 and the curve radius divided by the design stopping sight distance, R/S.

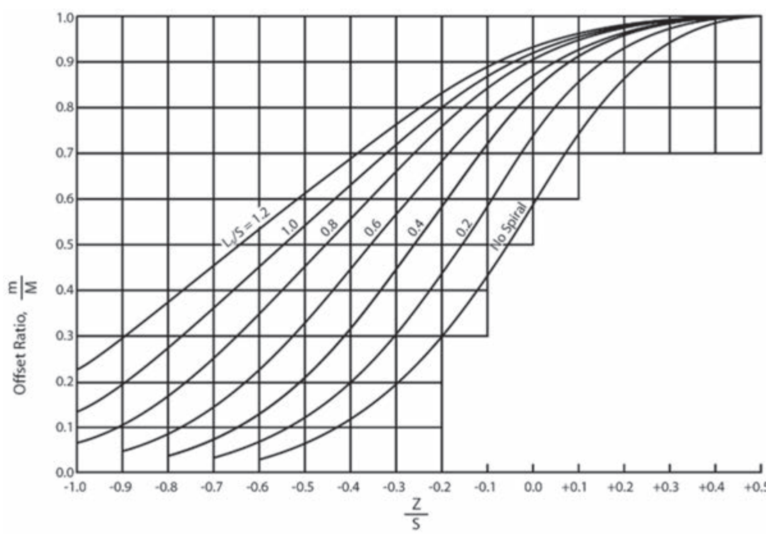

Figure A-2. Offset ratios for determining HSO (Raymond 1972)

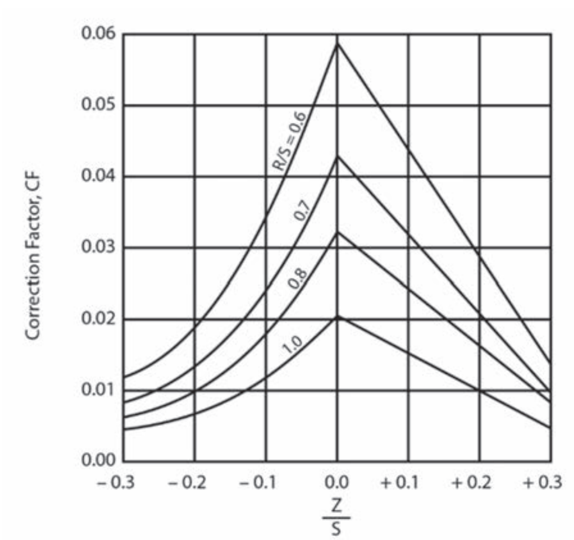

Figure A-3. Correction factor used in determining HSO (Raymond 1972)

Glennon (1987) used a graphical method to develop offset ratios similar to those developed by Raymond. The review by Mauga (2015b) indicates that Glennon's results are also suitable only for long curves (L ≥ S).

Other studies of the mathematics of horizontal sightline offsets have been performed by Waissi and Cleveland (1987), and Easa (1991).

A.3 Graphical Method

Mauga (2015b) indicates that a graphical method for estimating minimum offsets for horizontal sightlines can be performed drawing chords to the horizontal curve from a series of points on the road representing the driver's eye to a corresponding point at a distance equal to design stopping sight distance (S) downstream of the driver's eye, which represents the sightline along which the driver needs to be able to see. A curve is then drawn so that the curve is tangent to all of the chords. This curve defines the "clearance envelope," or the area on the inside of the horizontal curve that should be clear of sight obstructions. Figure A-4 illustrates this graphical method.

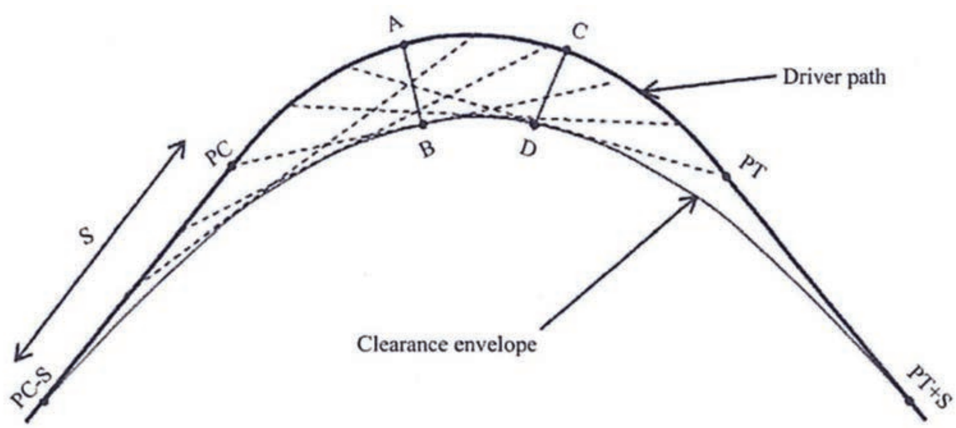

Figure A-4. Graphical method for determining minimum HSOs (Mauga 2015)

A.4 Computational Method for Horizontal Sightline Offsets Developed by Olson et al.

Olson et al. (1984) developed mathematical derivations of the horizontal sightline offsets on the inside of horizontal curves for any placement of the observer (i.e., the driver), a roadside obstacle which serves as a sight obstruction, and the object in the roadway to be seen. The observer and the object to be seen are, as defined in the AASHTO Green Book (2011), always along the centerline of the inside lane of the roadway. The roadside obstacle is on the inside of the horizontal curve at a specified distance, m, from the center of the inside lane, where m is often less than the value of HSO in Equation (A-1). Olson et al. considered both the long curve (L ≥ S) and short curve (L < S) cases. Mauga (2014, 2015b) found the derivation by Olson et al. to be only approximately correct. Furthermore, Olson et al. did not present a closed-form method for computing the value of m actually needed at any point on a curve. Therefore, Mauga's method for computing horizontal sightline offsets is preferred to Olson's method.

A.5 Computational Method for HSOs Developed by Mauga

Two related papers by Mauga (2014, 2015b) present an alternative computational method for determining HSO for horizontal curves. Six cases are addressed:

- Case 1(a) – Long curve (L > S), driver on the approach tangent and object on the curve;
- Case 1(b) – Long curve (L > S), both driver and object on the curve;
- Case 1(c) – Long curve (L > S), driver on the curve tangent and object on the departing tangent;
- Case 2(a) – Short curve (L < S), driver on the approach tangent and object on the curve;
- Case 2(b) – Short curve (L < S), driver on the approach tangent and object on the departing tangent; and
- Case 2(c) – Short curve (L < S), driver on the curve tangent and object on the departing tangent.

These cases together define the area that should be clear of sight obstructions, which Mauga refers to as the clearance envelope, like that shown in Figure A-4. The area that should be clear of sight obstructions begins at a distance equivalent to stopping sight distance in advance of the PC of the curve (i.e., PC – S) and ends at a distance equivalent to stopping sight distance beyond the PT of the curve (PT + S). Mauga designates the horizontal sightline offset needed at any location between PC – S and PT + S as m.

Mauga's computational method treats the plan view of a roadway (see Figure A-5) as an x-y coordinate system in which the x-axis lies along the approach tangent to the horizontal curve (with positive values in the direction from the PC to the PT) and the y-axis is perpendicular to the x-axis (with positive values toward the inside of the curve). Table A-1 defines the notation based on Mauga (2015b).

Table A-1. Summary of notation used in the Mauga Derivation of HSO equations for horizontal curves (adapted from Mauga 2015b)

R	=	radius of the curve (ft)
L	=	length of the curve (ft) from PC to PT
Δ	=	central angle or deflection angle of horizontal curve (degrees)
S	=	design stopping sight distance (ft)
X	=	station corresponding to driver position at any point along the curve or its tangents
m	=	horizontal sightline offset to the area that needs of be clear of sight obstructions at any point along the curve represented by Station X + S
x_d, y_d	=	coordinates of the driver's position on the horizontal curve or its tangents (see accompanying text for explanation of this coordinate system)
x, y	=	coordinates of the point on the edge of the clearance envelope when the drive's position is at x_d, y_d (see accompanying text for explanation of this coordinate system)
θ	=	angle between the horizontal sightline and the approach tangent (degrees)
T_H	=	length of the sightline from the driver to the point at which the sightline touches the clearance envelope tangentially (ft)
T_M	=	maximum length of T_H (ft); occurs at the point where the horizontal sightline offset is maximum
d_{chord}	=	length of the chord of the circular roadway curve from the PC to the position of driver's eye when the driver is on the curve (ft)
γ	=	angle between the curve radius at the PC of the horizontal curve and the line from the center of curvature to object location when the object is on the departing tangent (degrees) (see Figure A-6)
$C_1 \ldots C_6$	=	constant values (defined by equations in text)

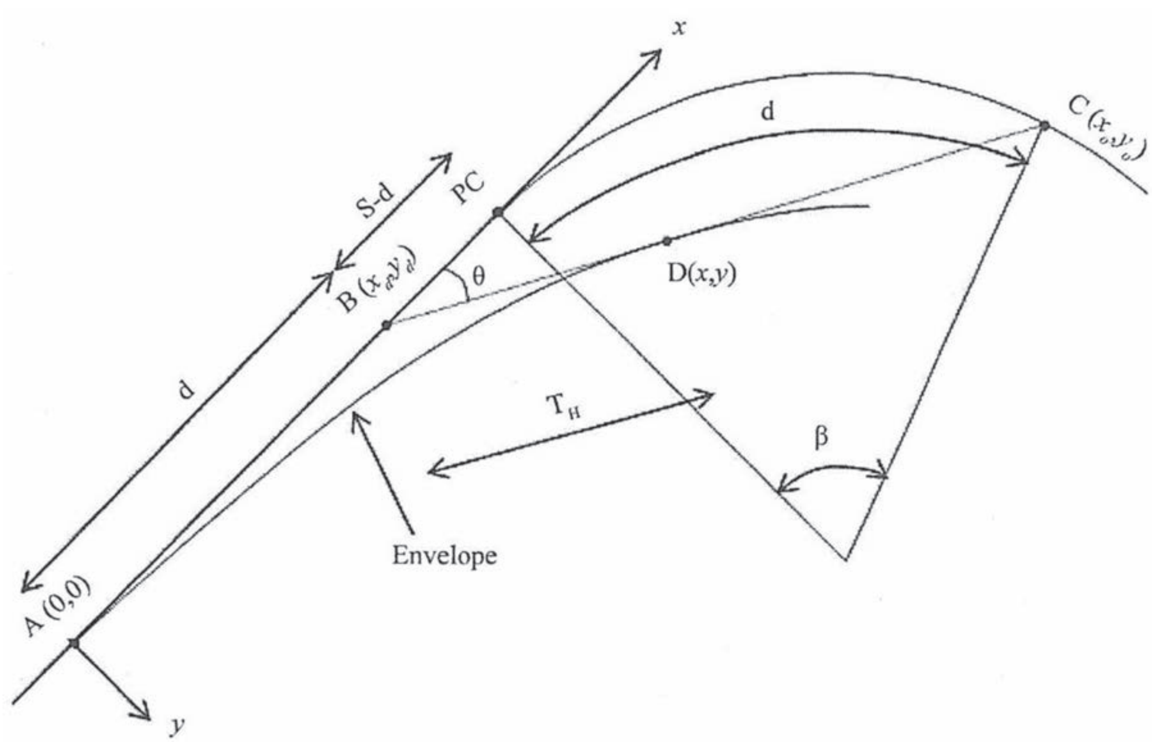

Figure A-5. Plan view showing approach tangent, horizontal curves, and clearance envelope showing definition of x-y coordinate system (Mauga 2015)

A.5.1 Case 1(a) – Long Curve (L > S), Driver on the Approach Tangent and Object on the Curve

Mauga develops equations to determine the horizontal sightline offset for a driver at any station along the road, X. For Case 1(a), the driver location is in the range PC – S ≤ X ≤ PC. The object location (which, by definition, is at X + S) is, therefore, in the range PC ≤ X + S ≤ PC + S. The horizontal sightline offset is determined through the following sequence of equations:

$$C_1 = \frac{R \sin\left(\frac{28.65\,S}{R}\right)}{S} \quad \text{(A-3)}$$

$$T_H = C_1\, d \quad \text{(A-4)}$$

$$C_3 = \frac{28.65}{R\,S} \quad \text{(A-5)}$$

$$\theta = C_3\, d^2 \quad \text{(A-6)}$$

$$y_d = 0 \quad \text{(A-7)}$$

$$y = y_d + T_H \sin\theta \quad \text{(A-8)}$$

$$m = y \quad \text{(A-9)}$$

A.5.2 Case 1(b) – Long Curve (L > S), Driver and Object Both on the Curve

For Case 1(b), the driver location is in the range PC ≤ X ≤ PT - S. The object location (which, by definition, is at X + S) is, therefore, in the range PC + S ≤ X + S ≤ PT. The horizontal sightline offset is determined through the following equation which is equivalent to Equation (A-1):

$$m = R\left[1 - \cos\left(\frac{28.65\,S}{R}\right)\right] \quad \text{(A-10)}$$

A.5.3 Case 1(c) – Long Curve (L > S), Driver on the Curve and Object on the Departing Tangent

For Case 1(c), the driver location is in the range PT - S ≤ X ≤ PT. The object location (which, by definition, is at X + S) is, therefore, in the range PT ≤ X + S ≤ PT + S. The horizontal sightline offset is determined through the following sequence of equations:

$$C_1 = \frac{R \sin\left(\frac{28.65\,S}{R}\right)}{S} \quad \text{(A-11)}$$

$$T_M = R\left[1 - \cos\left(\frac{28.65\,S}{R}\right)\right] \quad \text{(A-12)}$$

$$C_2 = S - T_M \quad \text{(A-13)}$$

$$C_3 = \frac{28.65}{R\,S} \quad \text{(A-14)}$$

$$T_H = T_M + C_2\,(d - L) \quad \text{(A-15)}$$

$$\Delta = \frac{57.3\,L}{R} \tag{A-16}$$

$$\theta = \Delta - C_3\,(S + L - d)^2 \tag{A-17}$$

$$d_{chord} = 2\,R\,\sin\left(\frac{28.65\,(d-S)}{R}\right) \tag{A-18}$$

$$y_d = R\left[1 - \cos\left(\frac{57.3\,(\Delta - S)}{R}\right)\right] \tag{A-19}$$

$$x_d = \sqrt{d_{chord}^2 + y_d^2} + S \tag{A-20}$$

$$x = x_d + T_H \cos\theta \tag{A-21}$$

$$y = y_d + T_H \sin\theta \tag{A-22}$$

$$\gamma - \Delta = \tan^{-1}\left(\frac{57.3\,(d-S-L)}{R}\right) \tag{A-23}$$

$$m = R - \sqrt{(x-S)^2 + (y-R)^2}\,\cos(\gamma - \Delta) \tag{A-24}$$

Figure A-6 illustrates the definitions of the angles Δ and γ for this case and for Case 2(c).

