MODELLING OF THREE-DIMENSIONAL INTERSECTION SIGHT DISTANCE

By

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BORROWER'S PAGE

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ABSTRACT

Intersection sight distance (ISD) is an important design element. Each intersection has a potential for several different types of vehicular conflicts that can be greatly reduced through the provision of proper sight distance. Current guidelines do not adequately address sight distance requirements for intersections located on horizontal curves alone or horizontal curves combined with vertical alignments. In many practical situations, however, sight distance is required to be checked for an existing or proposed three-dimensional (3D) intersection alignments. In this thesis, models were developed to check sight distance adequacy under complex situations. Case B and Case F in AASHTO (2001) were considered on 3D alignment: (1) Departure from stop-control minor-road and (2) Left-turns from major-road. For stop-control intersections, several cases were addressed. These include Case 1(a): Intersection and approaching vehicle (object) lie on the curve, Case 1(b): Intersection lies on the curve and object lies on the tangent, and Case 2: Intersection lies on the tangent and object lies on the curve. For both cases (1) and (2), obstruction may lie inside or outside the horizontal curve and the intersection and object can be anywhere with respect to the vertical alignment. Design aids for required minimum lateral clearance (from the minor and major roads) are presented for different radii of horizontal curve and major-road design speed. For left-turns at signalized intersections located on horizontal curves, guidelines are presented for offsetting opposing left-turn lanes to provide unobstructed required sight distance. Applications of the methodologies are illustrated using numerical examples.

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DEDICATION

"If you have knowledge, let others light their candles with it. "

-Sir Winston Churchill-

This thesis is dedicated to my parents, and my grandma who taught me wisdom and to all those who have the desire to seek knowledge.

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Chapter 1: INTRODUCTION

1.1. INTERSECTIONS

An intersection is defined as the general area where two or more highways join or cross; including the roadway and roadside facilities for traffic movement within the area. Intersection design has a large impact on facility capacity and safety. Basic types of intersections include three-leg, T, four-leg and multi-leg intersections. An intersection is known as rural, suburban, or urban depending upon the setting in which it is located. The efficiency of the road network very much depends on the quality of operation and design of the intersections.

1.1.1. Types of Intersections

Selection and design of the traffic control on intersection are traffic operations considerations. The details of these warrants can be found in the Manual on Uniform Traffic Control Devices (MUTCD). The American Association of State Highway and Transportation Officials (AASHTO) recommends that geometric design should not be considered complete nor should it be implemented until it has been determined that needed traffic devices will have the desired effect in controlling traffic. Intersections according to different types of traffic control are categorized as:

- Uncontrolled intersections: No signs or signals are provided. Warning signs are sometimes used. On four-leg intersections, usually traffic from the right has priority. For traffic from the same or opposite direction, straight going traffic has a priority over turning traffic.
- Yield-controlled intersections: Traffic on intersection approach controlled by yield sign need to stop only when necessary to avoid conflict with other traffic that is given the right-of-way.
- Stop-controlled intersections: An intersection may be two-way or all-way stop controlled. All vehicles approaching the stop sign must come to a complete stop. Vehicles must stop at the stop line if it is marked on the pavement. If

there is no stop line, they should stop at the crosswalk, marked or not. If there is no crosswalk, they must stop at the edge of sidewalk. If there is no sidewalk, they must stop at the edge of the intersection. Vehicles should wait until the way is clear before entering the intersection.

- Signal-controlled intersections: Traffic signals, usually computerized, assign time for each type of movement within the intersection.
- Modern roundabouts: Modern roundabouts are similar to rotary in which the traffic streams are directed around the circle. However, unlike rotaries, modern roundabouts have yield-at-entry, which means that vehicles on the circulatory roadway of the roundabout have the right-of-way to the entering traffic.

1.1.2. Intersection Design

One of the main objectives of intersection design is to aid the people crossing the facility in a comfortable and safe manner while enhancing the efficient movement of vehicles and pedestrians. The basic elements considered in intersection design as recognized by AASHTO (2001) and the Transportation Association of Canada (TAC 1999) include:

- Human Factors
- Traffic Factors/Considerations
- Physical Elements
- Economic Factors
- Functional Intersection Area

Human factors include driving habits, driver's expectation, perception of intersection from driver's perspective, etc. Traffic factors include turning movements, vehicle types, vehicle speeds, etc. Physical Elements include angle of intersection, geometric design features, vertical and horizontal curvature at the intersection, etc. Economic factors include land and construction costs, maintenance costs, etc.

1.2. INTERSECTION SIGHT DISTANCE

Intersection sight distance (ISD) is one of the most important design elements in highway geometric design. Adequate intersection sight distance is provided at intersections between a minor-road and a major-road to promote safe and efficient traffic operations. As described in the previous sections, each intersection has the potential for several different types of vehicular conflicts. The provision of proper sight distance in addition to proper traffic controls greatly reduces the likelihood of vehicular conflicts by allowing the drivers to perceive the presence of potentially conflicting vehicles. It is recommended that the drivers of stopped vehicles should have sufficient view of the intersecting highway to decide when to enter the intersecting highway or to cross it. AASHTO (2001) and TAC (1999) recommend that the sight distance requirement for vehicles approaching the intersection and departing from the stopped position should be considered.

1.2.1. Sight Triangles

The line from the driver's eye of the stopped vehicle on the minor-road, to the front of the approaching vehicle on the major-road, joined by the extension of the vehicles' paths up to their point of conflict, makes a triangle. The area within this triangle should be free of any obstruction that might block the driver's view of potentially conflicting vehicles. Two types of sight triangles are considered in intersection design:

- Approach Triangles: These are provided at uncontrolled or yield control intersections so that the approaching drivers have the view of any conflicting vehicles in sufficient time to slow or stop before colliding within the intersection. If the approach sight triangle cannot be provided, stop-control is often instituted for the minor highway.
- Departure Triangles: Although approach triangles are desirable at higher volume intersections, they are not needed for intersection approaches with stop signs or traffic signals. These approaches need a second type of clear

triangle called departure triangles. These triangles provide sufficient sight distance for a stopped driver on the minor-road to depart turning left, right or cross the major-road. Approach and departure sight triangles are shown in Figure 1.1.

Sight distance requirements vary with the type of traffic control used at intersections. Discussion of the detailed procedures for sight distance determination for all cases is beyond the scope of this thesis. A description of relevant cases is discussed in the following sections.

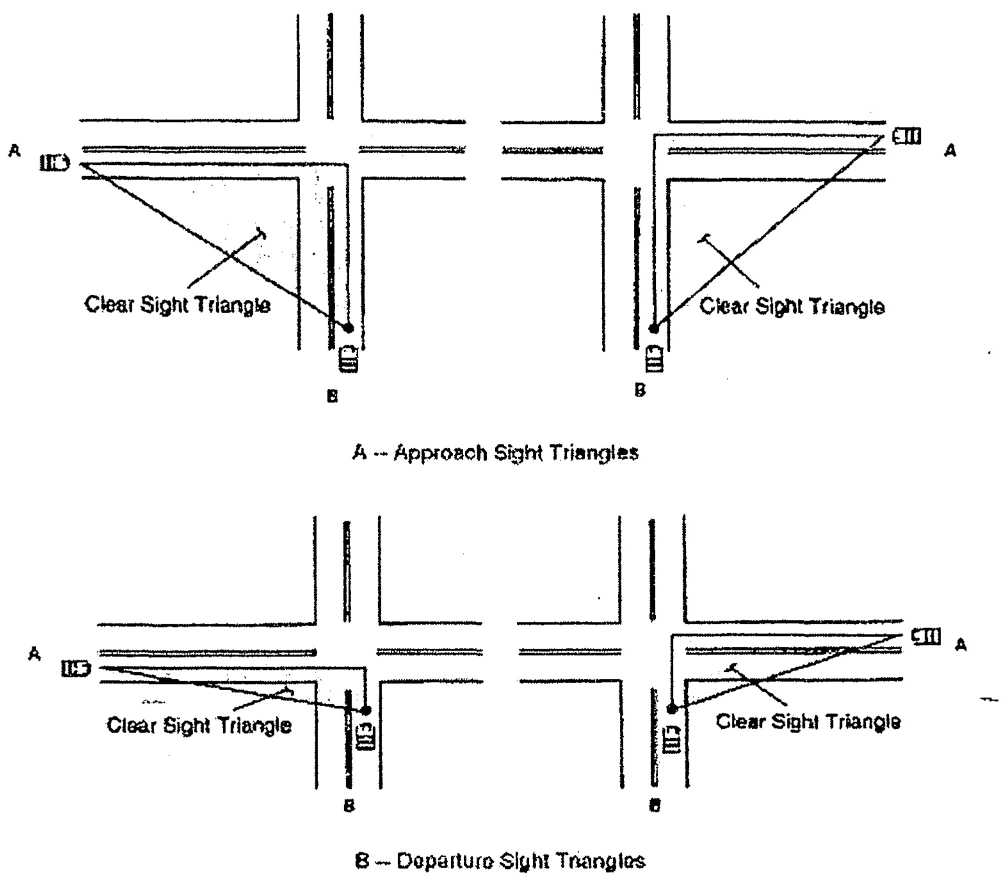


Figure 1.1 Intersection Sight Triangles [Source: AASHTO 2001]

1.2.2. ISD for Stop-Control Intersections

The idea of a stop-control intersection is that the minor-road vehicle driver waits until he/she can depart from the stopped position into the intersection and complete the intended maneuver without forcing a major-road vehicle to stop. For intersections with stop control on the minor-road, departure sight triangles should be considered for the following maneuvers:

- Left-turns from the minor-road
- Right-turns from the minor-road
- Crossing across the major-road

It should be noted that ISD for stop-control intersections is longer than stopping sight distance (SSD) (AASHTO 2001). Discussion of stop-control ISD is presented as Case B in AASHTO (2001).

1.2.3. ISD for Left-turns at Signalized Intersections

Left-turning vehicles need sufficient sight distance to decide when it is safe to turn left crossing the lane(s) used by the opposing traffic. AASHTO (2001) recommended that all locations on a major highway, including intersections from which left turns across opposing traffic are permitted, should have sufficient sight distance to accommodate safe left-turn maneuver. Sight distance should be based on vehicle stopped for making left turns as the vehicle that does not stop would require less sight distance.

AASHTO (2001) recognizes that at four-leg intersections on divided highways, opposing left-turning vehicles may block each other's view of oncoming traffic and suggests that the visibility of the opposing through traffic can be increased by offsetting the left-turn lanes. Other advantages of offsetting left-turn lanes include: decreased possibility of conflict between opposing left-turn movements within the intersections and efficient operation of left-turning traffic, particularly at signalized intersections. Parallel and tapered offsets are recommended for medians wider than 5.4 m. These are shown in Fig. 1.2. Detailed discussion of ISD for left-turns at intersections is presented as Case F in AASHTO (2001).