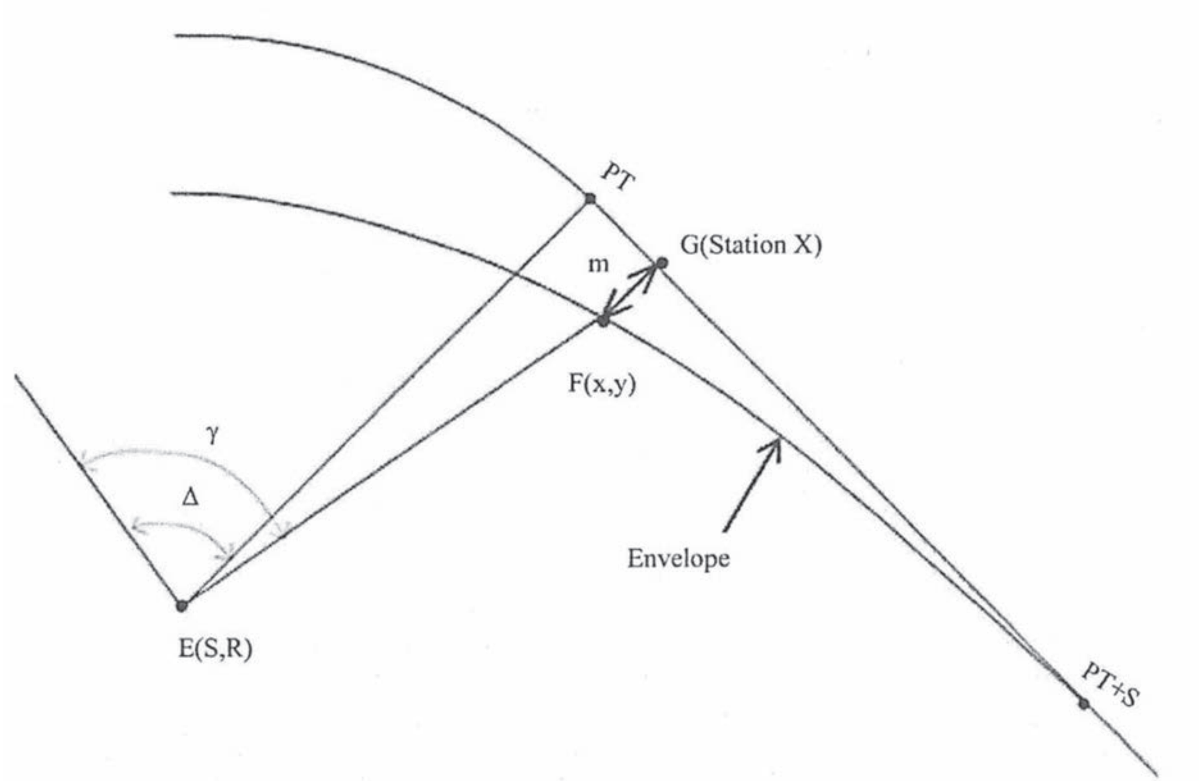

Figure A-6. Plan View Showing Angles Considered for an Object on the Departing Tangent Beyond the PT of a Horizontal Curve (Mauga 2015)

A.5.4 Case 2(a) – Short Curve (L < S), Driver on the Approach Tangent and Object on the Curve

For Case 2(a), the driver location is in the range PC – S ≤ X ≤ PC – S + L. The object location (which, by definition, is at X + S) is, therefore, in the range PC ≤ X + S ≤ PT. The horizontal sightline offset is determined through the following sequence of equations:

$$C_1 = \frac{R \sin\left(\frac{28.65\, S}{R}\right)}{S} \quad \text{(A-25)}$$

$$C_3 = \frac{28.65}{R\, S} \quad \text{(A-26)}$$

$$T_H = C_1\, d \quad \text{(A-27)}$$

$$\theta = C_3\, d^2 \quad \text{(A-28)}$$

$$y_d = 0 \quad \text{(A-29)}$$

$$y = y_d + T_H \sin\theta \quad \text{(A-30)}$$

$$m = y \quad \text{(A-31)}$$

A.5.5 Case 2(b) – Short Curve (L < S), Driver on the Approach Tangent and Object on the Departing Tangent

For Case 2(b), the driver location is in the range PC – S + L ≤ X ≤ PC. The object location (which, by definition, is at X + S) is, therefore, in the range PT ≤ X + S ≤ PT + S - L. The horizontal sightline offset is determined through the following equation:

$$C_1 = \frac{R \sin\left(\frac{28.65\, S}{R}\right)}{S} \quad \text{(A-32)}$$

$$T_M = R\left[1 - \cos\left(\frac{28.65\, S}{R}\right)\right] \quad \text{(A-33)}$$

$$C_3 = \frac{28.65}{R\, S} \quad \text{(A-34)}$$

$$C_4 = \frac{T_M - C_1\, L}{0.5\,(S - L)} \quad \text{(A-35)}$$

$$T_H = C_1\, L + C_4\,(d - L) \quad \text{(A-36)}$$

$$\Delta = \frac{57.3\, L}{R} \quad \text{(A-37)}$$

$$C_6 = \frac{\frac{\Delta}{28.65} + C_3\, L^2}{28.65\,(S - L)} \quad \text{(A-38)}$$

$$\theta = C_3\, L^2 + C_6\,(d - L) \quad \text{(A-39)}$$

$$x_d = d \quad \text{(A-40)}$$

$$y_d = 0 \quad \text{(A-41)}$$

$$x = x_d + T_H \cos\theta \quad \text{(A-42)}$$

$$y = y_d + T_H \sin\theta \quad \text{(A-43)}$$

$$m = R - \sqrt{(x-S)^2 + (y-R)^2} \quad \text{(A-44)}$$

A.5.6 Case 2(c) – Short Curve (L < S), Driver on the Curve and Object on the Departing Tangent

For Case 2(c), the driver location is in the range PC ≤ X ≤ PT. The object location (which, by definition, is at X + S) is, therefore, in the range PT + S - L ≤ X + S ≤ PT + S. The horizontal sightline offset is determined through the following sequence of equations:

$$C_1 = \frac{R \sin\left(\frac{28.65\,S}{R}\right)}{S} \quad \text{(A-45)}$$

$$T_M = R\left[1 - \cos\left(\frac{28.65\,S}{R}\right)\right] \quad \text{(A-46)}$$

$$C_5 = \frac{S - (2\,T_M - C_1\,L)}{L} \quad \text{(A-47)}$$

$$T_H = 2\,T_M - C_1\,L + C_5\,(d - S) \quad \text{(A-48)}$$

$$\Delta = \frac{57.3\,L}{R} \quad \text{(A-49)}$$

$$\theta = \Delta - \frac{28.65\,R}{S}\,(S + L - d)^2 \quad \text{(A-50)}$$

$$d_{chord} = 2\,R \sin\left(\frac{28.65\,(d-S)}{R}\right) \quad \text{(A-51)}$$

$$y_d = R\left[1 - \cos\left(\frac{57.3\,(\Delta - S)}{R}\right)\right] \quad \text{(A-52)}$$

$$x_d = \sqrt{d_{chord}^2 + y_d^2} + S \quad \text{(A-53)}$$

$$x = x_d + T_H \cos\theta \quad \text{(A-54)}$$

$$y = y_d + T_H \sin\theta \quad \text{(A-55)}$$

$$\gamma - \Delta = \tan^{-1}\left(\frac{57.3\,(d-S-L)}{R}\right) \quad \text{(A-56)}$$

$$m = R - \sqrt{(x-S)^2 + (y-R)^2}\,\cos(\gamma - \Delta) \quad \text{(A-57)}$$

A.6 Comparison of Methods

Figure A-7 shows a comparison by Mauga (2014) of his analytical model with the graphical procedure and the approaches used by Raymond (1972), Glennon (1987), and Olson et al. (1984). The comparison shows good agreement in clearance offsets (i.e., horizontal sightline offsets) except with the Olson et al. model for offsets less than 15 ft. There is a minor difference with the Glennon model for clearance offsets less than 5 ft, but that is of no practical importance since it would fall within the inside lane (see below).

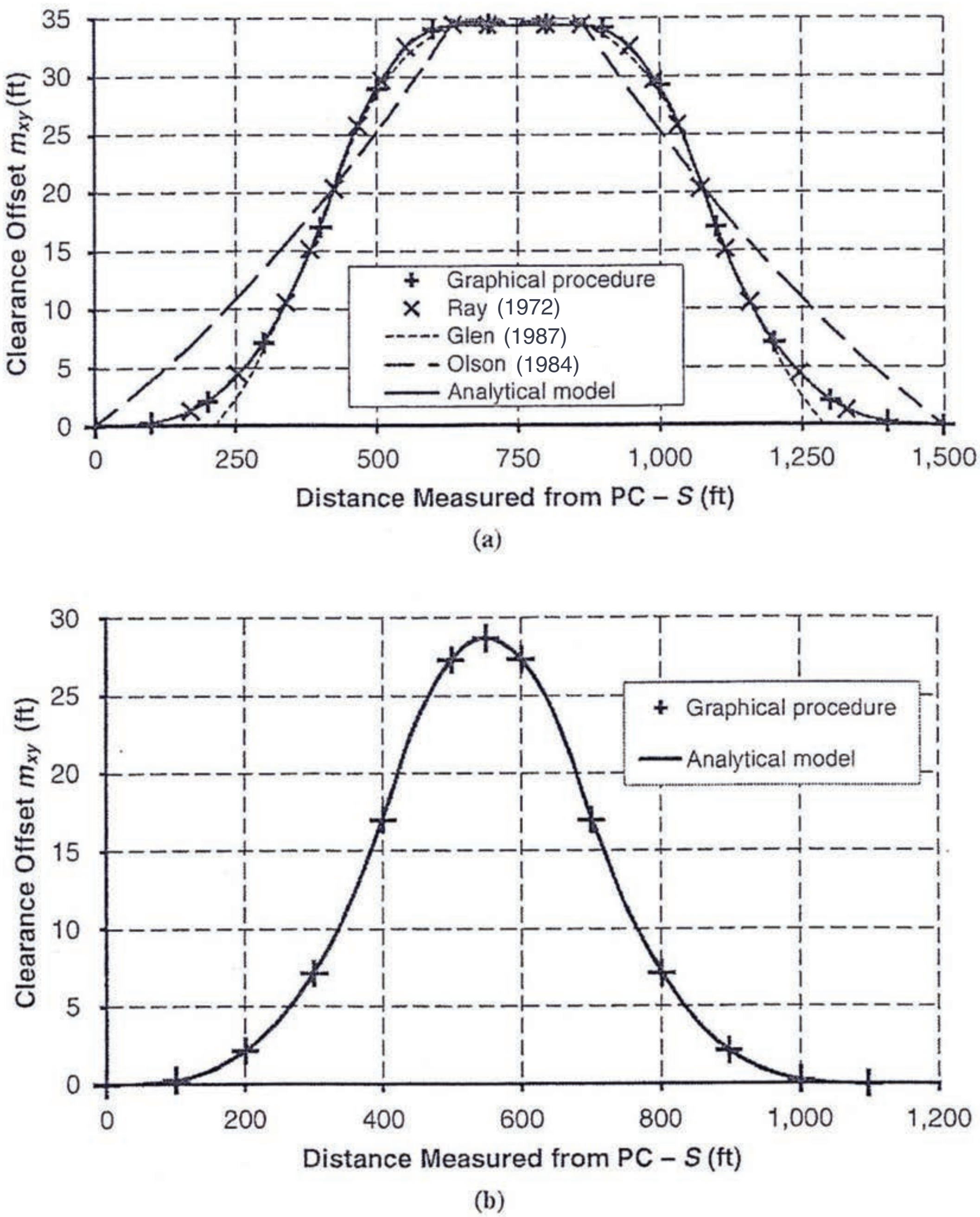

Figure A-7. Data plots comparing Mauga's analytical model to the graphical procedure and other computational models (Mauga 2014)

A.7 Computation of Roadside Clear Areas

Since sight distance is measured from the centerline of the inside lane and the travel lanes and shoulder are, by definition, clear of sight obstructions (with the possible exception of stopped vehicles on the shoulder), the value of horizontal sightline offset, m, is only of practical importance to design where:

$$m > \frac{LW}{2} + SW \qquad \text{(A-58)}$$

where

m = horizontal sightline offset on the inside of the curve (ft);
LW = lane width for the inside lane on the curve (ft); and
SW = shoulder width (ft).

The width of the roadside area (outside of the shoulder) that should be clear of sight obstructions at any location along the curve is:

$$m_{roadside} = m - \frac{LW}{2} - SW \qquad \text{(A-59)}$$

where $m_{roadside}$ is portion of horizontal sightline offset that is on the roadside area outside of the shoulder (ft).

If $m_{roadside}$ is less than or equal to zero, there is no portion of the roadside that needs to be clear of sight obstructions.

A.8 CADD Implementation

The output of the Mauga (2014, 2015b) method is the horizontal sightline offset (m) needed to provide design stopping sight distance at any point near a horizontal curve from Station PC-S to Station PT+S. The Mauga method may be too complex for manual application, but is suitable for implementation of CADD systems. A limitation of the Mauga method is that it is applicable only in two dimensions (i.e., to curves in a horizontal plane). The Mauga method should generally be very accurate for horizontal curves with grades that do not exceed three percent.

APPENDIX B

Users Guide for Reliability Analysis Tool

This appendix presents a users guide for the spreadsheet-based tool that implements the reliability analysis model described in Chapter 5. The tool enables users to assess the horizontal curves with horizontal sightline obstructions present on the inside of the curve. The tool computes the ASSD profile for a horizontal curve and determines the minimum ASSD at any location within the site. The tool also provides measures of the likelihood that drivers on a particular horizontal curve may encounter stopped vehicles in the sight-restricted area. This measure of the annual number of vehicles that may be potentially affected by a sight-distance limitation can be used to prioritize horizontal curves for improvement.

The users guide describes the hardware and software needed to run the spreadsheet tool, the entry of input data to the tool, the initiation of calculations, and output data provided.

B.1 Hardware and Software Requirements

The spreadsheet tool has been developed in Microsoft Excel® with supplementary programming in Visual Basic for Applications (VBA). All input data entry and output displays are in Microsoft Excel®. The spreadsheet tool is available on the TRB website by searching for NCHRP Research Report 910. Once this file has been copied to a user-selected folder on any computer with Microsoft Excel® installed, program execution can be initiated by clicking on the file name. The program should operate without modification on any Windows-based computer system with any version of Microsoft Excel® available at the time of the writing of this report. Program operation on non-Windows-based computer systems has not been verified.

All input data entry is performed on a worksheet entitled UserInput. The key output results are also displayed on the worksheet entitled UserInput. One key set of supplementary output results, the ASSD profile for each lane on the roadway analyzed, can be viewed in the worksheet named Profile. Other worksheets can be viewed to review the results of intermediate calculations. All cells in the worksheets are locked except those in which the user is expected to supply input values.

B.2 Input Data Entry

This section presents the input data that the user is expected to enter to apply the reliability tool to horizontal curves with horizontal sightline obstructions. All of the input data items discussed are entered on the UserInput worksheet.

B.2.1 Facility Type

The site analyzed by the spreadsheet tool is a roadway of user-specified type and number of lanes containing a horizontal curve. The roadway is analyzed for one direction of travel only. The analysis direction is selected by specifying the direction of curve and the offset distance from the edge of the traveled way to the horizontal sight obstruction. General roadway characteristics for the study site are entered in a table on the UserInput worksheet shown in Figure B-1.

Facility Type	
Urban freeway (6 lanes)	
Number of lanes in analysis direction	3
Average lane width (ft)	12.0
AADT (one direction, veh/d)	60000

Figure B-1. Selecting facility type and general characteristics.

- **Facility type:** Select the facility type on which the analysis will be performed using a drop-down menu. The facility types included in the dropdown menu are:
  - Rural two-lane highway
  - Rural four-lane undivided highway
  - Rural four-lane divided highway
  - Rural freeway (4 lanes)
  - Rural freeway (6 lanes)
  - Urban freeway (4 lanes)
  - Urban freeway (6 lanes)
  - Urban freeway (8 lanes)
  - Rural one-lane entrance ramp
  - Rural one-lane exit ramp
  - Urban one-lane entrance ramp
  - Urban one-lane exit ramp
  - Urban two-lane entrance ramp
  - Urban two-lane exit ramp
- **Number of lanes in analysis direction:** This value is automatically updated based on the facility type selection and displayed in the tabular format shown in Figure B-1. The number of lanes is for both directions of travel combined, except for ramp sites which are, by definition, one-way roadways. However, on two-way roads, only the lanes in the analysis direction (assumed to be half of the total number of lanes specified here) are analyzed.
- **Average lane width:** Enter the average lane width of the roadway, in feet.
- **AADT (one direction):** Enter the annual average daily traffic volume (veh/day) in the analysis direction. NOTE: If only two-way AADT data are available, enter half of the two-way AADT.

B.2.2 Obstruction Type and Vertical Alignment

Figure B-2 shows a screenshot of the form used on the UserInput worksheet to specify the obstruction type, the presence of a vertical curve, and the direction of curve selection. Each of these items is discussed.

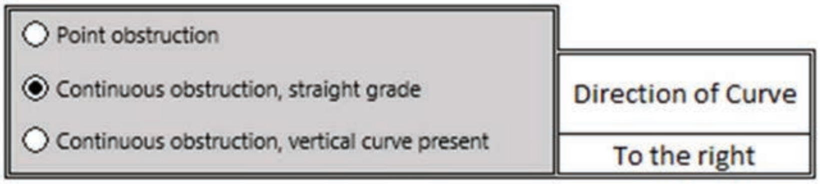

Figure B-2. Selecting obstruction type and curve type.

- **Point obstruction:** Select this option if a point obstruction, with no longitudinal extent, is present. The analysis of point obstructions is a simplified case that assumes there is no grade over 3 percent present, no vertical curve is present, and that the horizontal sight obstruction is sufficiently tall that a driver cannot see over it. If any of these assumptions is not met for a point obstruction, then analyze the site as a longitudinal obstruction with a very short longitudinal extent.
- **Continuous obstruction, straight grade:** Select this option if a continuous horizontal sight obstruction is present, but no vertical curve is present.
- **Continuous obstruction, vertical curve present:** Select this option if a continuous horizontal sight obstruction is present, and a vertical curve is also present.
- **Direction of curve:** Select the direction of the curve (to the left or to the right) using a drop-down menu.

B.2.3 Horizontal Curve and Obstruction Length and Location Input

The input data for the horizontal curve and obstruction length and location vary slightly depending on what options were chosen in Figure B-2.

B.2.3.1 Point Obstruction

Figure B-3 shows a screenshot of the table used on the UserInput worksheet to enter horizontal curve and obstruction length and location data when a point obstruction is being considered. Any point obstruction between Station PC-DSSD and Station PT+DSSD should be entered.

Horizontal Curve and Obstruction Data Input	
Curve Radius, R (ft)	1432.0
Curve Length, L (mi)	0.330
Design or Operating Speed (mi/h)	55
Longitudinal distance from PC to point obstruction, B (mi)	-0.100
Offset from edge of traveled way to sight obstruction, m (ft)	4.0

Figure B-3. Horizontal curve and obstruction length and location data input for point obstructions.

- **Curve radius:** Enter the horizontal curve radius, in feet.
- **Curve length:** Enter the horizontal curve length, in miles.
- **Design or operating speed:** Enter the design speed or operating speed of the analysis site, in mph. The design speed of the horizontal curve may be used, if available. If the design speed used when the curve was designed is not known or if speed conditions have changed since the curve was designed, enter an operating speed based on the posted speed limit or the measured or estimated 85th percentile speed of traffic.
- **Longitudinal distance from PC to point obstruction:** Enter the distance along the roadway from the PC of the horizontal curve to the point obstruction in miles. Enter a negative value if the point obstruction is located before the PC, zero if the point obstruction is located at the PC, or a positive value if the point obstruction is located after the PC.
- **Offset from edge of traveled way to sight obstruction:** Enter the distance from the point obstruction to the edge of the traveled way on the inside of the horizontal curve, in feet. On a divided highway with a median, the horizontal sight obstruction may be on the roadside on the inside of the curve for a curve to the right or in the median for a curve to the left. On an undivided roadway, either the curve to the right in the primary direction of travel (adjacent to the horizontal sight obstruction) or the curve to the left in the opposing direction of travel (separated from the horizontal sight obstruction by the travel lanes in the primary direction) may be analyzed. In the case of a curve to the left in the opposing direction of travel on an undivided roadway, the offset to the horizontal sight obstruction should be equal to the offset for the primary direction of travel plus the total width of all lanes in the primary direction of travel.

B.2.3.2 Continuous Obstruction

Figure B-4 shows a screenshot of the table used on the UserInput worksheet to enter horizontal curve and obstruction length and location data when a continuous obstruction is being considered. Any continuous sight obstruction located between Station PC-DSSD and Station PT+DSSD should be entered.

Horizontal Curve and Obstruction Data Input	
Curve Radius, R (ft)	1500.0
Curve Length, L (mi)	0.100
Design or Operating Speed (mi/h)	55
Longitudinal distance from PC to beginning of continuous obstruction, B1 (mi)	-0.100
Longitudinal distance from PC to end of continuous obstruction, B2 (mi)	0.100
Offset from edge of traveled way to sight obstruction, m (ft)	10.0
Height of obstruction above edge of traveled way (ft)	5.0

Figure B-4. Horizontal curve and continuous obstruction data input.

- **Curve radius:** Enter the horizontal curve radius, in feet.
- **Curve length:** Enter the horizontal curve length, in miles.
- **Design or operating speed:** Enter the design speed or operating speed of the analysis site, in mph. The design speed of the horizontal curve may be used, if available. If the design speed used when the curve was designed is not known or if speed conditions have changed since the curve was designed, enter an operating speed based on the posted speed limit or the measured or estimated 85th percentile speed of traffic.
- **Longitudinal distance from PC to beginning of continuous obstruction:** Enter the distance along the roadway from the PC of the horizontal curve to the beginning of the continuous obstruction, in miles. Enter a negative value if the continuous obstruction begins before the PC, zero if the point obstruction begins at the PC, or a positive value if the point obstruction begins after the PC. If a continuous sight obstruction that extends along the entire roadway, such as a median barrier or a long retaining wall, is present, enter the value of B1 as a negative value equal to -1*DSSD (i.e., DSSD with a leading minus sign).
- **Longitudinal distance from PC to end of continuous obstruction:** Enter the distance along the roadway from the PC of the horizontal curve to the end of the continuous obstruction, in miles. Enter a negative value if the continuous obstruction ends before the PC, zero if the continuous obstruction ends at the PC, or a positive value if the continuous obstruction ends after the PC. If a continuous sight obstruction extends along the entire roadway, such as a median barrier or retaining wall, enter the value of B2 as a positive value equal to the curve length (L) plus the DSSD (i.e., L+DSSD). This is equivalent to a location at a distance DSSD beyond the PT.
- **Offset from edge of traveled way to sight obstruction:** Enter the distance from the continuous obstruction to the edge of the traveled way on the inside of the horizontal curve, in feet. On a divided highway with a median, the horizontal sight obstruction may be on the roadside on the inside of the curve for a curve to the right or in the median for a curve to the left. On an undivided roadway, either the curve to the right in the primary

direction of travel (adjacent to the horizontal sight obstruction) or the curve to the left in the opposing direction of travel (separated from the horizontal sight obstruction by the travel lanes in the primary direction) may be analyzed. In the case of a curve to the left in the opposing direction of travel on an undivided roadway, the offset to the horizontal sight obstruction should be equal to the offset for the primary direction of travel plus the total width of all lanes in the primary direction of travel.

- **Height of obstruction above edge of traveled way:** Enter the height of the horizontal sight obstruction as the difference in elevation between the top of the obstruction and the edge of the traveled way on the inside of the horizontal curve, in feet.

B.2.4 Vertical Alignment Data

Vertical alignment data only needs to be entered for sites that have a continuous horizontal sight obstruction.

B.2.4.1 Continuous Obstruction, Straight Grade

Figure B-5 shows a screenshot of the table used on the UserInput worksheet to enter vertical alignment data for a site where no vertical curve is present. In this case, the only value to be entered is the percent grade of the roadway.

Profile Data	
Roadway grade (%)	2.00

Figure B-5. Vertical alignment data input, no vertical curve present.

- **Roadway grade:** Enter the roadway grade as a percent grade. Enter a negative value for a downgrade or a positive value for an upgrade. For a level roadway, enter 0.00%.

B.2.4.2 Continuous Obstruction, Vertical Curve Present

Figure B-6 shows a screenshot of the table used on the UserInput worksheet to enter vertical alignment data for a site where a vertical curve is present.

Vertical Curve Data	
Approach grade (%)	0.00
Departure grade (%)	2.00
Distance from PC to PVC (mi)	-0.033
Vertical curve length (mi)	0.050

Figure B-6. Vertical alignment data input, vertical curve present.

- **Approach grade:** Enter the roadway grade approaching the vertical curve as a percent grade. Enter a negative value for a downgrade or a positive value for an upgrade. For a level roadway, enter 0.00%.

- **Departure grade:** Enter the roadway grade departing the vertical curve as a percent grade. Enter a negative value for a downgrade or a positive value for an upgrade. For a level roadway, enter 0.00%.
- **Distance from PC to PVC:** Enter the distance from the PC of the horizontal curve to the PVC of the vertical curve, in miles. Enter a negative value if the PVC is located prior to the PC, zero if the PVC is located at the PC, or a positive value if the PVC is located after the PC.
- **Vertical curve length:** Enter the vertical curve length, in miles.

B.2.5 Advanced Options

Several advanced options are available in the spreadsheet tool. Figure B-7 shows a screenshot of the table on the UserInput worksheet to utilize these advanced options.

Advanced Options			AASHTO values	Alternative values
Analysis increment, x (ft)	10	Eye height (ft)	3.5	3.5
◉ Use AASHTO values		Object in road height (ft)	2.0	3.5
○ Use alternative values		Distance from left edge of lane to driver (ft)	6.0	4.0

Figure B-7. Advanced options data entry.

- **Analysis increment:** Enter the incremental distance along the roadway for which ASSD will be calculated, in feet. The recommended value is 10 ft.
- **Use AASHTO values:** Select this option to use sight distance default values from the AASHTO Green Book. These dimensions and their AASHTO-specified values are:
  - **Driver eye height:** The height of the driver's eye above the roadway, in feet. This value is set by default to 3.5 ft.
  - **Object in road height:** The height of the object in the roadway which the driver needs to see, in feet. This value is set by default to 2.0 ft.
  - **Distance from left edge of lane to driver:** The lateral distance from the edge of the lane to the driver's position in the lane. This value is set by default to half of the lane width.
- **Use alternative values:** Select this option to use values other than the default values from the Green Book. The alternative values may be set by the user in the column labeled "Alternative Values" as follows:
  - **Driver eye height:** The height of the driver's eye above the roadway, in feet. In most cases, this value should not be varied from the default value of 3.5 ft for a passenger car driver. An alternative value of 3.0 ft might be considered in special cases for a driver of a low-profile passenger car, such as a sports car. An alternative value of 8.0 ft might be considered in special cases for a truck driver.
  - **Object in road height:** The height of the object in the roadway which the driver needs to see, in feet. AASHTO uses a default value of 2.0 ft, equivalent to the taillight height of a passenger car. Where the object to be seen is definitely a passenger car, with a typical vehicle height of 4.5 ft, consideration should be given to using an

object height of 3.5 ft, equivalent to driver eye height, or 4.0 ft. Either of these choices allows for some of the upper portion of the vehicle to be visible to an approaching driver.

- **Distance from left edge of lane to driver:** The lateral distance from the edge of the lane to the driver's position in the lane. This value is set by default to half of the lane width. A more appropriate alternative value is one-quarter of the lane width. For a site with 12-ft lanes, this results in a driver's eye position 3 ft from the inside edge of the traveled way for a curve to the left and 9 ft from the edge of the traveled way for a curve to the right.

B.2.6 Traffic Data

Figure B-8 shows a screenshot of the k-factor selection and k-factor distribution options.

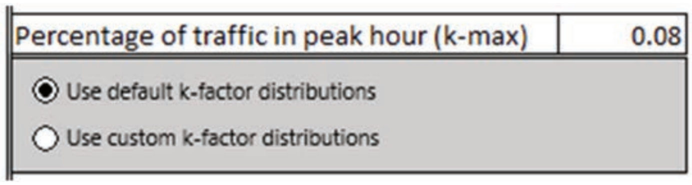

Figure B-8. K-factor selection and distributions.

- **Percentage of traffic in peak hour:** Select the k-max value for the analysis site from the dropdown menu. The k-max value is the proportion of AADT in the peak hour of the day. Available options include 0.08, 0.09, 0.10, 0.11, and 0.12.
- **Default k-factor distributions:** Select this option to use the default k-factor distribution for the selected k-max value.
- **Custom k-factor distributions:** Select this option to use a user-supplied k-factor distribution for the selected k-max value. Values for the k factors must be entered for all 24 hours of the day and the k values must sum to 1.00. If the k values in any column do not sum to 1.00, a warning message will be displayed. Enter the k factors in the "Custom" column under the appropriate k-max value, as shown in Figure B-9.

k-factor distributions										
	k-max = 0.08		k-max = 0.09		k-max = 0.10		k-max = 0.11		k-max = 0.12	
Hour	Default	Custom	Default	Custom	Default	Custom	Default	Custom	Default	Custom
1	1.02%		0.97%		0.93%		0.88%		0.84%	
2	0.73%		0.68%		0.64%		0.59%		0.55%	
3	0.67%		0.62%		0.58%		0.53%		0.49%	
4	0.78%		0.73%		0.69%		0.64%		0.60%	
5	1.21%		1.16%		1.12%		1.07%		1.03%	

Figure B-9. K-factor default values and custom k-factor data entry.