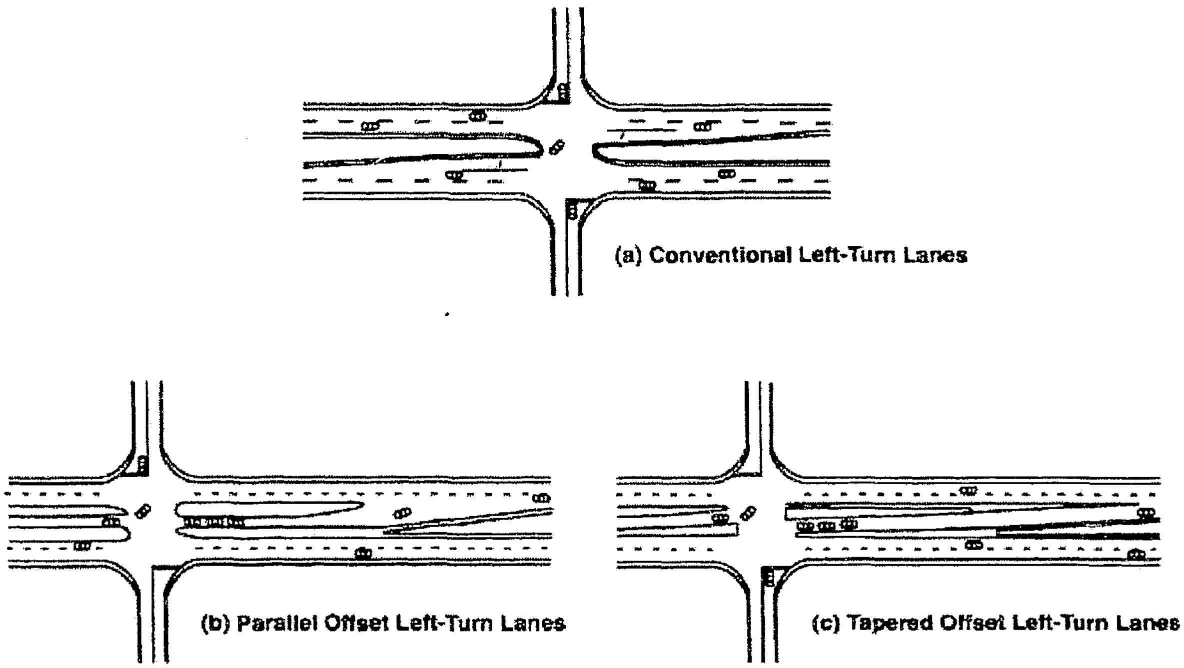


Figure 1.2 Parallel and Tapered Offset Left-turn Lanes [Source: AASHTO 2001]

1.3. SCOPE AND OBJECTIVES OF RESEARCH

1.3.1. Scope

The focus of this thesis is on the modeling of Case B and F of AASHTO (2001) assuming three-dimensional alignments. The AASHTO model for stop-control intersections (Case B) is based on two assumptions: (1) both minor and major roads are straight highways without any vertical or horizontal curvature; and (2) the highways intersect at 90-degree. Previous research has developed guidelines for the analysis of stop-control ISD on 3D intersections, where the major-road may have vertical and horizontal curves and the minor-road may have a longitudinal grade and skewed angle (Easa et al. 2004). These guidelines are based on the assumption that the intersection and the major-road vehicle lie within the horizontal and/or vertical curve. Also, the mathematical model is applicable only to the case when the obstruction is on the inside of the curve. There are situations, however, when the intersection lies on the major-road curve but very close to the tangent, or, when the intersection lies on the tangent but very close to the curve. In such cases, the approaching vehicle may not be within the curve and/or tangent, and the existing guidelines may be very conservative.

For Case F, AASHTO although recognizes the reduction of sight distance at opposing left-turn lanes and suggests the use of parallel or tapered offsets as a mean to reduce or overcome this problem, it does not provide any specific guidelines as to what offsets are required. Other research (McCoy et al. 1992) developed guidelines for offsetting opposing left-turn lanes at 90-degree intersections on level, tangent sections of four-lane divided roadways with 4.8 m medians. The application of these guidelines is limited to straight highways.

1.3.2. Objectives

The objectives of this thesis are as follows:

1. To develop three dimensional intersection sight distance model for stop-control intersections that addresses the following cases:
   (a) Intersection and approaching vehicle (object) lie on the curve, obstruction on the inside or outside of the horizontal curve.
   (b) Intersection lies on the curve and object lies on the tangent, obstruction on the inside or outside of the horizontal curve.
   (c) Intersection lies on the tangent and object lies on the curve, obstruction on the inside or outside of the horizontal curve.
   (d) Intersection and object can be anywhere on the curve or tangent on the vertical alignment
2. To develop three dimensional intersection sight distance model for Left-turns from major-road at signalized intersections that addresses the following cases:
   (a) Major-road has a horizontal curve

(b) Left-turn vehicle and approaching through vehicle (object) can be anywhere on the curve or tangent on the vertical alignment

1.4. THESIS ORGANIZATION

The thesis is presented in five chapters. Chapter 1 provided an introduction of the related terminologies, scope and object of research. A brief description of the following chapters is given below:

Chapter 2: This chapter contains a detailed literature review of horizontal and vertical alignments, and intersections on three-dimensional alignment. This chapter also discusses the current guidelines on the issue at hand and their limitations.

Chapter 3: This chapter describes the criteria used in the selection of all variables, model development, evaluation procedure and guidelines for the analysis of departure sight distance at 3D stop-control intersections.

Chapter 4: This chapter describes the criteria used in the selection of all variables, model development, evaluation procedure and guidelines for the analysis of left-turn sight distance at 3D signalized intersections.

Chapter 5: This chapter includes a practical application for stop-control intersections, in addition to a hypothetical example for stop-control intersections, and a hypothetical example for left-turns at signalized intersections.

Chapter 6: This chapter includes the summary and major findings of the research followed by some recommendations.

The flowchart in Figure 1.3 provides an overview of the thesis organization.

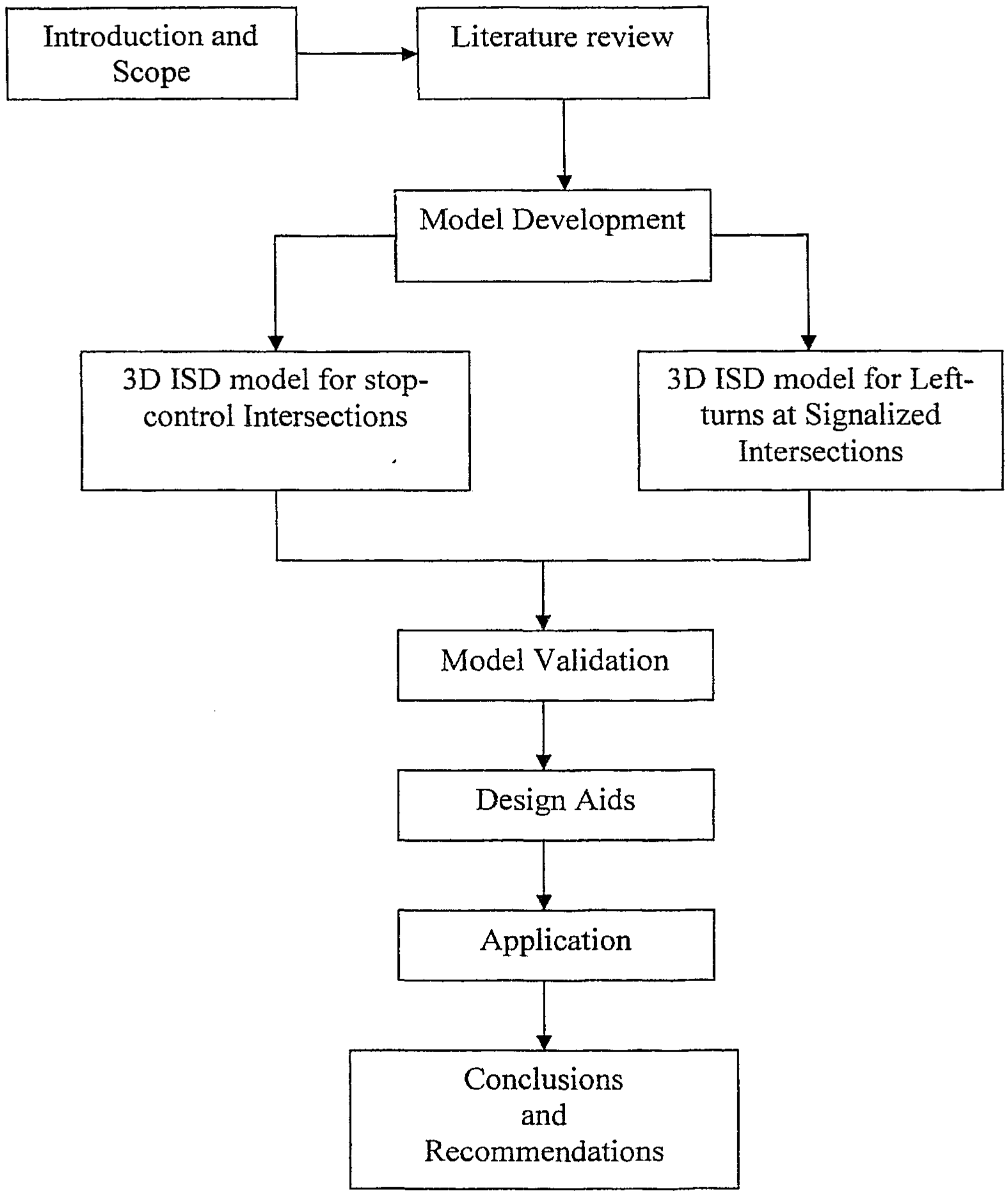


Figure 1.3 Thesis Overview

Chapter 2: LITERATURE REVIEW

2.1. HIGHWAY ALIGNMENT

All highways cannot be built straight. Aligning or realigning the highway is required due to different constraints such as buildings, parks, historic sites, etc. A highway usually consists of series of straight lines interconnected by curves that are used to change the direction and/or slope of the highway. Highway alignment is categorized as horizontal alignment and vertical alignment. The following sections will describe each of these alignments.

2.1.1. Horizontal Alignment

The horizontal alignment of a highway represents the projection of facility on a horizontal plane. Generally, it consists of straights commonly known as tangents and horizontal curves. The curves are used to change the direction of the road. The curves are connected to the tangents either directly or via intermediary curves called spirals or transition. The most commonly used horizontal curves in practically all modem highways are simple circular curves. The curve becomes sharper as its radius decreases and vice versa. For modern, high-speed highways, it is always preferable to use flat curves, rather than sharp. Design guidelines such as AASHTO (2001) and TAC (1999) provide recommendation on the minimum radii that should be used.

2.1.2. Vertical Alignment

The vertical alignment of a highway is the profile view shown in the vertical plane. Highway vertical alignment is comprised of tangent grades and vertical curves which are parabolic curves. The length of a vertical curve is measure along the horizontal alignment, and any point on the curve is specified by its station location and its elevation from the datum. The beginning and end of a vertical curve are denoted by PVC (point of vertical curvature) and PVT (point of vertical tangency), respectively.

There are two basic considerations for the design of a vertical curve involving (1) Smooth passage from one grade to another, and (2) safe sight distance over the full length of the curve. The design policies with respect to vertical curves are based on the need to provide drivers with adequate stopping sight distance. AASHTO (2001) recommends that the available sight distance on a roadway should be sufficiently long to enable a vehicle traveling at or near the design speed, to stop before reaching a stationary object in its path.

The parameters that determine sight distance on crest vertical curves include the change of grade, the length of the curve, the height of driver's eye above the ground, and the height of the obstacle to be seen. Stopping sight distance is the sum of two distances: (1) the distance traversed by the vehicle from the instant the driver sights an object necessitating a stop to the instant the brakes are applied; and (2) the distance needed to stop the vehicle from the instant brake application begins. These distances are referred as brake reaction distance and braking distance respectively (AASHTO 2001). Current practice assumes a driver's eye height of 1.08m and object height of 0.6 m.