Figure B-10 shows a screenshot of the lane utilization data entry. Enter the percentage of directional traffic that is present in each lane. The sum of all lane percentages must equal 100%. If the lane utilization factors do not sum to 100%, a warning message will be displayed.

Lane Utilization (%)	
Lane 1 (closest to obstruction)	40%
Lane 2	30%
Lane 3	30%

Figure B-10. Lane utilization data entry.

B.2.7 Crash Prediction

Figure B-11 shows a screenshot of the crash prediction model options and custom data entry.

SPFs Used as Crash Prediction Models

- (●) Use default SPF Coefficients
- ( ) Use custom SPF Coefficients

Calibration factor	1.00

Functional Form of SPFs

$$N(crashes/yr) = X_1 L e^{(a_1+b_1\ln[c_1 AADT]+d_1[c_1 AADT])}$$
$$+X_2 L e^{(a_2+b_2\ln[c_2 AADT]+d_2[c_2 AADT])}$$
$$+X_3 L e^{(a_3+b_3\ln[c_3 AADT]+d_3[c_3 AADT])}$$
$$+X_4 L e^{(a_4+b_4\ln[c_4 AADT]+d_4[c_4 AADT])}$$

Facility Type	Coefficients for MV-FI SPF				
Urban freeway (6 lanes)	X_1	a_1	b_1	c_1	d_1
Default	1	-5.587	1.492	0.001	0
Custom					

Facility Type	Coefficients for MV-PDO SPF				
Urban freeway (6 lanes)	X_2	a_2	b_2	c_2	d_2
Default	1	-6.809	1.936	0.001	0
Custom					

Facility Type	Coefficients for SV-FI SPF				
Urban freeway (6 lanes)	X_3	a_3	b_3	c_3	d_3
Default	1	-2.055	0.646	0.001	0
Custom					

Facility Type	Coefficients for SV-PDO SPF				
Urban freeway (6 lanes)	X_4	a_4	b_4	c_4	d_4
Default	1	-2.274	0.876	0.001	0
Custom					

Figure B-11. Crash prediction model options.

- **Use default SPF coefficients:** Select this option to use SPF coefficients from the *Highway Safety Manual*.
- **Use custom SPF coefficients:** Select this option to enter custom SPF coefficients for use in crash prediction modeling.
- **Calibration factor:** Enter the SPF calibration factor. If no calibration factor for the local jurisdiction is available, use 1.00.

- **SPF coefficients:** The default SPF coefficients are shown on four "Default" rows. The functional form for all SPFs are shown in the equation above the coefficients. Custom SPF coefficients can be entered on the four "Custom" rows, but the custom coefficients must be from SPFs following the same functional form of the equation shown.

B.3 Perform Calculations

Once all input data have been entered, click the "Calculate" button to perform all calculations for the reliability analysis. The location of the button is shown in Figure B-12.

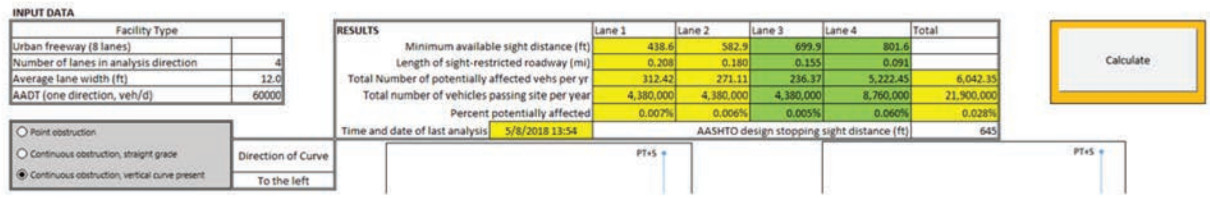

Figure B-12. Location of calculate button.

B.4 Results

Figure B-13 shows a screenshot of the results of the reliability analysis.

RESULTS		Lane 1	Lane 2	Lane 3	Lane 4	Total
Minimum available sight distance (ft)		438.6	582.9	699.9	801.6	
Length of sight-restricted roadway (mi)		0.208	0.180	0.155	0.091	
Total Number of potentially affected vehs per yr		312.42	271.11	236.37	5,222.45	6,042.35
Total number of vehicles passing site per year		4,380,000	4,380,000	4,380,000	8,760,000	21,900,000
Percent potentially affected		0.007%	0.006%	0.005%	0.060%	0.028%
Time and date of last analysis	5/8/2018 13:54	AASHTO design stopping sight distance (ft)				645

Figure B-13. Reliability analysis results.

- **Minimum available sight distance:** The minimum ASSD is shown for each lane, in feet. The column of output results for a particular lane will be green if ASSD is equal to or greater than the applicable DSSD or yellow if the ASSD is less than the applicable DSSD. If the analysis finds that the obstruction does not obstruct the driver's view of the downstream roadway at any point (i.e., the driver can see over the obstruction), a value of 9999.0 will appear.

- **Length of sight-restricted roadway**: The length of the area, in miles, which is not visible to approaching drivers for the full DSSD. The sight-restricted area is the portion of the roadway with ASSD less than DSSD.

- **Total number of potentially affected vehicles per year:** The total number of vehicles per year that may be potentially affected by a crash-involved vehicle or a queue of stopped vehicles in the sight-restricted area is shown for each lane.

- **Total number of vehicles passing site per year:** The total number of vehicles passing through a site per year is shown for each lane.

- **Percent potentially affected:** The percentage of total vehicles passing through a site that may be potentially affected by a crash-involved vehicle or a queue of stopped vehicles in the sight-restricted area is shown for each lane.
- **Time and date of last analysis:** The date and time of the last analysis is shown and is updated every time the "Calculate" button is clicked.
- **AASHTO design stopping sight distance:** The AASHTO DSSD for the applicable design speed is shown, in feet.

B.5 View Calculations

Intermediate calculations can be viewed in the Crash and Capacity worksheets. The Crash worksheet shows the computation of the total number of potentially affected vehicles per year per lane if stopped vehicles are present in the sight-restricted area due to a crash. The Capacity worksheet shows the computation of the total number of potentially affected vehicles per year per lane if stopped vehicles are present in the sight-restricted area due to congestion.

B.6 View Intermediate Results

ASSD values at incremental locations are shown for each lane in the Profile worksheet. The first column shows the driver's location, in feet, relative to the PC of the horizontal curve.

APPENDIX C

Case Studies of Existing Roadways with Sight Obstructions

This appendix presents case studies of seven horizontal curve sites selected from among the 263 field sites reviewed by Potts et al. (2018). These case studies address horizontal curves with limited SSD for a range of roadway types, directions of curvature, curve radii, and sight obstruction types. Each case study addresses the characteristics of the site, available sight distance profiles, traffic operational performance, safety performance, mitigation challenges, and lessons learned. The case study sites are located in the states of Illinois, Kansas, Pennsylvania, and Washington.

The case study sites were selected without reference to crash history data. The objective was to choose case study sites that represented a range typical of site conditions, not to select locations that were known to be low crash or high crash sites.

The case studies include:

- Case Study 1—Site IL009—Curve to the Right on a Rural Two-Lane Highway
- Case Study 2—Site IL035—Curve to the Right on an Urban Interchange Ramp
- Case Study 3—Site KS009—Curve to the Left on an Urban Interchange Ramp
- Case Study 4—Site KS025—Curve to the Right on a Rural Two-Lane Highway
- Case Study 5—Site PA002—Curve to the Left on a Rural Mainline Freeway
- Case Study 6—Site WA082—Curve to the Left on an Urban Mainline Freeway
- Case Study 7—Site WA091—Curve to the Right on an Urban Interchange Ramp

Each case study is presented below.

C.1 Case Study 1—Site IL009—Curve to the Right on a Rural Two-Lane Highway

Site IL009 consists of a horizontal curve on a rural two-lane undivided highway. The primary study direction for this horizontal curve is eastbound because, in the eastbound direction of travel, the curve is to the right and traffic is immediately adjacent to the horizontal sight obstruction on the inside of the curve. The curve has a radius of 819 ft and is 0.15 mi in length. The sight obstruction on the inside of the horizontal curve consists of a continuous row of trees (essentially a forest) along the entire length of the curve. The line of trees extends beyond both ends of the curve by 0.08 mi. The trees begin at an offset of 7 ft from the inside edge of the traveled way. The rural two-lane highway has a speed limit of 55 mph; there is a signed advisory speed of 50 mph on the curve. The two-way AADT on the roadway is 6,750 veh/day.

Figure C-1 shows a photograph of the curve, showing the trees on the inside of the horizontal curve. More details are presented in the sight distance profile discussion. Figure C-2 presents a drawing of the roadway curve showing the position of the trees.

Figure C-1. Photograph of the rural two-lane highway curve for Case Study 1.

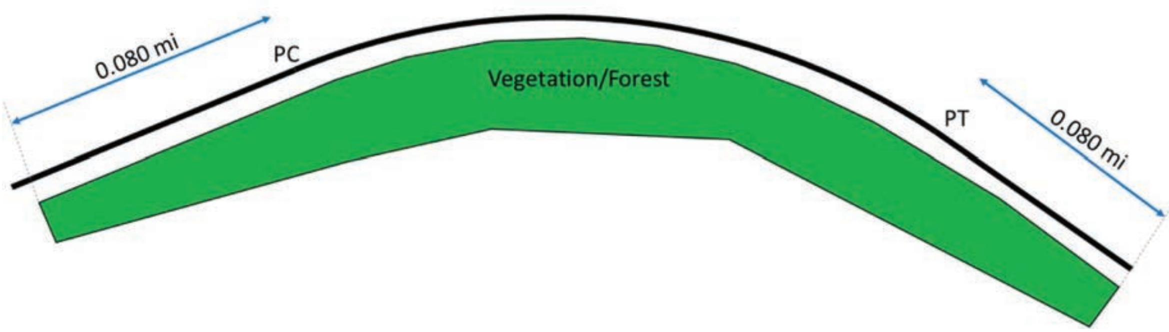

Figure C-2. Two-lane highway alignment showing the position of the horizontal sight obstructions.

C.1.1 Sight Distance Profile

The minimum ASSD at this location is 292 ft, as compared to the DSSD of 495 ft for a 55-mph roadway, or a DSSD of 425 ft for a 50-mph roadway. There is a railroad bridge abutment with an offset from the edge of traveled way of 2 ft, located approximately 250 ft upstream of the PC of the curve. However, the limitation on sight distance imposed by the bridge abutment does not create an ASSD less than the DSSD of 425 ft.

Figure C-3 shows a sight distance profile for the primary direction of travel (eastbound) at the site. The figure shows that ASSD becomes less than the DSSD approximately 250 ft upstream from the PC and decreases to the minimum of 292 ft at the PC. The sight distance continues at its minimum value until 275 ft from the PT. At this point ASSD rapidly increases.

The trees on the inside of the curve (adjacent to the eastbound direction of travel) also obstruct the view of westbound vehicles slightly. Figure C-4 shows a sight distance profile for the westbound direction of travel. The minimum ASSD in the westbound direction of travel is 406 ft, which is just below the DSSD of 425 ft. In fact, if the line of trees were 3 ft further from the traveled way on the inside of the curve, there would be no limited sight distance in the westbound direction.

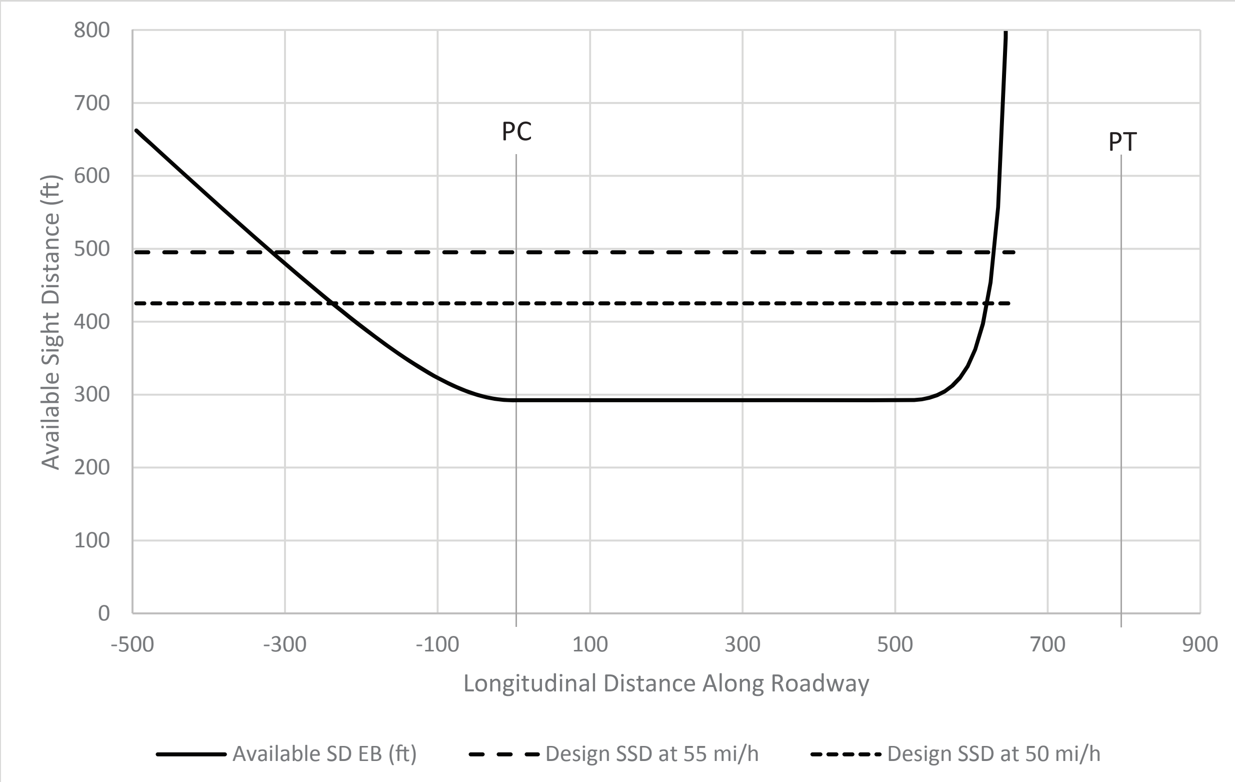

Figure C-3. Sight distance profile for the primary (eastbound) direction of travel at the rural two-lane highway site for Case Study 1.

The reliability analysis model presented in Chapter 5 was applied to consider the effect of alternative sight distance measurement assumptions. For the eastbound or primary direction of travel, if the driver's eye is positioned 3 ft from the left edge of the travel lane, the ASSD increases to 324 ft. However, the ASSD for the westbound direction would decrease to 380 ft if the driver's eye were positioned 3 ft from the left edge of the westbound travel lane. These alternative assumptions are more realistic in that the driver's eye is positioned a quarter of the way across the lane, rather than at the center of the lane. However, even with these alternative assumptions, the ASSD is less than the DSSD for speeds of 50 and 55 mph in both directions of travel.

C.1.2 Traffic Operational Performance

The AADT of the rural two-lane highway at this site is 6,750 vehicles per day. This site operates well below capacity.

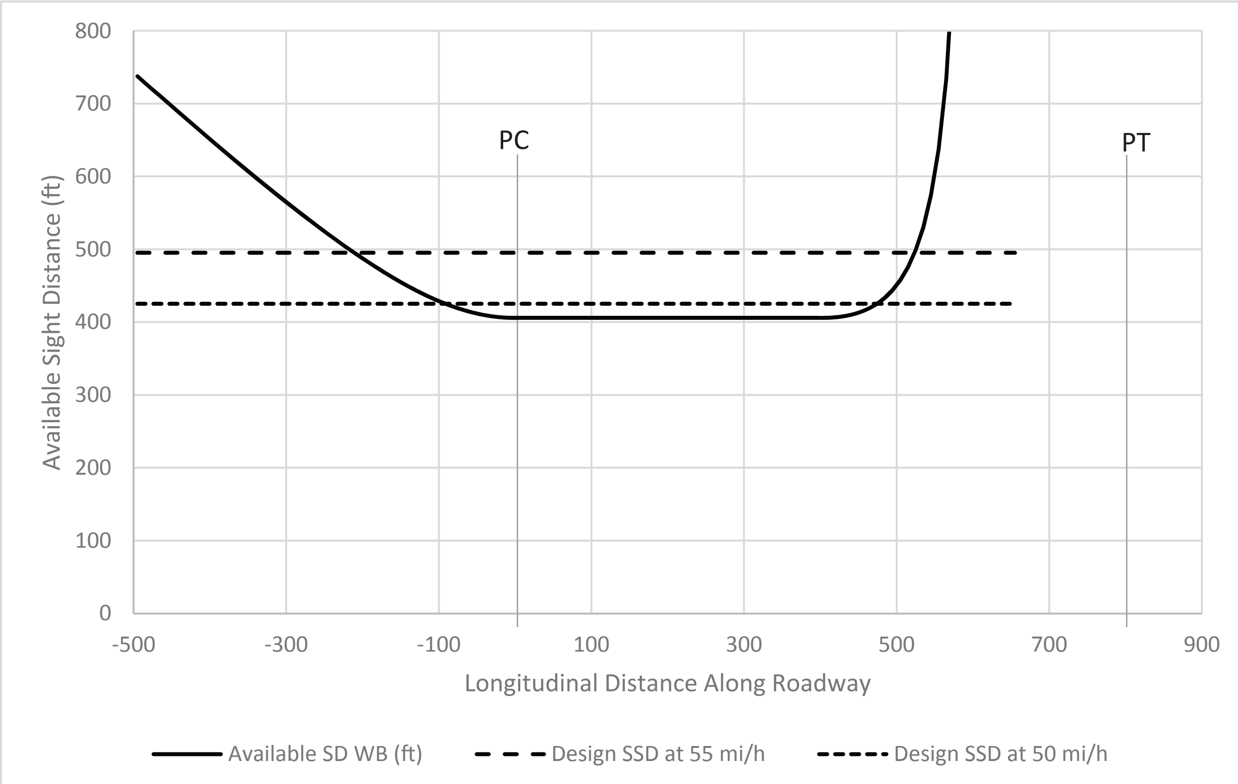

Figure C-4. Sight distance profile for the secondary (westbound) direction of travel at the rural two-lane highway site for Case Study 1.

C.1.3 Safety Performance

There was just one sight-distance-related crash that occurred at this site during the 5-year study period in the primary direction of travel. The crash was a rear-end collision that resulted in property damage only. Thus, there is no indication that the sight distance limitation at this site results in any pattern of sight-distance-related crashes.

C.1.4 Mitigation Challenges

The only logical mitigation measure for application at this site is the clearing of trees on the inside of the curve. The tree line would need to be pushed back by an additional 3 ft to remove the sight distance limitation for the westbound direction of travel or by 15 ft to remove the sight distance limitation for the primary or eastbound direction of travel. Given the density of trees at this site, this would involve a relatively high cost. The trees appear to be outside the right-of-way, so either additional right-of-way or a sight easement would need to be acquired. The limited crash experience provides no indication that a sight distance improvement is needed.

C.1.5 Lessons Learned

There are several lessons that can be learned from Case Study 1. These include:

1. A sight obstruction on the inside of the horizontal curve on a two-lane undivided highway may limit the ASSD in both directions of travel on some curves. The ASSD for traffic in

the direction of travel on the outside of the curve is likely to be only slightly limited unless the curve radius is very small and/or the sight obstruction on the inside of the curve is very close to the traveled way.

2. Where crash experience is limited, high-cost sight distance improvements are not likely to be practical.

C.2 Case Study 2—Site IL035—Curve to the Right on an Urban Interchange Ramp

Site IL035 consists of a curve to the right on an urban interchange ramp. The ramp in question is an outer connection off-ramp in a full cloverleaf interchange on an urban freeway. The curve is located approximately 0.02 mi downstream from the gore area at which point the ramp departs from the mainline freeway. The ramp consists of a single travel lane with paved shoulders. The curve has a radius of 275 ft and is 0.03 mi in length. The width of the ramp traveled way is 16 ft. The sight obstruction on the inside of the horizontal curve consists of trees and a concrete traffic barrier that begin 0.014 mi downstream of the PC of the curve and continue to the PT. The sight obstruction is located 12 ft from the inside edge of the ramp traveled way. The mainline freeway has a speed limit of 55 mph, while the ramp curve has a signed advisory speed of 25 mph. No speed studies are available, but traffic frequently exceeds the 25 mph advisory speed. The mainline freeway carries a two-way AADT of 149,700 veh/day. The AADT of the ramp is 3,700 veh/day.

Figure C-5 shows a photograph of the ramp, illustrating that the trees and the roadside barrier substantially limit the driver’s view of the roadway ahead. More details are presented in the sight distance profile discussion. Figure C-6 presents a drawing of the ramp curve showing the position of the horizontal sight obstruction.

C.2.1 Sight Distance Profile

The minimum ASSD on the ramp is 220 ft, as determined with the AASHTO Green Book sight distance measurement assumptions. The minimum ASSD is substantially less than the AASHTO DSSD for the mainline posted speed limit of 55 mph, but slightly exceeds the DSSD for the signed advisory speed of 25 mph. The minimum ASSD is between the AASHTO DSSD values for 30 and 35 mph. However, this indicates that vehicles traversing the ramp curve at speeds above 35 mph may not have sufficient SSD.

Figure C-7 shows the sight distance profile for the ramp curve. The figure indicates that the ASSD becomes less than the DSSD for the posted speed limit on the freeway approximately 240 ft upstream of the gore area and continues to decrease until reaching the minimum ASSD value of 220 ft approximately 35 ft upstream of the PC. The ASSD continues at approximately its minimum value past the PC and opens up to essentially unlimited sight distance by 35 ft downstream of the PC. The point at which the driver’s view opens up to essentially unlimited sight distance is approximately 40 ft upstream of the beginning of the sight obstruction. At this point, the trees no longer limit the driver’s view and the driver can see over the roadside barrier. Thus, the area with limited ASSD is entirely upstream of the sight obstruction.

Figure C-5. Photograph of the ramp curve for Case Study 2.

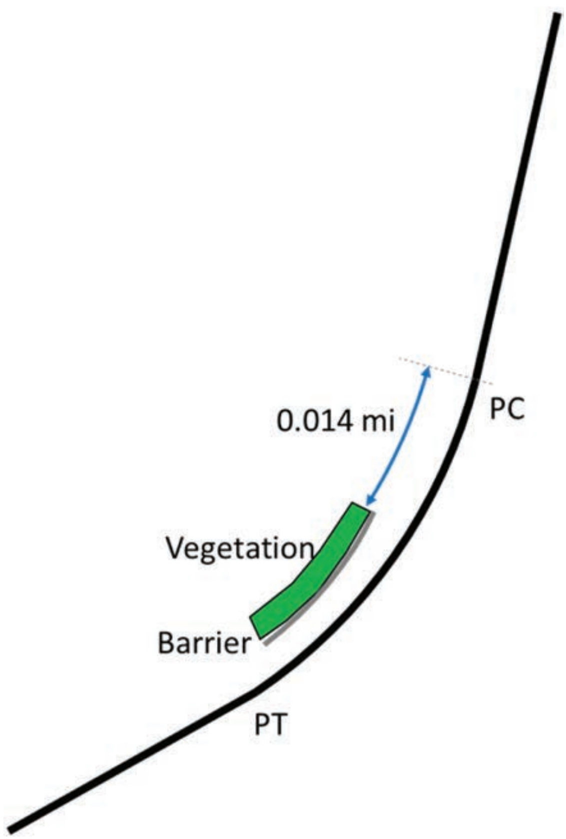

Figure C-6. Ramp alignment showing the position of the horizontal sight obstructions.

The reliability analysis model presented in Chapter 5 was applied to consider the effect of alternative sight distance measurement assumptions. If the driver's eye were positioned 4 ft from the left edge of the ramp traveled way (i.e., one quarter of the way across the traveled way) and the object height to be seen in the roadway was increased to 3.5 ft, the ASSD would increase to 248 ft, which is still substantially lower than the DSSD for the mainline freeway speed.

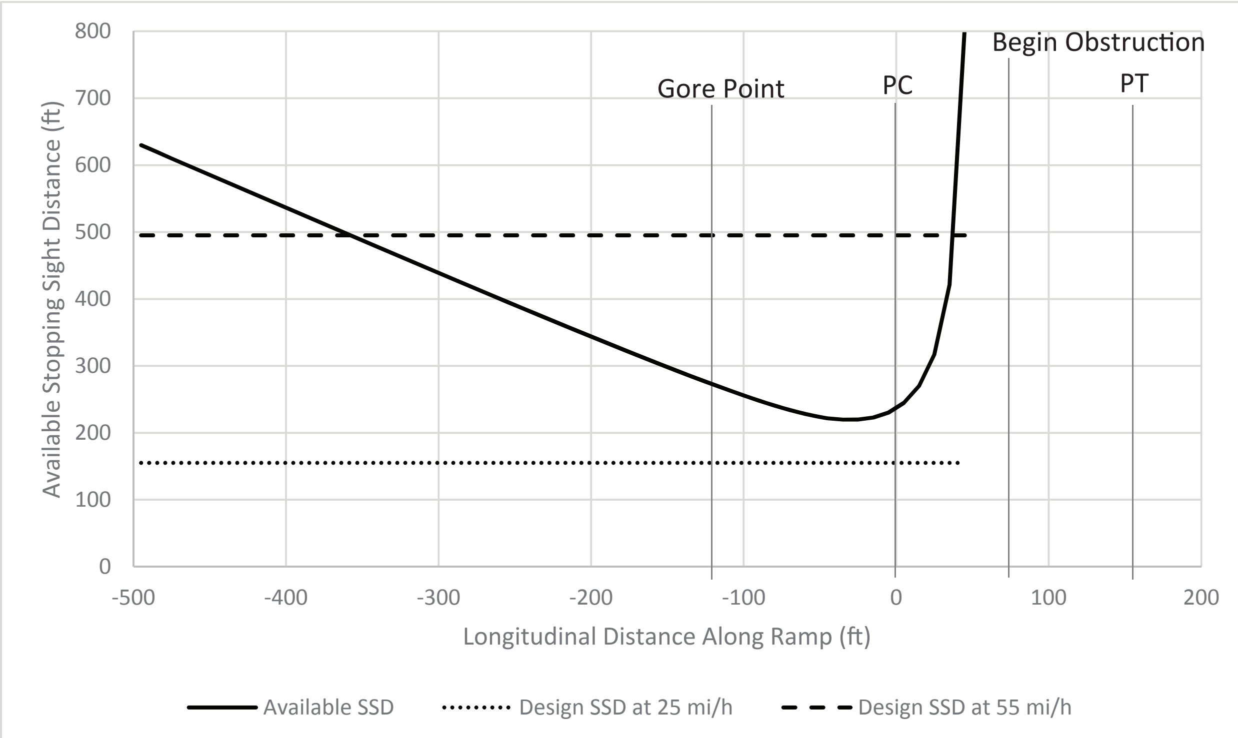

Figure C-7. Sight distance profile for the existing condition at the ramp site for Case Study 2.

C.2.2 Traffic Operational Performance

The mainline freeway adjacent to the ramp is an urban 6-lane freeway with an AADT upstream of the ramp diverge of 149,700 veh/day. The mainline freeway operates above capacity for part of the day.

The off-ramp has an AADT of 3,700 veh/day. Congestion on the off ramp is unlikely unless a crash occurs or a bottleneck is located downstream.

C.2.3 Safety Performance

Seven crashes of types that are potentially related to sight distance occurred on or near the curve of interest during a 5-year period. Based on the reported latitude and longitude coordinates for the crashes, only two of these seven crashes occurred in the area with limited sight distance. One of these crashes was a severe-injury overturning crash that occurred at the gore area, while the other was a property-damage-only crash just downstream of the PC of the curve that involved running off the road and striking a fixed object. There is no definitive evidence that either of these crashes was attributable to limited sight distance, but this is a possibility.

The reported locations for the other five crashes were in the downstream portion of the ramp curve where sight distance is not limited.

C.2.4 Mitigation Challenges

The simplest and lowest cost mitigation measure for this site has already been implemented—signing of a 25-mph advisory speed. While signing of an advisory speed warns drivers of the need to slow down, it does not necessarily reduce travel speeds to 25 mph.

Another possible low-cost mitigation measure would be to post a flashing beacon activated when a vehicle speed over 25 or 30 mph is detected. However, this mitigation measure may not be appropriate at a location this close to a key decision point, the gore area of a freeway off-ramp.

There are two sight obstructions at this site: a line of trees and a 2.5-ft tall concrete barrier that is situated at the base of the trees. An obvious mitigation measure would be to remove the trees. This would increase the minimum ASSD from 220 to 252 ft. As shown in Figure C-8, the available sight distance at a point about 10 ft upstream of the gore point immediately becomes unlimited because drivers can see over the concrete barrier. This mitigation measure would have low to medium cost depending on the difficulties involved in tree removal at the site. If the alternative assumptions of the object height to be seen in the roadway is 3.5 ft, ASSD is not affected by the concrete barrier.