2.1.3. Highway Alignment and Sight Distance

Highway alignment effects driving performance. Researchers have related highway alignments with driving performance for over half a century. Some studies focused on straights, horizontal and vertical curves individually, while others considered the overall alignment of highway sections. Horizontal alignment studies have focused on circular and spiral transition curve elements. Studies involving vertical curves focused on grades and optimum sight distance characteristics, while the studies involving horizontal alignment focused on sight distance and speeds related to the entire length of the geometric features of the highway.

Sight distance is the length of the highway visible to a driver. It is one of the most important and basic design elements in a highway network. Adequate sight distance allows drivers the time they need to slow down, stop, turn or cross safely, without any conflicts. Guidelines such as AASHTO (2001) and TAC (1999) provide guidelines for the required sight distance that are directly applicable to most common cases. As this thesis focuses on Case B and F of AASHTO, required sight distance for only these cases will be discussed.

2.1.3.1. Required Sight Distance for stop-control intersections

The required sight distance values can be computed using the model developed in the National Cooperative Highway Research Program (NCHRP) report 383 and presented in AASHTO (2001). It is given:

$$d = 0.278 \times V_{major} \times t_g \qquad 2.1$$

where d = required sight distance for a vehicle approaching from left or from right (m), V_{major} = design speed on major-road (km/h), t_g = the time gap required for the stopped vehicle on minor-road to maneuver (sec).

For a stop-control intersection, the leg of the sight triangle along the major-road (Figure 1.1) should be equal to the distance traveled at the design speed of the major-road during the time shown in Table 2.1. The values of time gap should be adjusted for multilane highways and minor-road approach grades. For more details, see AASHTO (2001)

Table 2.1 Recommended travel time for Determining Sight Distance for Left and Right-turns onto the Major-Road at Stop-control Intersections [Source: AASHTO (2001)]

Design Vehicle	Time Gap t_g (s)
Passenger car	7.5
Single-unit truck	9.5
Combination truck	11.5

Table 2.2 Recommended travel time for Determining Sight Distance for Left-turns from Major-Road [Source: AASHTO 2001]

Design Vehicle	Time Gap t_g (s)
Passenger car	5.5
Single-unit truck	6.5
Combination truck	7.5

Note: For left turning vehicles that cross more than one opposing lane, add 0.5 sec for passenger cars or 0.75 for trucks for each additional lane to be crossed.

2.1.3.2. Required Sight Distance for Left-turns at Signalized Intersections

The required sight distance along the major-road to accommodate left-turns is the distance traversed at the design speed of the major-road in the travel time for the design vehicle. This distance is also calculated using Equation (2.1). The time gaps used for this case are shown in Table 2.2.

2.2. ISD AND CURRENT RESEARCH

2.2.1 Stop-control Intersections

Four-leg intersections are the most commonly used intersections in North America (AASHTO 2001). They are where two highways intersect at-grade on right (or skew) angle. Many safety issues may arise with the use of four-leg intersections with the fact that they have the highest number of conflict points, which could be as many as 32 conflict points (HCM 2000). Provision of adequate sight distance allows drivers to perceive the presence of potentially conflicting vehicles and adjust accordingly.

Intersection sight distance was initially introduced as a function of vehicle speed and perception reaction time (AASHTO 1984). The primary changes in intersection sight distance arose from the change in vehicle acceleration characteristics. The current AASHTO policy uses gap-based method, which assumes that the gap acceptance time does not vary with approach speed on the major-road. Larger values of the time gap to accommodate older drivers have been recommended by Staplin et al. (2001).

Several authors have addressed extensions to the AASHTO method by considering the effect of different variables on ISD, including vehicle type (Fitzpatrick et al. 1990), driver's eye and vehicle heights (Fitzpatrick et al. 1998), and intersection skew angle (Gattis and Low 1998). Easa (1998) modified Case 1 of the AASHTO (1994) model for calculating ISD without control to incorporate the design speeds of both intersecting roads. The author demonstrated that there are conditions when using deceleration rates rather than stopping distances can result in sight distances that are less than desired and suggested that the difference is greater when the difference between the design speeds of the intersecting roads is larger.

Easa (1994, 2000) introduced reliability analysis of sight distance for stop-control intersections and railway-grade crossings considering the moments (mean and variance) of the probability distribution of each random variable. The author noted that the advantage of the reliability method is that it provides the reliability associated with ISD design and hence different highway classes could be designed based on different levels of reliability, for example higher-class facilities should have larger reliability and vice versa for the lower-class facilities .

Analytical geometry was also used to determine ISD for a horizontally curved roadway with tangential intersection (Gattis 1992). Evaluation of the sight distance adequacy with single or multiple obstacles on open highway with horizontal and vertical curves has been addressed (Easa et al. 1991-1998). A comprehensive review of recent geometric design research, including ISD, can be found in NCHRP Synthesis 299 (Fitzpatrick and Wooldridge 2001).

The required sight distance d is taken as a function of the time gap t_g required for the stopped vehicle on the minor-road to turn left, turn right or pass through the major-road. In most cases, the most critical maneuver is left turn. However, there are some situations where it is advised to check the availability of sight distance for crossing maneuvers (AASHTO 2001). The time gap method is based on the recommendations by Harwood et al (1996).

The underlying principle for gap-acceptance concept is that if left-turn drivers will accept a specific critical gap in the major-road traffic stream, and such maneuvers are routinely completed safely, then sufficient intersection sight distance should be provided to enable drivers to identify that critical gap. The details of this work are documented in NCHRP Report 383. Field studies were conducted at 25 intersections located in 4 states. Authors noted that AASHTO (1994) ISD models appear to have too much emphasis on the ISD criteria for the crossing maneuver. They suggested that since the ISD values for left and right turns exceed those for the crossing maneuvers, any intersection that is designed to accommodate such maneuvers should have adequate sight distance for the crossing maneuver.

Current AASHTO policy assumes that both minor and major roads are straight without any vertical or horizontal curvature. Horizontal curvature on the approaches to an intersection makes it difficult for drivers to determine suitable travel paths because their visual focus is directed along lines tangential to the curved paths. It was found that collision rates increased by 35 percent for highway segments with curved intersections compared with those with straight intersections (Kihlberg and Tharp 1968). AASHTO (2001) also recommended that intersections should not be located on a sharp horizontal curve. However, in many practical situations, sight distance adequacy is to be checked for an existing or proposed three-dimensional (3D) intersection alignment, where vertical curves and horizontal curves overlap.

Intersection Diagnostic Review Module (IDRM) is an expert system for diagnostic review of at-grade intersections on rural two-lane highways. It serves as a component of Interactive Highway Safety Design Model (IHSDM). The development of this expert system is sponsored by Federal Highway

Administration (FHWA) IDRM provides diagnosis and recommendations for proposed designs by highlighting the discrepancies it may have. It gives advisories to user, shows the concern and its reason, and suggests treatments which include design improvements and mitigation measures. Another important component of the IHSDM is a Policy Review Module (PRM). PRM review a proposed design for a roadway or intersection and flag any geometric design element that does not comply with the established design policy in an automated fashion. The authors recommend that the concerns identified by and treatments suggested by IDRM should be investigated by the user, but the final decision should be made on the basis of engineering judgment and evidence available to the user.

A model for SSD on horizontal curves is applied in IDRM wherever the driver's view of an intersection or potentially conflicting vehicle is limited by an obstruction on the inside of a horizontal curve. A similar SSD model is applied when the sight restriction is the crest of a vertical curve. In some situations a more conservative model based on ISD is used. The difference between the ISD model, as it is applied in geometric design practices, and the ISD model, as it is applied in IDRM, is that the IDRM uses the 85th percentile speed, or the best estimate of actual speed, rather than a particular design speed. IDRM also recommends an increased value of time gap (not finalized for all scenarios yet) for certain special situations where complex geometrics place greater demand on drivers; for example at skewed intersections, or intersections on horizontal curves. The limitation of ISD due to horizontal alignment and due to roadside obstruction is determined by asking the user whether particular sight triangles displayed by IDRM are clear of sight obstructions.

To eliminate the need for the graphical procedure and check sight distance adequacy on existing or proposed intersections on 3D alignments, previous research (Easa et al. 2004), has developed guidelines for the analysis of stop-control ISD on 3D intersections, where the major road may have vertical and horizontal curves and the minor-road to have a longitudinal grade and skewed angle. The authors presented a new analytical model for ISD on three–dimensional (3D) alignments, where the major-road has both horizontal and vertical geometry, and the minor-road has a grade. The intersection could also be skewed. These guidelines, however, are applicable only when the intersection and the major-road vehicle lie on the curve. Also, the obstruction was assumed to be on the inside of the curve.

2.2.2 Left-turns at Signalized Intersections

The required ISD for left-turn vehicles from the major-road is the distance traveled by an approaching vehicle at the design speed of the major-road for the time gap. Harwood et al. 1996 recognized the importance of sight distance requirement for left-turns from major-road and recommended that sight distance policy for this case should be presented in AASHTO as a separate case. The details of this work are presented in NCHRP report 383. This work was accepted and is included in AASHTO (2001).

AASHTO (2001) recommends that all locations on a major-road, including intersections from which the left-turn maneuver across opposing traffic is permitted, should have sufficient sight distance to enable safe operation. However, no specific guidelines for the required offsets are provided. Continuous provision of stopping sight distance (SSD) along the major-road and provision of sight distance for Case B (stop control) for each minor-road generally eliminates the need for a separate check for sight distance requirement for left-turn vehicles from the major-road. However, it is advisable to check the adequacy of sight distance for left-turn vehicles because the opposing left-turn vehicles can block a driver's view of oncoming traffic. Current AASHTO policy suggests the use of parallel and tapered offsets to overcome this problem.

It is evident from previous studies that left-turning vehicles at 4-leg intersections often block the sight line for the drivers of opposing left-turn vehicles (Joshua and Saka 1992, McCoy et al. 1992). Guidelines have been established for offsetting opposing left-turn lanes on divided straight roadways (McCoy et al. 1992). The offset was defined as the distance from the left-edge of a left-turn lane to the right-edge of the opposite left-turn lane. When the distance from the left edge to the right edge is zero, the offset equals zero. Where the opposite left-turn lane is shifted to the left (i.e. the right edge of the opposite left-turn lane lies to the left of the left edge of the given left-turn lane), the offset is negative. When the opposite left-turn lane is shifted to the right, the offset is positive. Negative and positive offsets are illustrated in Figure 2.1.

The authors noted that the guidelines should not be used for situation outside the scope, such as at skewed intersection or intersections on horizontal curves. Further guidelines have been also developed using different vehicle positioning (McCoy et al. 1997). These guidelines were based on left-turning vehicle positioning and maneuver-time data collected at intersections with left-turn lane offsets ranging from (-4.3 to 1.8 m). Many studies showed that the available sight distance could be increased without the need to reconstruct the left-turn lanes (McCoy et al. 1999, McCoy and Geza 1999, McCoy et al. 2001). A relationship between the left-turn lane-line and available sight distance was developed and guidelines for designing the left-turn lane-lines to provide the required sight distance for the opposing left-turn vehicles were established. The guidelines were established by equating the available sight distance with the required sight distance.

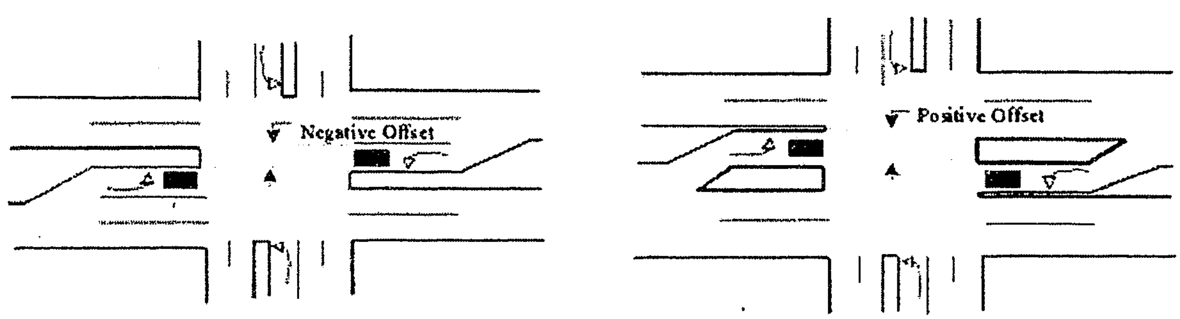


Figure 2.1 Negative and Positive Offsets [Source: McCoy et al. 1999]

Easa and Ali (2004) modified the guidelines for left-turn lane geometry and recommended that the actual available sight distance for the left-turn vehicle should be measured from the point of conflict. It was found that the previous guidelines overestimated the available sight distance, hence, underestimated the requirements for left-turn lane geometry (offset, length and lane-line width). It should be noted, however, that these guidelines are only limited to straight intersections.

The following limitations are recognized, and will be addressed in this thesis:

- Intersections are ideally located on tangent sections. Location of intersections on curves reduces visibility and increases conflict potentials for vehicles crossing the major-road. The current guidelines for 3D stop-control intersections (Easa et. al.) address this issue; however they are applicable only when the intersection and the major-road vehicle lie on the curve. Also. the obstruction was assumed to be on the inside of the curve. The research presented in this thesis extends previous work by allowing the intersection and the major-road vehicle to be anywhere on the curve with respect to the horizontal and/or vertical curves or anywhere on the tangent. Guidelines for the case when the obstruction is located on the outside of the curve are also established.
- The current guidelines for left-turn lane offset are applicable only to intersections on straight highways. The problem of sightline blockage by opposing left-turns is even more pronounced when the major-road has a horizontal curvature. This thesis establishes guidelines for offset requirements that provide unobstructed required sight distance for intersections located on horizontal curves.

Chapter 3: MODEL DEVELOPMENT: I. DEPARTURE SIGHT DISTANCE AT 3D STOP-CONTROL INTERSECTIONS

3.1. INTERSECTION GEOMETRY

To check the required sight distance, *d*, the proposed models consider two main cases with respect to the location of intersection on horizontal alignment. Case1 – Intersection on Major-road horizontal Curve and Case 2 – Intersection on Tangent of Major-road horizontal curve. There are two sub-cases of case 1; (1a) Intersection and object on curve, (1b) Intersection on the curve and object on tangent. Case 2 considers the object on the major-road horizontal curve. Note that if the object is within the tangent, AASHTO guidelines can be used to evaluate sightline obstruction. For both cases (1 and 2), models are developed considering the obstruction on the inside as well as on the outside of the curve. In addition, the intersection and the object can be anywhere on the vertical curvature i.e., both intersection and object are on vertical curve, intersection is on vertical curve while object is on tangent, and/or intersection is on first tangent while object is on second tangent.

The sightline, which is a straight line between the driver's eye on the minor-road and the top of an approaching vehicle on the major-road at a distance *d* from the intersection (Figure. 3.1), is checked against all possible obstructions. If any element representing sightline obstruction crosses the sightline, the sightline is obstructed and the obstruction should be moved to satisfy the required sight distance. Otherwise, it is unobstructed.

The main variables governing the sight distance in horizontal plane are (Figure. 3.1)

1. Required sight distance *d*, which is calculated using Equation (2.1).

2. Distance d_1, which is the distance along the major-road between the intersection and the point of curvature (PC)
3. Slope of required sightline $tan\alpha$, which is a function of d and road horizontal curvature
4. Distance M_1 between the obstruction corner and the edge of the major-road (along the line passing through the center of the horizontal curve)
5. Distance M_2 between the obstruction corner and the edge of the minor-road
6. Distance D between the minor-road driver's eye and the edge of major-road

The geometric alignment data required as input to the model are given in Table 3.1. The following section describes the development of the mathematical model. The evaluation procedure and design graphs are then presented, followed by an application example.

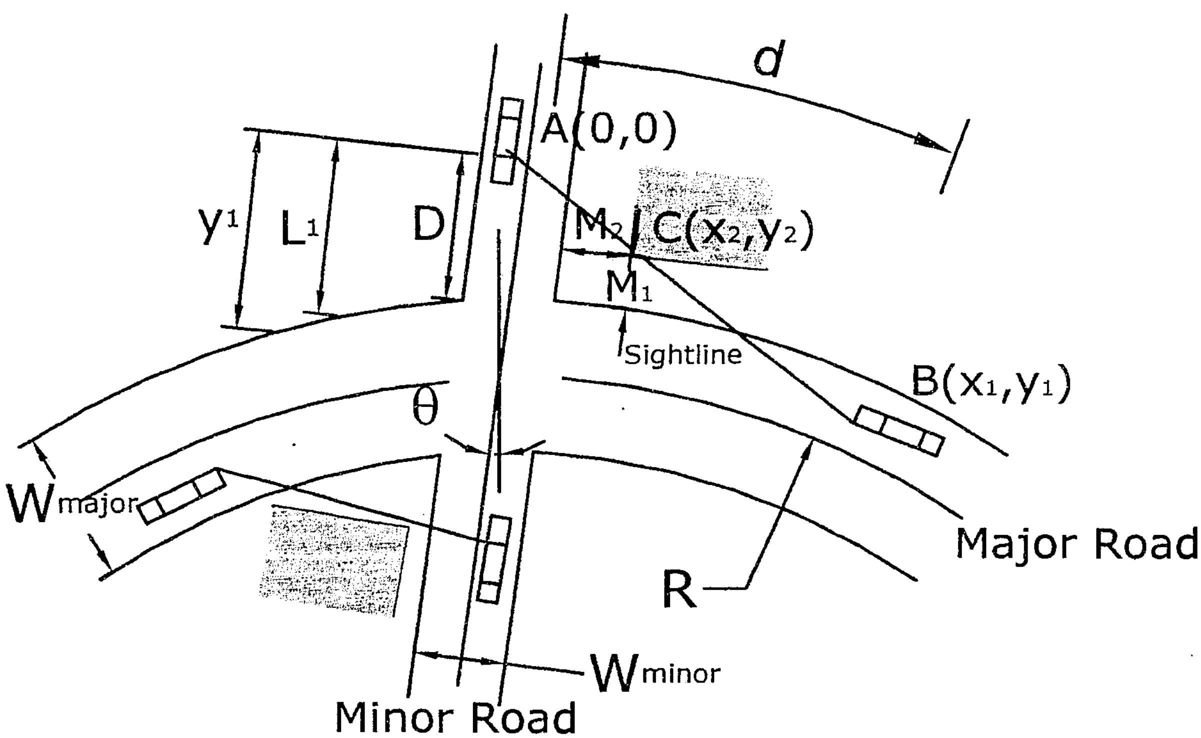


Figure 3.1 Intersection Geometry (Case 1(a): Intersection and Object within the curve)

3.2. MATHEMATICAL MODEL

Similar to previous research (Easa et. al. 2004) the point of origin for the Cartesian coordinates is assumed to be located at the road surface under the driver's eye on the minor-road with the y-axis being along the centerline of the stopped vehicle on the minor-road. Driver's eye is assumed to be located at the center of the lane. The coordinates of Point A (Driver's eye) are $(0,0,h_d)$; the coordinates of Point B (Object), which is the approaching vehicle, are (x_1,y_1,z_1). (Figure 3.2)

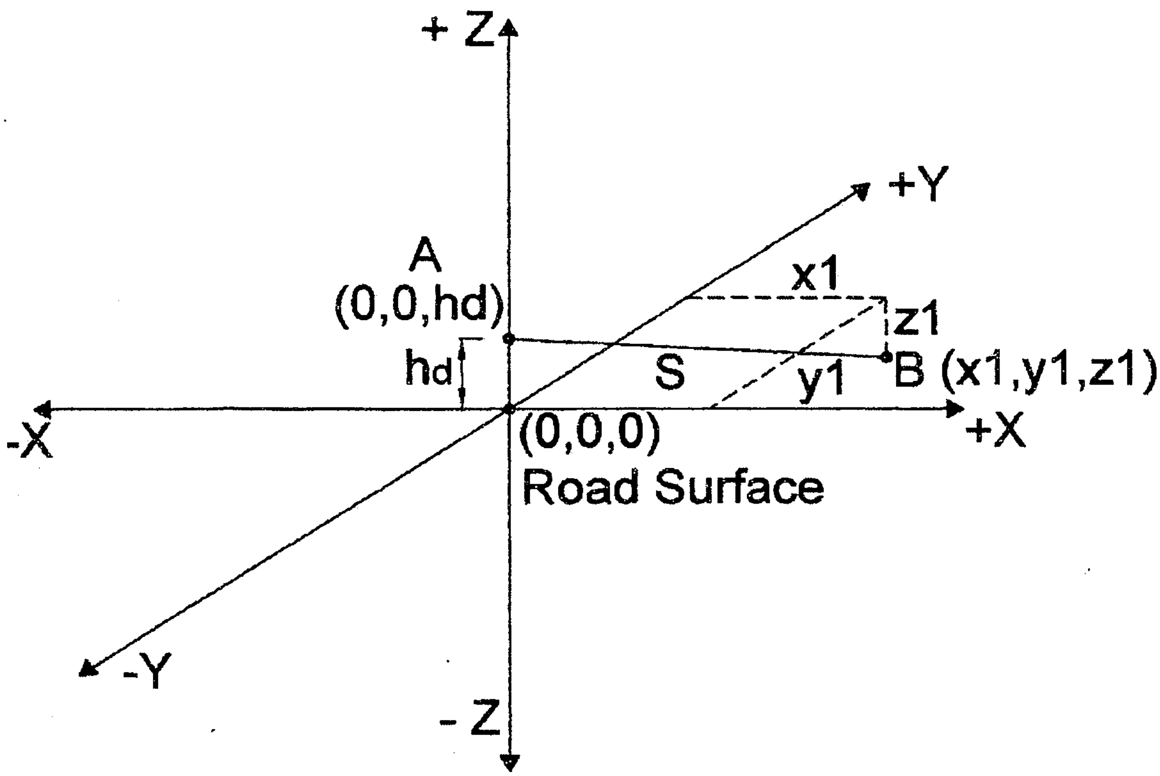


Figure 3.2 Coordinates of different points of intersection sight distance on 3D alignments [Easa et.al. 2004]

The radius of the horizontal-curve path for a vehicle approaching from left or from right given by (Easa et. al 2004) is

$$R_n = R - W_{major}/2 + w_{major}/2 \qquad (3.1a)$$

(vehicle approaching from left)

$$R_n = R + w_{major}/2 + M_{major}/2 \qquad (3.1b)$$

(vehicle approaching from right)

Note that Eqs. (3.1a) and (3.1b) are applicable when the obstruction is on the inside of the horizontal curve. For the obstruction on the outside of the curve, the radius of the horizontal-curve path for a vehicle approaching from left and from right (in terms of driver's perspective views) is

$$R_n = R + W_{major}/2 - w_{major}/2 \qquad (3.2a)$$

(vehicle approaching from left)

$$R_n = R - M_{major}/2 - w_{major}/2 \qquad (3.2b)$$

(vehicle approaching from right)

where R_n = radius of horizontal-curve path of the approaching vehicle, R = radius of horizontal curve (along centerline of major-road), W_{major} = total width of major-road, w_{major} = lane width of major-road, and M_{major} = median width. The total width W_{major} equals ($2nw_{major}$ + M_{major}), where n = number of lanes of the major-road (one direction). It should also be noted that (3.1a), (3.1b), (3.2a) and (3.2b) assume that the approaching vehicle on the major-road is on the nearest lane to the minor-road driver (inside lane for a vehicle approaching from right and outside lane for a vehicle approaching from left), as this situation produces the most critical case.