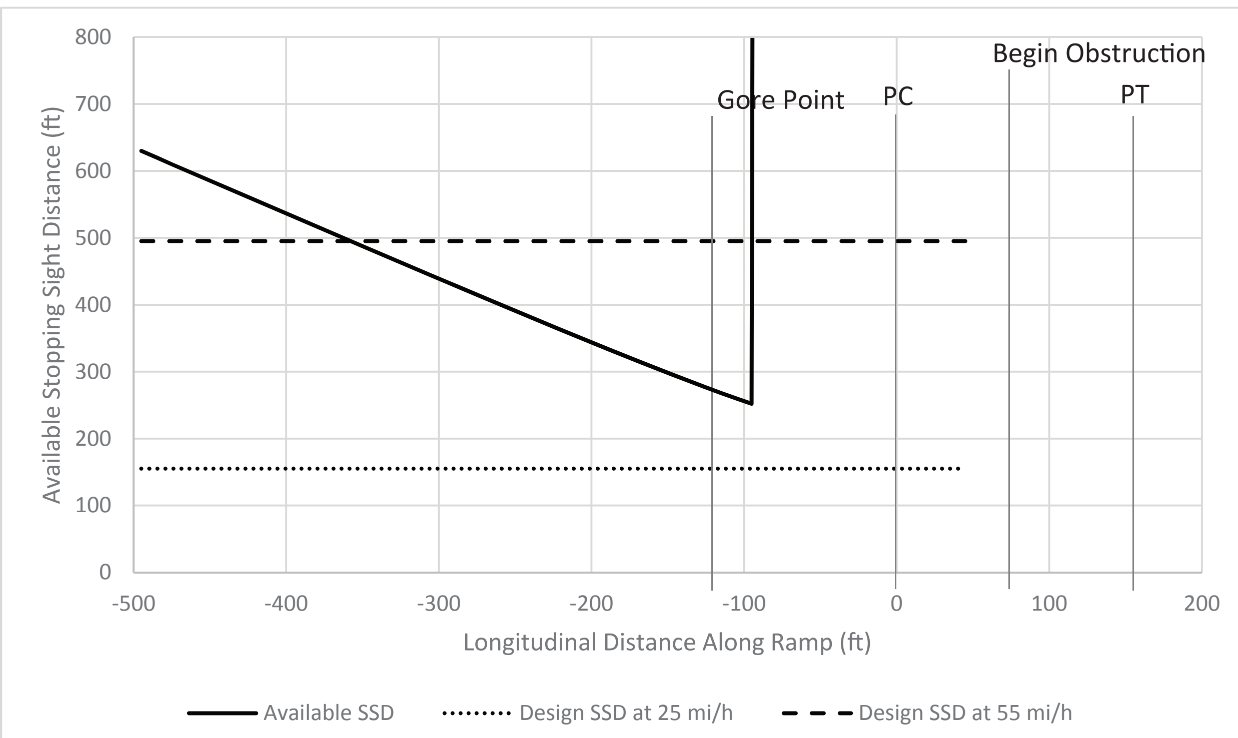

Figure C-8. Sight distance profile with trees removed at the ramp site for Case Study 2.

A high-cost mitigation measure would be realignment of the ramp to increase the radius of curvature and/or move the traveled way further from the sight obstructions. The crash history of the site does not suggest the need for any high-cost mitigation measure of this type.

C.2.5 Lessons Learned

There are several lessons that can be learned from Case Study 2. These include:

1. Depending on the location and offset of the horizontal sight obstructions, sight distance limitations may extend upstream of a horizontal curve and may end before the PT of the curve is reached.
2. Advisory speed signing is useful for warning drivers of the need to slow down, but does not necessarily result in drivers traveling at or below the advisory speed.
3. Where multiple horizontal sight obstructions are present, removing even one of those sight obstructions (in this case the sight obstruction with greater height) may substantially reduce the resulting sight distance restriction. At the case study site, the removal of the trees would substantially reduce the area of restricted sight distance, because drivers can more readily see over a 2.5-ft concrete barrier.

C.3 Case Study 3—Site KS009—Curve to the Left on an Urban Interchange Ramp

Site KS009 consists of a curve to the left on an urban interchange ramp. The ramp in question is a parclo loop off ramp within a partial cloverleaf (folded diamond) interchange on an urban freeway. The curve begins approximately 0.21 mi downstream from the gore area, at which point the ramp departs from the mainline freeway and ends approximately 0.08 mi upstream from the at-grade crossroad ramp terminal. The ramp consists of a single travel lane with paved shoulders. The curve has a radius of 495 ft and is 0.05 mi in length. The sight obstruction on the inside of the horizontal curve consists of a continuous concrete median barrier, with a height of 4 ft, separating the off-ramp in question from the adjacent on-ramp on which traffic operates in the opposite direction. The sight obstruction is located 5 ft from the inside edge of the ramp traveled way. The mainline freeway has a speed limit of 65 mph, while the ramp curve has a signed advisory speed of 30 mph. No speed studies are available, but traffic substantially exceeds the 30-mph advisory speed. The mainline freeway carries a two-way AADT of 77,000 veh/day. The AADT of the ramp is 1,930 veh/day.

Figure C-9 shows a photograph of the ramp curve and the concrete barrier. Figure C-10 presents a drawing of the ramp curve in question showing the position of the horizontal sight obstruction on the inside of the curve.

C.3.1 Sight Distance Profile

The minimum ASSD at this site is 214 ft. The DSSD for the mainline speed limit of 65 mph is 645 ft. The DSSD for the ramp advisory speed of 30 mph is 200 ft. Thus, the ASSD on the ramp curve slightly exceeds the DSSD for the ramp advisory speed, but is substantially below the DSSD for the mainline freeway speed.

Figure C-11 shows the sight distance profile for the ramp curve. The figure indicates that the minimum ASSD begins at the PC and opens up to essentially unlimited sight distance near the midpoint of the curve. At this point, the barrier no longer limits the driver's view.

Figure C-9. Photograph of the ramp curve for Case Study 3

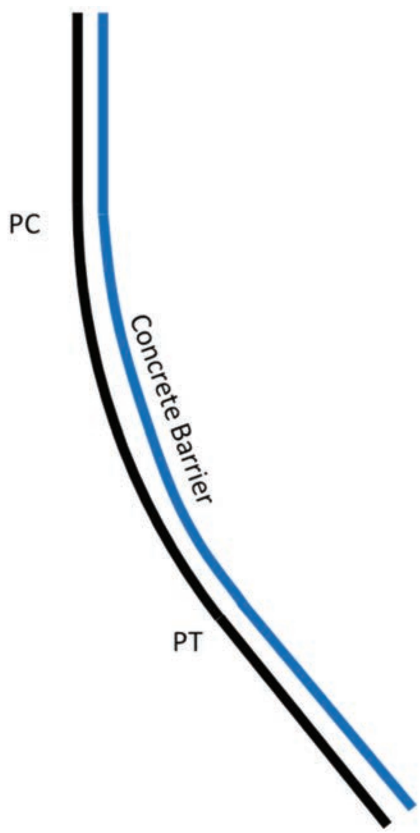

Figure C-10. Ramp alignment showing the position of the horizontal sight obstructions.

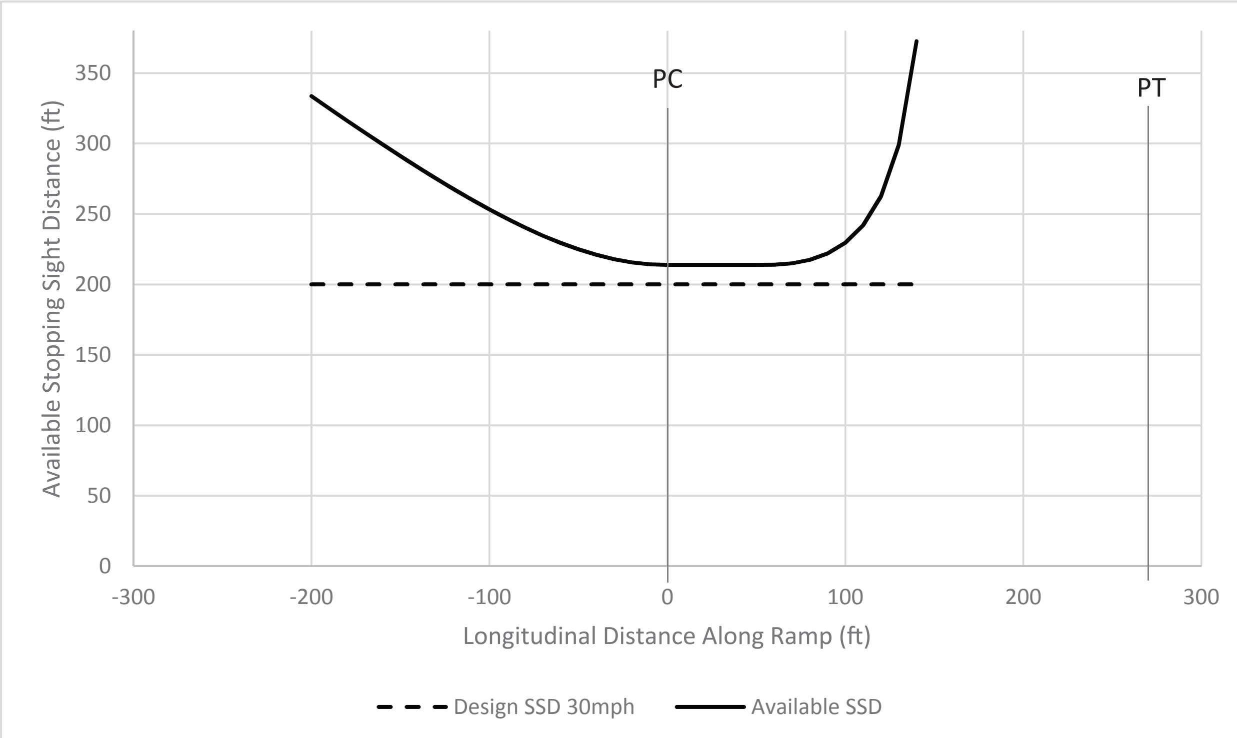

Figure C-11. Sight distance profile for the existing condition at the ramp site for Case Study 3

C.3.2 Traffic Operational Performance

The AADT of this exit ramp is 1,930 veh/day. The volume on this off-ramp is much lower than capacity. A stop sign is located at the ramp terminal 440 ft downstream of the horizontal curve. However, significant queueing does not occur at this ramp terminal, so spillback of traffic into the study curve is unlikely. The mainline freeway is an urban six-lane freeway carrying approximately 77,000 veh/day. The freeway segment adjacent to the ramp does not experience any capacity limitation likely to result in recurring congestion.

C.3.3 Safety Performance

No crashes of types potentially related to sight distance occurred during the five-year study period at this site.

C.3.4 Mitigation Challenges

If the barrier height cannot be lowered, increasing the ASSD on the ramp curve would need an increase in the lateral distance between the barrier and the edge of the traveled way. Any increase in the barrier offset would require either a sharper curve upstream, just downstream of the gore area or reconstruction of the opposing ramp on the other side of the median barrier. Such an improvement would have a relatively high cost. Since there is no history of sight-distance-related crashes at this site, there is no apparent need for an improvement that would make an upstream curve sharper or require the opposing ramp to be reconstructed.

C.3.5 Lessons Learned

There are several lessons that can be learned from Case Study 3. These include:

1. At ramp sites where stopping sight distance is sufficient for the advisory speed posted on a ramp, traffic on the ramp is likely to be traveling at speeds substantially above the advisory speed.
2. Improvement of sight distance on a ramp is likely to be impractical where the appropriate mitigation strategy would involve realignment of the ramp.
3. Even where the conditions for sight-distance-related collisions appear to exist, crashes will not necessarily occur. Drivers are often very effective at adapting to conditions they encounter in the field.

C.4 Case Study 4—Site KS025—Curve to the Right on a Rural Two-Lane Highway

The rural two-lane undivided highway on which Site KS025 is located connects a city of approximately 5,000 population with an Interstate highway. The study site is a horizontal curve with a radius of 1,400 ft and a length of 0.17 mi. The primary direction of travel studied is the northbound direction. A tall embankment covered with vegetation is located on the inside of the curve adjacent to the northbound lane and obstructs the view of northbound drivers. The sight obstruction has an offset of 14 ft from the inside edge of the traveled way. The obstruction begins approximately 0.09 mi upstream of the PC and ends approximately 0.08 mi downstream of the PC. A very low-volume roadway (likely carrying 100 veh/day or less) intersects the two-lane highway from the west on the curve near the end of the obstruction. The posted speed limit of the highway is 65 mph, however, the horizontal curve has an advisory speed of 50 mph. Observation of the site indicates that vehicles regularly travel at speeds greater than 50 mph on this curve. The two-way AADT of the two-lane highway is 3,540 veh/day.

Figure C-12 presents a photograph of the horizontal curve and the sight obstruction looking to the north. Figure C-13 shows a diagram of the curve showing the location of the sight obstruction.

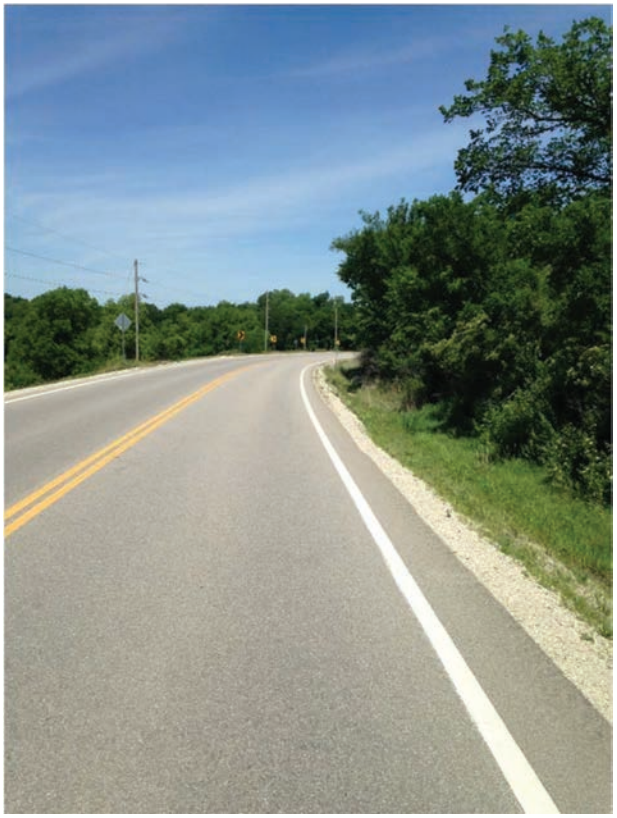

Figure C-12. Photograph of the rural two-lane highway curve for Case Study 4.

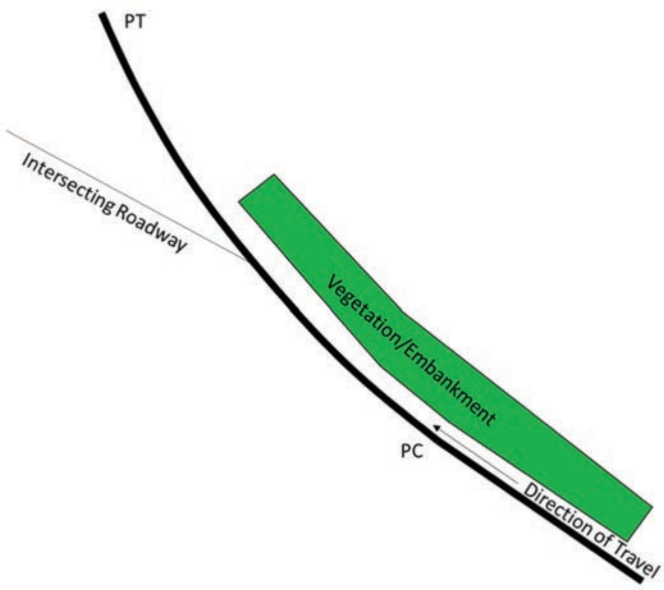

Figure C-13. Two-lane highway alignment showing the position of the horizontal sight obstructions.

C.4.1 Sight Distance Profile

The minimum ASSD for northbound drivers due to the obstruction is 474 ft. This available sight distance is greater than the DSSD of 425 ft for the advisory speed of 50 mph, but is substantially less than the DSSD of 645 ft for the posted speed limit of 65 mph.

Figure C-14 shows a sight distance profile for the horizontal curve site for traffic in the northbound direction. The figure shows that ASSD becomes less than the DSSD approximately 320 ft upstream from the PC and decreases to the minimum of 474 ft at the PC. The sight distance continues at its minimum value until 215 ft downstream of the PC. At this point ASSD rapidly increases.

The obstruction on the inside of the curve (adjacent to the northbound direction of travel) also obstructs the view of southbound vehicles slightly. Figure C-15 shows a sight distance profile for the southbound direction of travel. The minimum ASSD in the southbound direction of travel is 600 ft, which is below the DSSD of 645 ft.

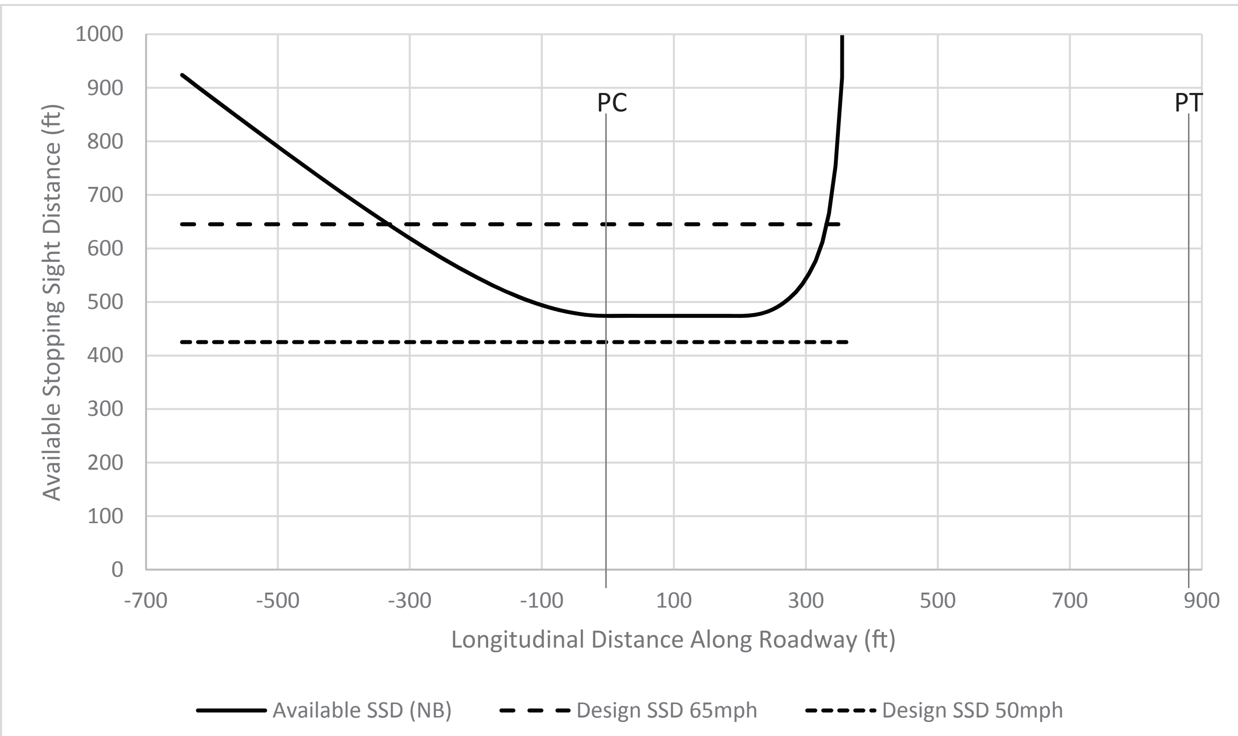

Figure C-14. Sight distance profile for the primary (northbound) direction of travel at the rural two-lane highway site for Case Study 4.

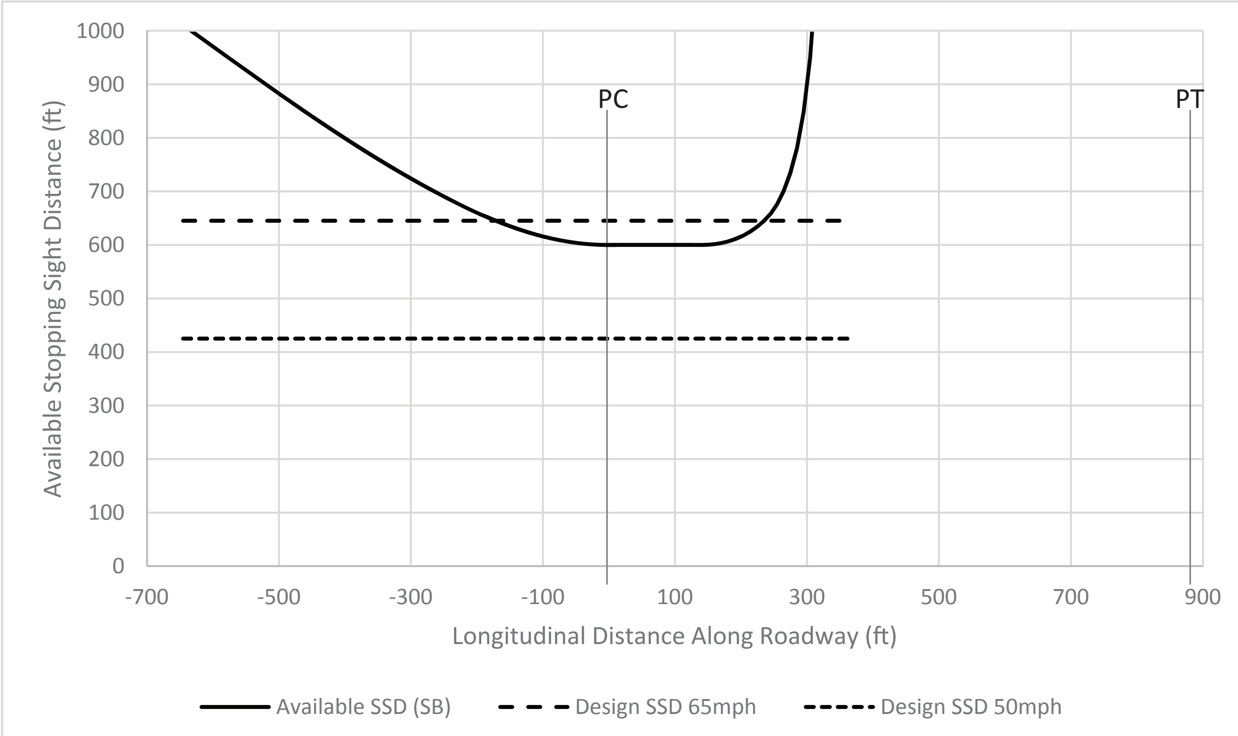

Figure C-15. Sight distance profile for the primary (eastbound) direction of travel at the rural two-lane highway site for Case Study 4

The reliability analysis model presented in Chapter 5 was applied to consider the effect of alternative sight distance measurement assumptions. If the driver's eye is positioned 3 ft from the left edge of the travel lane, the ASSD for the northbound direction increases to 508 ft. However, the ASSD for the opposing southbound direction decreases to 571 ft.

C.4.2 Traffic Operational Performance

The AADT of the rural two-lane highway is 3,540 veh/day. Roadway capacity is not an issue on this facility.

C.4.3 Safety Performance

During the 5-year study period, no crashes of types potentially related to sight distance occurred at this site.

C.4.4 Mitigation Challenges

The embankment is a hill that extends upwards away from the roadway. In order to push back the embankment, vegetation would need to be removed and a retaining wall would most likely need to be built. To achieve a minimum ASSD greater than the DSSD for the posted speed limit, the embankment would need to be pushed back 17 ft from its current position. This would involve a relatively high cost. Given that there is no history of sight-distance-related crashes at this location, there appears to be little need to implement any mitigation measures.

C.4.5 Lessons Learned

There are several lessons that can be learned from Case Study 4. These include:

1. A sight obstruction on the inside of the horizontal curve on a two-lane undivided highway may limit the ASSD in both directions of travel on some curves. The ASSD for traffic in the direction of travel on the outside of the curve is likely to be only slightly limited unless the curve radius is very small and/or the sight obstruction on the inside of the curve is quite small.
2. More realistic positioning for the driver's eye on a horizontal curve to the right on a two-lane undivided highway will increase the sight distance for that direction of travel. However, the opposite is true for the curve to the left in the opposing direction of travel, where the available sight distance may decrease if measured with more realistic positioning of the driver's eye.
3. Where there is no history of potentially sight-distance-related crashes, high-cost sight distance improvements are not likely to be needed.

C.5 Case Study 5—Site PA002—Curve to the Left on a Rural Mainline Freeway

Site PA002 consists of a curve to the left on a rural mainline freeway. The curve has a radius of 1,432 ft and is 0.33 mi in length. The roadway has two basic lanes in each direction of travel, with passing lanes on grades where needed. There is a passing lane in the westbound direction at this location. Thus, there are three travel lanes in the primary direction of travel on a 3 to 3.5 percent upgrade. The sight obstruction on the inside of the horizontal curve consists of a 4.5-ft tall continuous concrete median barrier located 4 ft from the inside edge of the traveled way. The posted speed limit on the roadway is 55 mph. The roadway carries a two-way AADT of 14,572 veh/day.

C.5.1 Sight Distance Profile

The minimum ASSD for the inside (left) lane on the horizontal curve is 339 ft, as determined with the Green Book sight distance measurement assumptions. The minimum ASSD is substantially less than the AASHTO DSSD of 495 ft for the mainline posted speed limit of 55 mph.

Figure C-16 shows the sight distance profile with the sight obstruction on the inside of the horizontal curve. The figure shows that only the inside (left) has an ASSD less than the DSSD. The ASSD in the left lane becomes less than the DSSD approximately 265 ft upstream of the PC. The ASSD reaches its minimum value of 339 ft at the PC. At a point approximately 330 ft upstream of the PT, ASSD starts to increase.

The minimum ASSD for the center lane is 505 ft, slightly higher than the DSSD of 495 ft. The minimum ASSD for the right lane is greater than 600 ft.

The reliability analysis model presented in Chapter 5 was applied to consider the effect of alternative sight distance measurement assumptions. If the driver's eye for a vehicle in the left lane is positioned 3 ft from the left edge of the lane, the ASSD for the inside lane decreases to 283 ft, which is 56 ft less than the ASSD of 339 ft measured along the centerline of the lane. Using the alternative driver's eye position, the ASSD for the center lane decreases to 469 ft, which is slightly lower than the DSSD. Thus, on a curve to the left these more realistic assumptions for the driver's eye position decrease the ASSD.

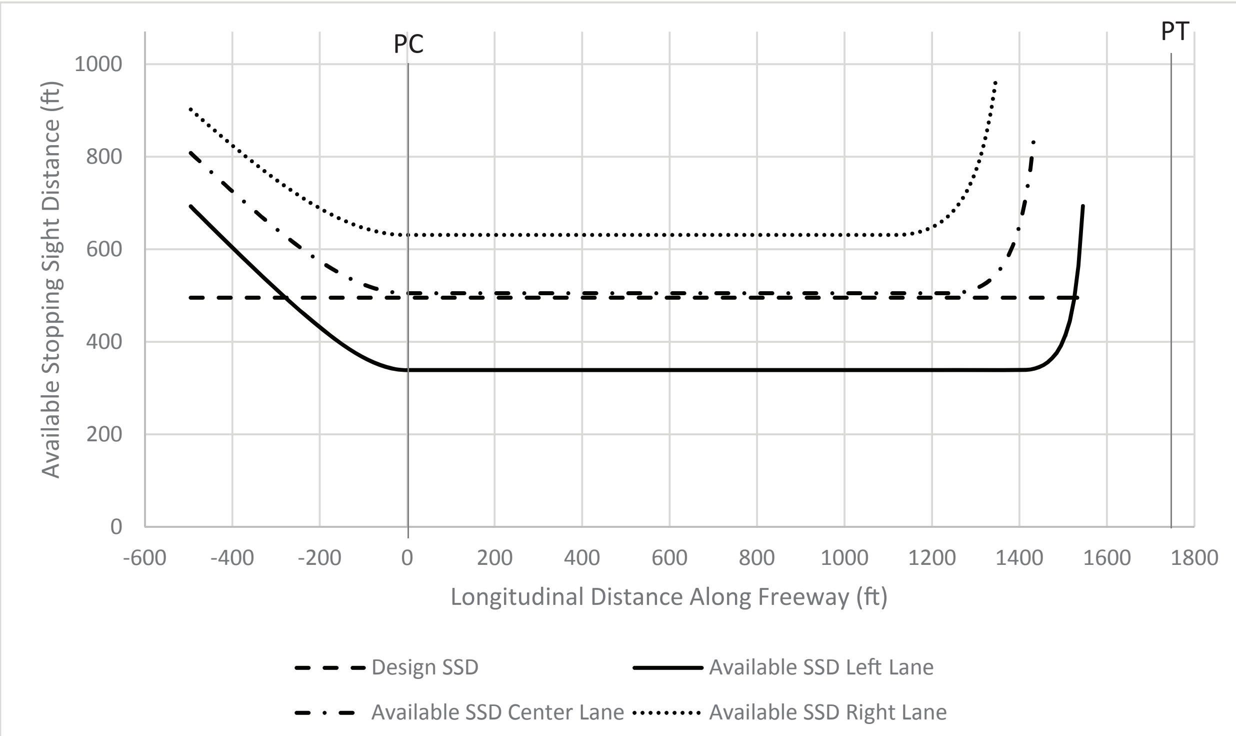

Figure C-16. Sight distance profile for rural multilane freeway curve in Case Study 5.