The central angle ϕ (in degrees) for the arc with length d' (measured up to the centerline of the minor-road) equals $180°d'/\pi R_n$. Note that for a two lane minor-road d' is nearly equal to d. Let the intersection angle θ (skew) be measured from the perpendicular line to the tangent to the horizontal curve. When the obstruction is on the outside of the curve, for a major-road vehicle approaching from the left of the driver, the skew angle θ is considered positive if it is clockwise and negative otherwise (and vice versa for a vehicle approaching from the right). It should be noted here that it is reverse when the obstruction is on the inside of the curve (Easa et al 2004).

The sightline to the object may be obstructed in two ways; either by any *off-road obstruction* such as building, parked vehicle, bushes etc. or by the *road surface* due to a presence of a crest vertical curve. The model involves two main aspects: checking sightline obstruction in the x-y plane (i.e. off-road obstruction) and the x-z plane (i.e. major-road surface obstruction). To simplify the ISD analysis, analytical geometry is used to determine the adequacy of the required sight distance.

3.2.1 Checking Sightline Obstruction in the X-Y Plane

To check sightline obstruction in the x-y plane, the slopes of sightline to the object and obstruction corner need to be determined first. Then the check is performed for Case 1(a) where the intersection and object lie on the curve, Case 1(b) where the intersection lies on the curve and the object lies on the tangent, and Case 2 where the intersection lies on the tangent and the object lies on the curve.

3.2.1.1.Sighline Slopes to Object and Obstruction

The slope of the sightline to the object in the X-Y plane is (Figure 3.3)

$$\tan \alpha = y_1 / x_1 \tag{3.3}$$

where α is the angle between the sightline to the object and the x-axis. For an obstruction at C(x_2, y_2):

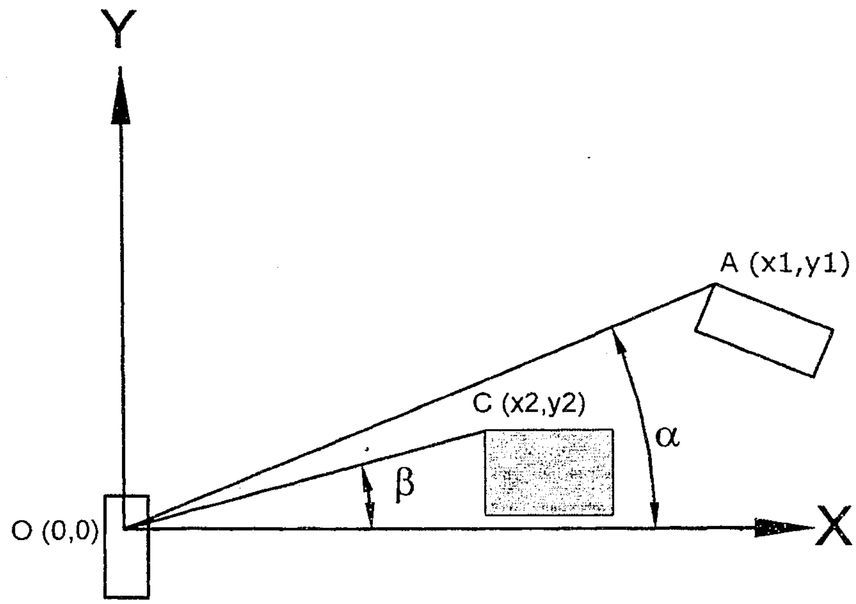


Figure 3.3 Sightlines to the Object and Obstruction

$x_2 = M_2 + (W_{minor} - w_{minor}/2)$ (3.4a)

(vehicle approaching from left)

$x_2 = M_2 + w_{minor}/2$ (3.4b)

(vehicle approaching from right)

Note that (3.4a) and (3.4b) are applicable for all cases to calculate x_2. For the calculation of y_2 appropriate equations should be used depending upon the case.

For Case 1 (a & b), y_2 can be calculated as:

$$y_2 = \frac{\sqrt{q^2 - \left(M_2 + \frac{W_{\min or}}{2}\right)^2} + W_{major}/2 + D - R}{\cos\theta} + x_2 \sin\theta \qquad (3.5a)$$

(Obstruction inside the curve)

$$y_2 = \frac{\sqrt{q^2 - \left(M_2 + \frac{W_{\min or}}{2}\right)^2} - W_{major}/2 - D - R}{\cos\theta} + x_2 \sin\theta \qquad (3.5b)$$

(Obstruction outside the curve)

with

$$q = R + \frac{W_{major}}{2} + M_1 \qquad (3.6a)$$

(Obstruction outside the curve)

$$q = R - \frac{W_{major}}{2} - M_1 \qquad (3.6b)$$

(Obstruction inside the curve)

where W_{minor} = total width of minor-road, w_{minor} = lane width of minor-road, M_2 = distance between the obstruction corner and the edge of the minor-road, M_1 = distance between the obstruction corner and the edge of the major-road (along the line passing through the centre of the horizontal curve), and D = distance of driver's eye of vehicle on minor-road and edge of major-road. For Case 2, y_2 can be calculated as:

For obstruction corner within the tangent ($x_2 \leq d_1$), where d_1 is the distance of intersection from PC, then

$$y_2 = \frac{M_1 - D}{\cos\theta} + x_2 \sin\theta \qquad (3.7a)$$

(Obstruction outside the curve)

$$y_2 = \frac{D - M_1}{\cos\theta} + x_2 \sin\theta \qquad (3.7b)$$

(Obstruction inside the curve)

For obstruction corner beyond tangent ($x_2 > d_1$), then

$$y_2 = \frac{\sqrt{q^2 - (x_2 - d_1)^2} - W_{major}/2 - D - R}{\cos\theta} + x_2 \sin\theta \qquad (3.7c)$$

(Obstruction outside the curve)

$$y_2 = \frac{\sqrt{q^2 - (x_2 - d_1)^2} + W_{major}/2 + D - R}{\cos\theta} + x_2 \sin\theta \qquad (3.7d)$$

(Obstruction inside the curve)

The slope of the sightline to the obstruction in the X-Y plane equals $\tan\beta = y_2/x_2$, where β is the angle between the sightline to the obstruction and the x-axis. The sightline to the object (major-road vehicle) is not obstructed if the angle α (for sight line to the object) is greater than or equal to the angle β (sightline to the obstruction). That is, for unobstructed sightline,

$$\beta \leq \alpha$$

$$\tan\beta \leq \tan\alpha$$

$$y_2/x_2 \leq y_1/x_1 \qquad (3.8)$$

Now, the coordinates of sightline to the object (x_1, y_1), needs to be established in order to carryout the check in Equation (3.8). Following sections considers two main cases to establish these coordinates.

3.2.1.2. Case 1(a) Intersection and Object lie on Horizontal Curve

Previous research (Easa et al. 2004) has established guidelines for the case when the obstruction is located on the inside of the curve. Figure 3.4 shows the geometry of ISD on the X-Y plane for an object on the horizontal curve (obstruction outside the horizontal curve). Note that the outside obstruction is clearly more critical than the inside obstruction for a minor-road vehicle driving towards the center of the curve. Then,

$$x_1 = R_n \sin\phi \cos\theta + R_n(1 - \cos\phi)\sin\theta \qquad (3.9a)$$

(Obstruction inside or outside)

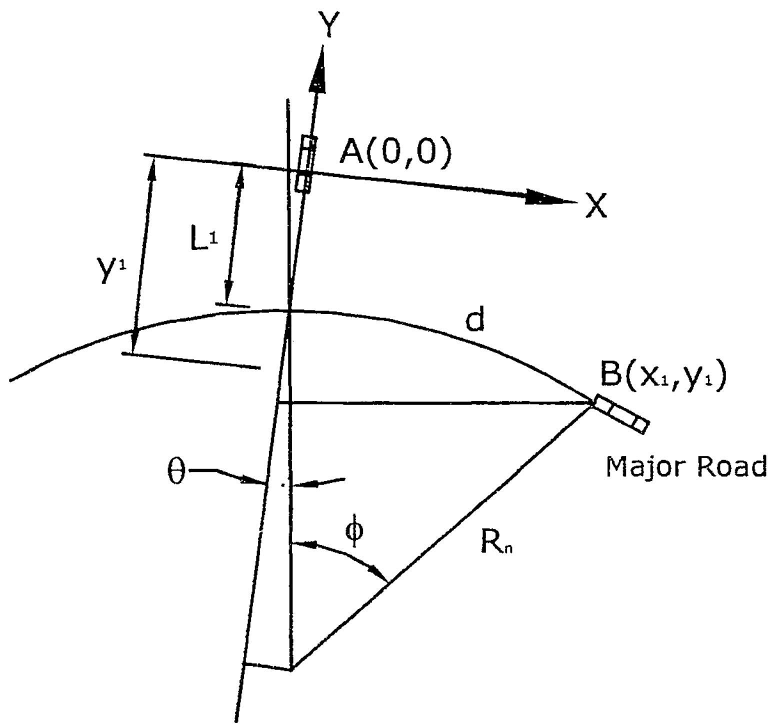


Figure 3.4 Case 1(a) ISD on X-Y plane – Obstruction is located on the outside of the curve (skew angle θ).

If there is no skew (θ = 0), (9a) becomes

$$x_1 = R_n \sin \phi \tag{3.9b}$$

Similarly

$$y_1 = R_n \sin\theta \sin\phi + R_n(\cos\phi - 1)\cos\theta - L_1 \tag{3.10a}$$

(Obstruction outside the curve)

$$y_1 = L_1 - R_n \cos\theta(1 - \cos\phi - \sin\varphi \tan\theta) \tag{3.10b}$$

(Obstruction inside the curve)

If there is no skew (θ = 0), (3.11a) and (3.11b) becomes (3.11a) and (3.11b) respectively

$$y_1 = R_n(\cos\phi - 1) - L_1 \tag{3.11a}$$

$$y_1 = L_1 - R_n(1 - \cos\phi) \tag{3.11b}$$

where

$$L_1 = \frac{w_{major}}{2\cos\theta} + D \tag{3.12a}$$

(vehicle approaching from left)

$$L_1 = \frac{W_{major} - \left(\frac{w_{major}}{2}\right)}{\cos\theta} + D \tag{3.12b}$$

(vehicle approaching from right)

3.2.1.3. Case 1(b) Intersection lies on Horizontal Curve and Object lies on Tangent

In this case, the intersection lies on the horizontal curve and the object lies on the tangent at distances d_1 and d_2 from PC, respectively (Figure 3.5). The distances represent the components of the required sight distance on the curve and tangent. The location of intersection from the PC is known from the field or drawing plan. The required distance d can be calculated using the appropriate time gap and the design speed on major-road.