C.5.2 Traffic Operational Performance

The mainline freeway has an AADT of 14,572 veh/day. There is no recurrent daily congestion of this roadway.

C.5.3 Safety Performance

Two crashes of the types that are potentially related to sight distance occurred on the curve of interest during a 5-year period. Both were property-damage-only rear-end crashes. These crashes may or may not be related to limited sight distance, but there is clearly no definitive pattern of sight-distance-related crashes.

C.5.4 Mitigation Challenges

If the height of the median barrier cannot be decreased, mitigation of the limited sight distance at this location would involve widening the median and/or realigning the roadways. Given the lack of any consistent pattern of sight-distance related crashes, there appears to be little justification for such a high-cost improvement.

C.5.5 Lessons Learned

There are several lessons that can be learned from Case Study 5. These include:

1. The assumption of more realistic positioning for the driver's eye on a horizontal curve with a sight obstruction on the inside of the curve can reduce the minimum ASSD for the curve. In this case, the minimum ASSD for the left lane was reduced from a value below applicable DSSD to a lower value. The minimum ASSD for the right lane was reduced from above the applicable DSSD to below the applicable DSSD.
2. Even where ASSD is below DSSD on a high-speed highway, substantial patterns of sight-distance-related crashes do not necessarily occur. Sight-distance-related crashes occur only where the sight distance is limited and a stopped or slowing vehicle, or another unexpected object, is present in the sight-restricted area.

C.6 Case Study 6—Site WA082—Curve to the Left on an Urban Mainline Freeway

Site WA082 consists of a curve to the left on an urban mainline freeway. The curve has a radius of 1,975 ft and is 0.25 mi in length. The roadway has three travel lanes in both directions of travel. The sight obstruction on the inside of the horizontal curve consists of a 6-ft tall continuous concrete median barrier located 6 ft from the inside edge of the traveled way. The freeway has a posted speed limit of 60 mph and carries a two-way AADT of 143,684 veh/day.

Figure C-17 presents a photograph of the freeway showing the concrete median barrier that limits the driver's view of the roadway ahead.

Figure C-17. Photograph of the urban mainline freeway for Case Study 6

C.6.1 Sight Distance Profile

The minimum ASSD for this horizontal curve is 436 ft, compared to the DSSD of 570 ft for the posted speed limit of 60 mph. Figure C-18 shows the sight distance profile for the primary direction of travel with the sight obstruction on the inside of the horizontal curve. The figure shows that only the inside (left) lane has an ASSD less than the DSSD. The ASSD in the inside lane becomes less than the DSSD approximately 270 ft upstream of the PC. The ASSD reaches its minimum value at the PC. At a point approximately 400 ft upstream of the PT, ASSD in the inside lane starts to increase. The minimum ASSD for the center lane is 618 ft, slightly higher than the DSSD of 570 ft.

The reliability analysis model presented in Chapter 5 was applied to consider the effect of alternative sight distance measurement assumptions. If the driver's eye is positioned at a more realistic position 3 ft from the left edge of the inside travel lane and the object height to be seen in the roadway is 3.5 ft, the ASSD for the inside lane decreases to 377 ft, which is a substantial decrease of 59 ft. The ASSD for the center lane decreases to 578 ft, which is only 8 ft greater than the DSSD.

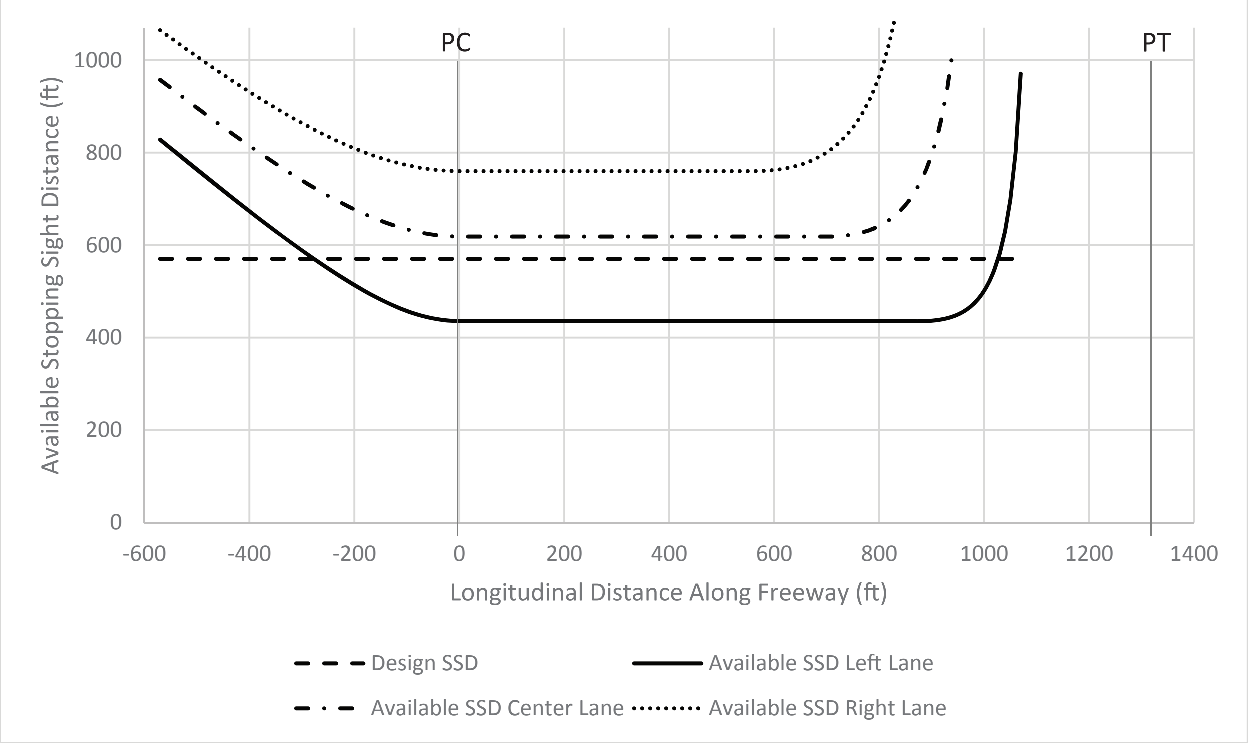

Figure C-18. Sight distance profile for northbound direction of travel at the urban six-lane freeway site for Case Study 6

C.6.2 Traffic Operational Performance

The two-way AADT of the freeway is 143,684 veh/day. There is recurrent congestion with slowing or stopped traffic during portions of each day. A substantial number of crashes at sites such as this one are likely to be related to the presence of congestion, rather than sight distance.

C.6.3 Safety Performance

The basic safety analysis for this site identified 10 crashes of types that are possibly related to sight distance during the 5-year study period, including six rear-end crashes, three sideswipe same-direction crashes, and one run-off-road crash. A more detailed review found that the run-off-road crash involved running off the outside (right side) of the road, which seems unlikely to be related to sight distance. Only four of the crashes were found to involve an impact in the inside travel lane. Furthermore, two of those four crashes occurred during peak-hour traffic conditions and could be explained by congestion rather than limited sight distance. The other two crashes that may be sight-distance-related included two rear-end injury crashes.

C.6.4 Mitigation Costs

If the height of the traffic barrier cannot be lowered, mitigation of the limited sight distance at this location would involve widening the median and/or realigning the roadways. Given the lack of any consistent pattern of sight-distance related crashes, there is little justification for such a high-cost improvement.

C.6.5 Lessons Learned

There are several lessons that can be learned from Case Study 6. These include:

1. At this site, as at many multilane sites with horizontal sight obstructions, only the inside lane experiences minimum ASSD less than DSSD.
2. The assumption of more realistic positioning for the driver's eye on a horizontal curve with a sight obstruction on the inside of the curve can reduce the minimum ASSD for the curve. In this case, the minimum ASSD for the left lane was reduced from a value below applicable DSSD to a lower value.

C.7 Case Study 7—Site WA091—Curve to the Right on an Urban Interchange Ramp

Site WA091 is a curve to the right on a directional ramp within a freeway-to-freeway interchange. The ramp allows traffic to make a right-turn movement from the southbound roadway on one freeway to the westbound roadway on another. The ramp has a radius of 1,200 ft and a length of 0.24 mi. The ramp has a signed advisory speed limit of 50 mph. The upstream mainline freeway has a posted speed limit of 60 mph. The ramp has two travel lanes and is located on a bridge structure. The ramp AADT is 40,000 veh/day.

The sight obstruction on this ramp is a continuous bridge rail on the right side of the structure. The bridge rail is 4 ft in height and is offset 10 ft from the inside edge of the traveled way.

C.7.1 Sight Distance Profile

The minimum ASSD available on this horizontal curve is 392 ft in the inside lane, compared to the DSSD of 425 ft for the advisory speed limit of 50 mph and 570 ft for the mainline freeway speed limit of 60 mph. Figure C-19 shows the sight distance profile with the sight obstruction on the inside of the horizontal curve. The figure shows that only the inside (right) lane has a minimum ASSD less than the DSSD. The ASSD becomes less than the DSSD approximately 115 ft upstream of the PC. The ASSD reaches its minimum value at the PC. At a point approximately 370 ft upstream of the PT, ASSD starts to increase. The minimum ASSD for the left lane is 522 ft, substantially higher than the DSSD of 425 ft.

The reliability analysis model presented in Chapter 5 was applied to consider the effect of alternative sight distance measurement assumptions. If the driver's eye is assumed to be positioned at a more realistic 3 ft from the left edge of the inside lane and the object height to be seen in the roadway is 3.5 ft, the ASSD for the inside lane increases to 428 ft, which is 3 ft greater than the applicable AASHTO value of DSSD, but still less than the applicable DSSD for the mainline freeway speed limit of 60 mph.

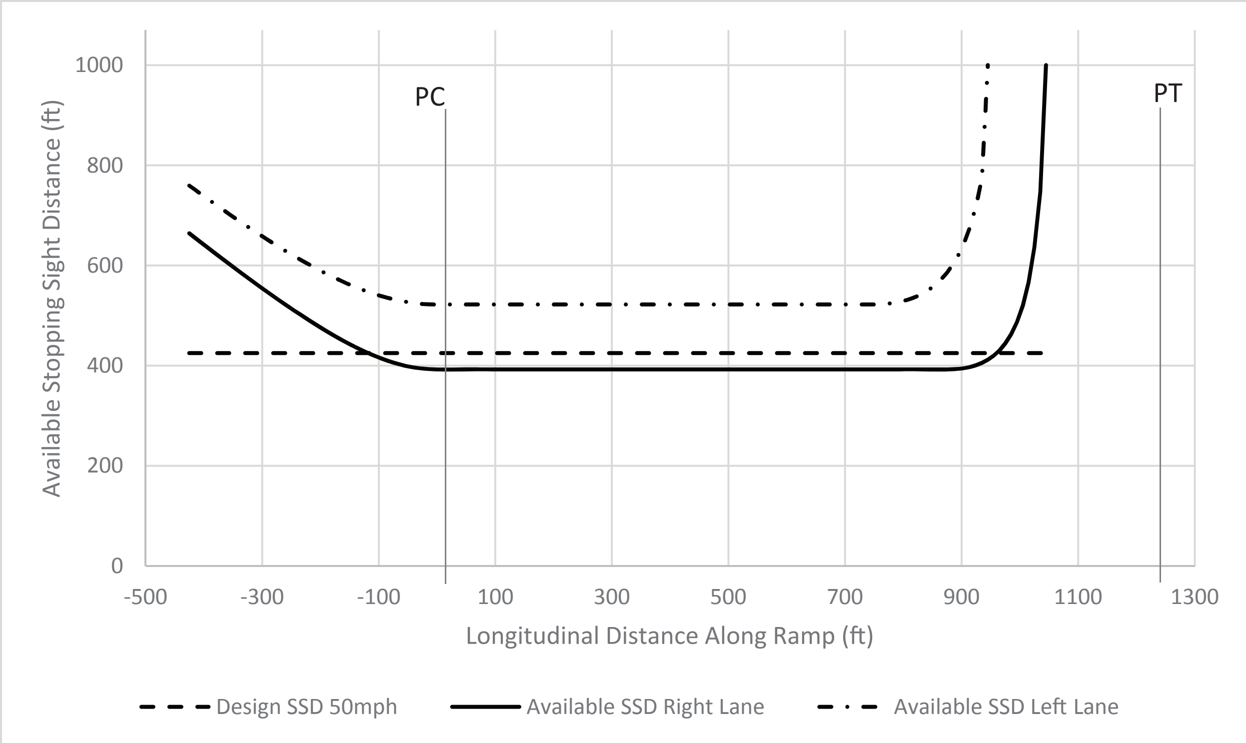

Figure C-19. Sight distance profile for the urban two-lane ramp site for Case Study 7.

C.7.2 Traffic Operational Performance

The mainline freeway upstream of the ramp has an AADT of 164,000 veh/day. This freeway experiences recurring daily congestion during some hours of the day. The ramp has an AADT of 40,000 veh/day. The ramp is unlikely to experience recurrent daily congestion generated by its own traffic volume. The freeway which the ramp traffic enters downstream of the ramp has an

AADT of 133,000 veh/day. Congestion on this downstream freeway could create spillback congestion onto the ramp of interest.

C.7.3 Safety Performance

This ramp curve experienced no crashes of crash types potentially related to limited sight distance during the 5-year study period.

C.7.4 Mitigation Challenges

On this ramp, traffic ahead generally appears visible to drivers in the inside (right) lane, because the vehicles are generally higher than 3.5 ft. This observation, and the lack of any history of crash types potentially related to sight distance, does not suggest any need for high-cost mitigation strategies such as realigning the ramp.

C.7.5 Lessons Learned

There are several lessons that can be learned from Case Study 7. These include:

1. Where the upper portion of vehicles can be seen over a barrier on the inside of a horizontal curve, the sight distance on the curve may be effectively adequate, even where sight distance measures using AASHTO criteria appear limited.
2. On a curve to the right, a more realistic assumed lateral position for the driver's eye will increase the estimated ASSD.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

TRANSPORTATION RESEARCH BOARD
500 Fifth Street, NW
Washington, DC 20001

ADDRESS SERVICE REQUESTED

NON-PROFIT ORG.
U.S. POSTAGE
PAID
COLUMBIA, MD
PERMIT NO. 88

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

The nation turns to the National Academies of Sciences, Engineering, and Medicine for independent, objective advice on issues that affect people's lives worldwide.
www.national-academies.org

ISBN 978-0-309-48054-3