For an exiting intersection, the d_1 component of the required sight distance is the distance between the intersection and the PC, and subtracting d_1 from the total required sight distance d will provide d_2. If the required sight distance is less than d_1,,it implies that the object lies within the curve, and therefore Case 1(a) should be used. For a proposed intersection, the designer can allocate the d_1 and d_2 components of the required sight distance according to other constraints, and then calculate M_1 and M_2 to provide unobstructed sightlines to the approaching vehicles. Once these data are available, the coordinates of the object can be established as follows:

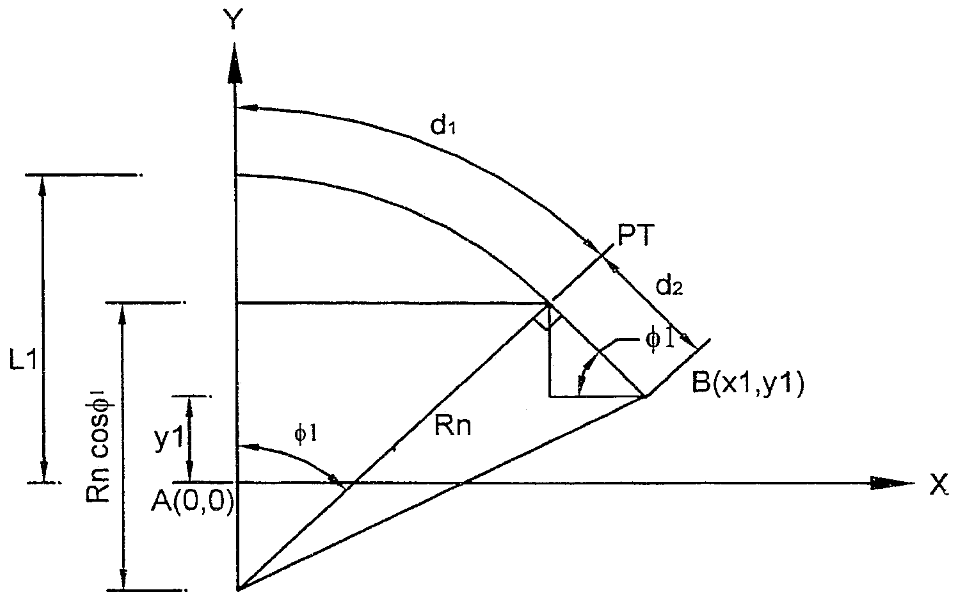


Figure 3.5 Case 1(b) Intersection on Curve and Object beyond PT

The central angle for arc of length d_1 is given by $\phi_1 = 180°d_1/\pi R_n$. (Figure. 3.4). For a skew angle θ, and an object on tangent (obstruction inside or outside the horizontal curve), then

$$x_1 = R_n \sin\phi_1 \cos\theta + R_n(1-\cos\phi_1)\sin\theta + d_2\cos(\phi_1-\theta) \tag{3.13}$$

Similarly,

$$y_1 = R_n \sin\theta \sin\phi_1 + R_n(\cos\phi_1 - 1)\cos\theta - L_1 - d_2\sin(\phi_1-\theta) \tag{3.14a}$$

(Obstruction outside the curve)

$$y_1 = L_1 - d_2\sin(\phi_1-\theta) - R_n\cos\theta(1-\cos\phi_1 - \sin\varphi_1\tan\theta) \tag{3.14b}$$

(Obstruction inside the curve)

where L_1 is given by Equations (3.12a) and (3.12b).

Using the obstruction coordinates from Equations (3.4 to 3.5), for a vehicle approaching from left or right, Equation (3.8) can be written as (with an equality)

$$M_1 = \sqrt{\left[\frac{y_1}{x_1}\cos\theta(x_2) + R + D + \frac{W_{major}}{2} - \cos\theta(x_2)\sin\theta\right]^2 + \left(M_2 + \frac{W_{\min or}}{2}\right)^2} - R - \frac{W_{major}}{2}$$

(Obstruction outside the curve) (3.15)

where x_2 is given by Equations (3.4a) and (3.4b), and x_1, y_1 and are given by Equations (3.9a) and (3.10a) for Case 1(a) or Equations (3.13) and (3.14a) for Case 1(b).

Similarly, based on previous research (Easa et al. 2004), for the obstruction on the inside of the horizontal curve, Equation (3.8) can be written as

$$M_1 = R - \frac{W_{major}}{2} - \sqrt{\left[\frac{y_1}{x_1}\cos\theta(x_2) + R - D - \frac{W_{major}}{2} - \cos\theta(x_2)\sin\theta\right]^2 + \left(M_2 + \frac{W_{\min or}}{2}\right)^2}$$

(Obstruction inside the curve) (3.16)

where x_2 is given by Equations (3.4a) and (3.4b), and x_1 *and* y_1 are given by Equations (3.9a) and (3.10b) for Case 1(a) or Equations (3.13) and (3.14b) for Case 1(b).

Note that Equations (3.15) and (3.16) provide the minimum required value of M_1 for which the required minimum sight distance is unobstructed. Hence, for a given highway, for any value of M_2, use appropriate equation to calculate x_1, y_1 and x_2 and then use Equation (3.15) or Equation (3.16) to calculate M_1 for obstruction on the outside or inside of the curve. If M_1 is given, substiture for x_2 in Equation (3.15) or Equation (3.16) from Equation (3.4a) or Equation (3.4b) and calculate M_2 by trial and error. The values of M_1 and M_2 should be greater than or equal to zero or other minimum values required by road authority regulations. When y_1 is negative, M_1 and M_2 refer to the corner of obstruction that is farther from the minor-road vehicle for obstruction on the inside of the horizontal curve and vice versa for the obstruction on the outside of the horizontal curve. It should be noted that for the obstruction on the outside of curve, farther corner is highly unlikely to control as y_1 will only be positive in case of very large skew. In this case, the obstruction always lies at the corner near the approaching vehicle.

Note that M_1 is the distance measured along the radius to the curve. It is measured from the corner of obstruction to the outside or inside edge of the major-road for obstruction on the outside or inside of the curve, respectively, for Case 1(a) and Case 1(b). Now, for Case 1(b) there may be situations when the obstruction is closer to the major-road but much farther from the minor-road (i.e. the obstruction lies beyond PC). In this case, M_1 will provide the distance up to the extension of the horizontal curve. Therefore, the distance beyond M_1 to the tangent M_3 needs to be calculated. It is needed when the following condition is justified (Figures. 3.6 and 3.7)

$$M_2 > q \sin\phi_1 - \frac{W_{\min or}}{2} \tag{3.17}$$

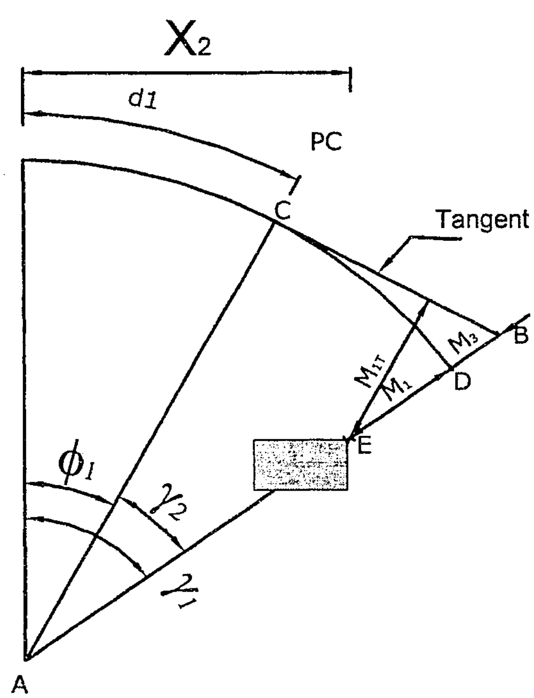


Figure 3.6 Condition for M_{1T} (Obstruction inside the curve)

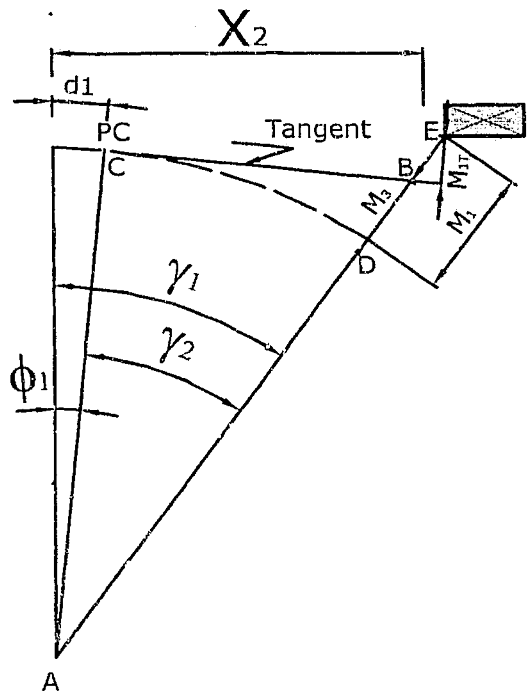


Figure 3.7 Condition for M_{1T} (Obstruction outside the curve)

where M_2 is measured from the field/drawing and q is given by Equation (3.6a) and (3.6b) for the obstruction on the outside and inside of the curve, respectively, according to the given conditions. Once M_3 is calculated, the distance perpendicular to the tangent M_{1T} is determined. The procedure for the calculation of M_{1T} is as follows.

From ΔABC, (Figures. 3.6 and 3.7), the side AC is given by

$$AC = R + \frac{W_{maj}}{2}$$

(Obstruction outside the curve)

Similarly

$$AC = R - \frac{W_{maj}}{2}$$

(Obstruction inside the curve)

And

$$BC = AC\tan(\gamma_2)$$

where

$$\gamma_2 = \gamma_1 - \phi_1$$

$$\gamma_1 = \sin^{-1}\left(\frac{x_2}{q}\right)$$

Using the Pythagoras theorem,

$$AB = \sqrt{AC^2 + BC^2}$$

Then,

$$M_3 = AB - AC$$

Now, the distance perpendicular to the tangent from the corner of the obstruction M_{1T} can be calculated as

$$M_{1T} = (M_1 - M_3)\sin(90 - \gamma_2) \qquad (3.18a)$$

(Obstruction outside the curve)

$$M_{1T} = (M_1 + M_3)\sin(90 - \gamma_2) \qquad (3.18b)$$

(Obstruction inside the curve)

3.2.1.4. Case 2 Intersection lies on Tangent and Object lies on Horizontal Curve

There are situations, when the minor-road lies on the tangent of a major-road horizontal curve. This case would affect sight distance, especially when the horizontal curve is sharp and the minor-road is close to the start (or end) or the horizontal curve. The geometry of this case is shown in Figure 3.8.

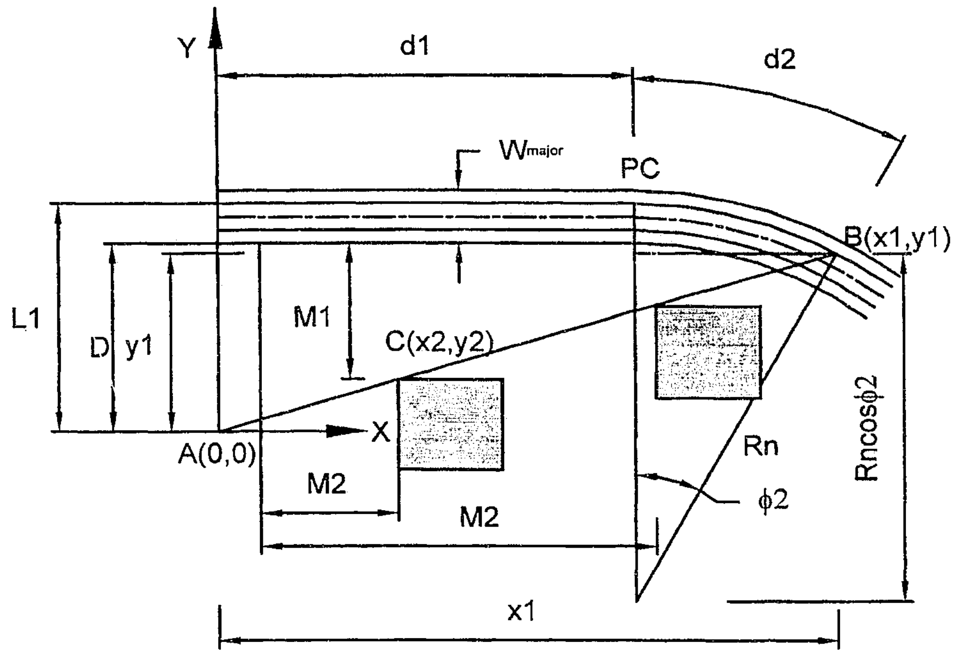


Figure 3.8 Intersection on tangent of Major-road Horizontal Curve

Similar to Case 1 (b), the distance of the intersection from PC can be obtained from the geometry. The intersection is at a distance d_1 from PC. If the required sight distance is found to be greater than d_1, then, according to the current case, the object will lie on the curve. The distance d_2 can be calculated by subtracting d_1 from the required sight distance. Then, the central angle for the arc of length d_2 is given by $\phi_2 = 180°d_2/\pi R_n$ (Figure 3.8). For a skew angle θ, obstruction inside or outside the curve and object beyond PC (i.e., on the curve), the coordinates (x_1, y_1) are given by

$$x_1 = R_n \sin\phi_2 \cos\theta + R_n(1-\cos\phi_2)\sin\theta + d_1\cos\theta \qquad (3.19)$$

(Obstruction inside or outside)

Similarly,

$$y_1 = R_n \sin\theta \sin\phi_2 + R_n(\cos\phi_2 - 1)\cos\theta - L_1 - d_1\sin\theta \qquad (3.20a)$$

(Obstruction outside the curve)

$$y_1 = L_1 - R_n \cos\theta(1 - \cos\phi_2 - \sin\varphi_2 \tan\theta) + d_1 \sin\theta \qquad (3.20b)$$

(Obstruction inside the curve)

where L_1 is given by Equations (3.12a) and (3.12b).

Using the coordinates of obstruction from Equations (3.4a, 3.4b and 3.7a to 3.7d) for a vehicle approaching from left Equation (3.8) for the obstruction may be written as

$$M_1 = \left(\frac{y_1}{x_1} - \sin\theta\right)(x_2 \cos\theta) + D$$

$(x_2 \leq d1)$

(Obstruction outside the curve) (3.21a)

$$M_1 = \sqrt{\left[\frac{y_1}{x_1}\cos\theta(x_2) + R + D + \frac{W_{major}}{2} - \cos\theta(x_2)\sin\theta\right]^2 + (x_2 - d_1)^2} - R - \frac{W_{major}}{2}$$

$(x_2 > d1)$

(Obstruction outside the curve) (3.21b)

Similarly,

$$M_1 = D - \left(\frac{y_1}{x_1} - \sin\theta\right)(x_2 \cos\theta)$$

$(x_2 \leq d1)$

(Obstruction inside the curve) (3.22a)

$$M_1 = R - \frac{W_{major}}{2} - \sqrt{\left[\frac{y_1}{x_1}\cos\theta(x_2) + R - D - \frac{W_{major}}{2} - \cos\theta(x_2)\sin\theta\right]^2 + (x_2 - d_1)^2}$$

$(x_2 > d1)$

(Obstruction inside the curve) (3.22b)

For all the situations of Case 2, x_2 is given by Equations (3.4a) and (3.4b), and x_1 y_1, are given by Equations (3.19), (3.20a) and (3.20b).

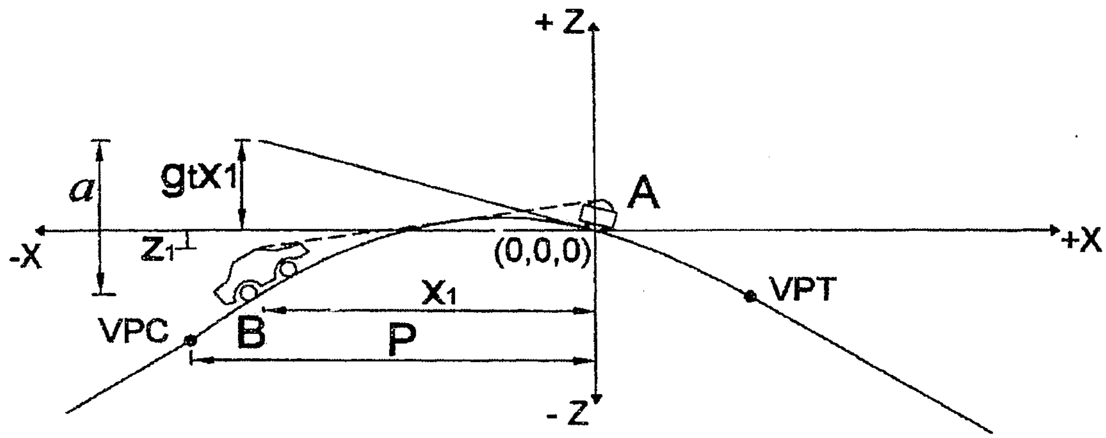


Figure 3.9 Intersection and Object on the vertical curve [Source: Easa et al. 2004]

3.2.2 Checking Sightline Obstruction in the X-Z Plane

Let the minor-road grade be g_m in decimal. Then, z_1 is given by (Figure 3.9)

$$z_1 = \frac{rx_1^2}{2} - g_t x_1 + h_o + y_1 g_m \tag{3.23a}$$

(Observer and Object on curve)

where g_t = slope of the vertical curve at the minor-road vehicle path, r = rate of change of grade of vertical curve, and h_0 = height of the approaching vehicle on major-road. The variable r and g_t are given by

$$r = \frac{g_2 - g_1}{L}$$

$$g_t = g_1 + r P$$

where g_1 and g_2 = first and second grades of the vertical curve in decimal, L = length of vertical curve (m), and P = distance from the point of vertical curvature (PVC) to the path of the minor-road vehicle (m).

Now, if the object is on the tangentz_1 is given by (Figure 3.10)

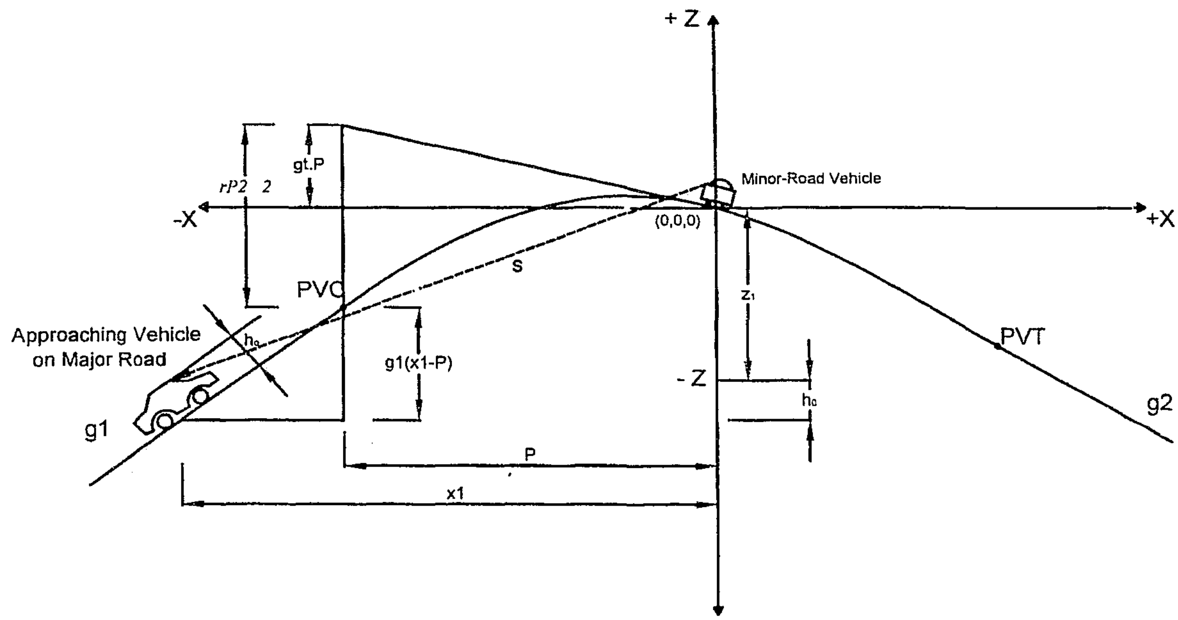


Figure 3.10 Intersection on the vertical curve and Object on Tangent

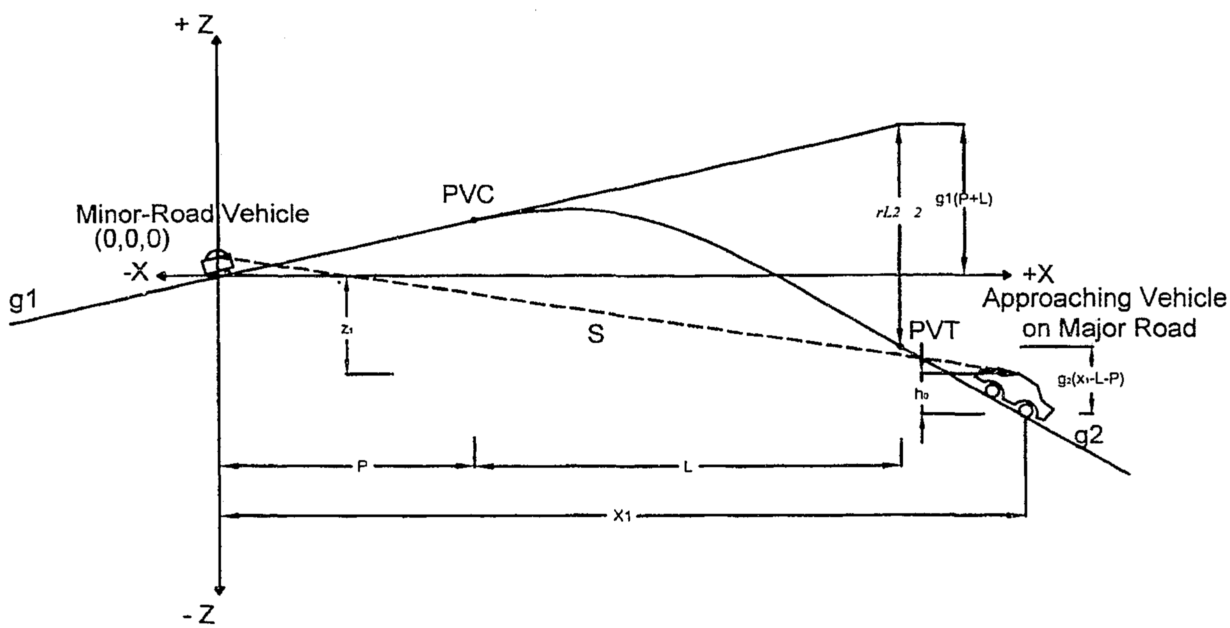


Figure 3.11 Intersection on First Tangent and Object on Second Tangent

$$z_1 = \frac{rP^2}{2} - g_t P - g_1(x_1 - P) + h_0 + y_1 g_m \tag{3.23b}$$

(Observer on curve & Object before PVC)

Similarly, for the case when the intersection is on first grade and the object is on second, z_1 is given by (Figure 3.11)

$$z_1 = g_1(P+L) + \frac{rL^2}{2} + g_2(x_1 - L - P) - h_0 + y_1 g_m \tag{3.23c}$$

(Observer before PVC and Object beyond PVT)

To check whether the sight line is obstructed by the major-road surface, it is assumed that the driver on the minor-road is located on the vertical curve (at the centerline of the major-road). This approximation is expected to be reasonably accurate as the distance between the actual location of the minor-road driver and the assumed location is very small compared with the sight distance. Previous research developed guidelines to check road-surface obstruction when both intersection and the object lie on the vertical curve. This research has extended this work by considering two new cases: (a) Observer on curve and approaching vehicle on tangent i.e. before PVC. This case exists when there is a vertical curve and x_1 calculated for any case of 'Off-Road Obstruction' is greater than P. (b) Observer on First tangent and Object on Second tangent.

Note that the approaching vehicle is considered to be on the first tangent for the purpose of this development. This assumption is made to avoid the confusion of positive or negative sign of x_1. For all previous situations, the coordinate z at any point x on the curve is given by,

$$z = \frac{rx^2}{2} - g_i x + y_1 g_m \tag{3.24}$$

The sightline to the approaching vehicle is a straight line with a starting point at the driver's eye $(0,h_d)$ and an end point at the top of the approaching vehicle (x_1,z_1). Comparing the slopes using equation of a straight line, we have

$$\frac{z-h_d}{x-0} = \frac{z_1-h_d}{x_1-0} \tag{3.25}$$

Substituting for z_1 and z from Equations (3.23a), (3.23b), (3.23c) and (3.24) into Equation (3.25), then

$$\frac{rx_1}{2}x^2 - (\frac{rx_1^{\,2}}{2} + h_o - h_d + y_1 g_m)x - (h_d - y_1 g_m)x_1 = 0 \qquad (3.26a)$$

(Observer and Object on curve)

$$\frac{rx_1}{2}x^2 + \left(g_1(x_1 - P) + g_t P - h_0 - y_1 g_m + h_d - g_t x_1 - \frac{rP^2}{2} \right)x + (y_1 g_m - h_d)x_1 = 0$$

(Observer on curve & Object before PVC) (3.26b)

$$\frac{rx_1}{2}x^2 + \left(g_1(P + L) + \frac{rL^2}{2} + g_2(x_1 - L - P) - h_0 + y_1 g_m - h_d + g_t x_1 \right)x + (y_1 g_m - h_d)x_1 = 0$$

(Observer before PVC and Object beyond PVT) (3.26c)

The major-road surface obstructs the sightline only if Equation (3.26a), (3.26b) or (3.26c) has a solution within the range,

$$0 \le x \le x_1$$

3.3. MODEL VERIFICATION

The developed model was verified by comparing the results obtained by the software with those obtained graphically using AutoCAD. The positions of observer and object were fixed according to the scenario and the sightline was drawn for each case. As the points on the sightline correspond to the values of M_1 or M_{1T} and M_2, the values were noted and compared with those established mathematically. The results obtained by the mathematical models for all cases were in compliance with those obtained graphically.

All models including the model for the special case (case 2), when the intersection is located on the straight major-road were also verified by comparing results with AASHTO (2001) models. This was done by considering very large value of R hence making the major-road virtually straight. The values of M_1 at different M_2 were then calculated. The values were compared with the departure triangles given in AASHTO (2001). The triangles were drawn using the recommended time gaps and a value of D equals 5.4m. For a design speed of 40km/h along major-road, for vehicle approaching from left, M_1 is 2.81 for M_2 equals 24.6m. Values at other speeds were also in accordance with the values obtained using AASHTO model.

3.4. EVALUATION PROCEDURE

Whether an obstruction such as building is proposed, or it exists, the guidelines presented in this chapter can be applied directly. For an existing obstruction with given M_1 and M_2, and the location of the intersection from PC, it is required to determine if the existing obstruction provides the adequate sight distance or not. The procedure is as follows:

1. Calculate the required sight distance d using Equation (2.1).
2. When intersection is on curve (Case 1), compare d with d_1
   (a) If $d \leq d_1$, then it is Case 1(a), hence use Equations (3.8a) to (3.10b) to calculate x_1 and y_1
   (b) If $d > d_1$, then it is Case 1(b), hence use Equations (3.13) to (3.14b) to calculate x_1 and y_1
   (c) For Cases 1(a) and 1(b), using given M_2, determine minimum required M_1 using Equations (3.15) or (3.16), for obstruction on the outside and/or inside of the curve respectively.
   (d) If the existing $M_1 \geq$ calculated M_1, then the sight line is not obstructed. Note that for Case 1(b), if the condition in Equation (3.17) is true, calculate M_{1T} and compare it with existing M_{1T}.
   (e) If the existing M_1 or M_{1T} < calculated M_1 or M_{1T} respectively, then the sightline is obstructed and the obstruction should be moved.
3. When the intersection lies on the tangent, compare d with d_1
   (a) If $d \leq d_1$, then the object lies within the tangent and the obstruction distance M_1 can be calculated by formulating departure sight triangles

using AASHTO (2001) model. The obstruction values for two-lane straight major and minor roads are presented as Figure 3.18.

(b) If $d > d_1$, then it is Case 2, hence use Equations (3.19) to (3.20b) to calculate x_1 and y_1

(c) Using given M_2, determine x2 using Equations (3.4a) and (3.4b) for vehicle approaching from left and right respectively, compare x_2 with d_1,

(d) If $x_2 \leq d_1$, using given M_2, determine minimum required M_1 (from the tangent) using Equations (3.21a) and (3.22a), for obstruction on the outside and/or inside of the curve respectively.

(e) If $x_2 > d_1$, using given M_2, determine minimum required M_1 (from the cruve) using Equations (3.21b) and (3.22b), for obstruction on the outside and/or inside of the curve respectively.

(f) If the existing $M_1 \geq$ calculated M_1, then the sight line is not obstructed.

To save time and effort, the developed mathematical procedure was translated to various Excel worksheets to determine the values of M_1 or M_{1T}, if applicable, for user chosen or existing initial value of M_2. Upon the input of required data, the results are shown accordingly. The results include: (a) required sight distance, (b) road surface obstruction equation, (c) values of x_1, and y_1 and (d) table for the minimum values of M_1 corresponding to different values of M_2 (an increment of 4m is used by default to display the effect of M_2 on M_1). This table may be used to plot the minimum values for both M_1 and M_2 graphically. The procedure is also applicable to ISD analysis for proposed intersection design.

3.5. DESIGN AIDS

Design aids were established using the mathematical models presented earlier assuming general values for the design variables. Please not that for Case 1(a) i.e. when both the intersection and object lie within the curve, and the obstruction is on the outside of the curve, values of M_1 and M_2 in Figure 3.12(b) provide unrestricted sightlines independent of the speed along major-road. To check if these graphs can be applied directly, a quantity Q must be calculated. It follows:

$$Q = R\sin\phi \tag{3.27}$$

A vertical line is drawn upward from Figure 3.12(a) for the design radius. The design graphs given in Figure 3.12(b) are only applicable if Q is above the shaded region. If Q lies within the shaded region, then the sightline may be obstructed and hence the user must go through the complete analysis procedure as explained earlier. The design graphs based on the analysis are presented from Figure 3.13 – 3.16. The following recommended values (AASHTO 2001) were used in developing these design aids:

- Driver's eye height, h_d = 1.08 m.
- Height of approaching vehicle on major-road, h_o = 1.08 m.
- The design vehicle i.e. minor-road vehicle is a passenger car.
- Lane width = *3.6 m* (for both minor and major roads).
- Distance of driver's eye of vehicle on minor-road and the edge of major-road, *D = 5.4 m.*

Since stop-control intersections and combined alignments are likely to exist in two-lane highways, both major and minor roads are assumed to be two-lane highways with a total width of 7.2 m each. No skew or slope of the minor-road was assumed.

According to AASHTO the required time gap for two lane major-road, is 7.5 s. Note that for V_{major} = 80 km/h, the minimum radius is likely to be some value between 195 m and 280 m, depending on superelevation, therefore the radius of 100 m was not included with this design speed. Also, for V_{major} = 100 km/hr, the minimum radius is likely to be some value between 330 m and 490 m, depending on superelevation, and therefore a radius less than 300 m was not included.

The design aids are also useful for evaluating an existing obstruction, as the values for M_1 and M_2 for an obstruction may be plotted as one point on the graph. If the point lies under the corresponding line, that means M_1 and M_2 are less than the minimum values and the sightline is obstructed. If the point lies above the line, that means M_1 and M_2 are more than the minimum values and the sightline is not obstructed.

For the obstruction on the inside of horizontal curve, a positive slope of a curve in the design graph means that the farther corner of the obstruction controls (that is, y_1 is negative). A negative slope means that the obstruction corner near the minor-road vehicle controls. Note that for obstruction on the outside of curve, the obstruction corner near the minor-road vehicle controls and the slopes are always negative, as expected. Figures 3.13 and 3.15 show graphs at different speeds for Case 1(a) i.e. the object lies within the horizontal curve, for the obstruction on the outside and inside of curve respectively. It should be noted that the rate of decrease in M_1 with the increase in M_2 is likely to decrease as the radius becomes larger in this case of obstruction on the outside of the curve (Figure 3.13). In other words, the slope of the curves in the design graphs becomes flatter.

The design graphs for Case 1(b) i.e when the object lies on the tangent, for obstruction on the outside and inside of the curve, respectively, are shown in Figures 3.14 and 3.16. Note that these graphs were established assuming that the required sight distance is twice the distance of intersection from PC, which means that the object is on the tangent at a distance equal to half of the total required sight distance ($d = 2d_1$). Any other value can be calculated by interpolation. Figure 3.17 shows the actual and calculated values through interpolation for a radius of 500 at major-road design speed of 60 km/h. The values were calculated using graphs of $d = 2d_1$ and $d = d_1$. As the values are very close, therefore it would be appropriate to estimate in-between values through interpolation. The design aids when $d = 10d_1$ are presented in Tables 3.2 – 3.9. Note that these tables include the values of M_{1T} in addition to M_1 when condition in Equation (3.17) is true.

Figure 3.18 shows the obstruction distances M_1 and M_2 when the intersection and object lie on the tangent of major-road horizontal curve (i.e. straight major-road), Case 2 – ($d < d_1$). The design graphs for the Case 2, when the intersection lies on the tangent and object lies on the horizontal curve ($d > d_1$) are shown in Figures 3.19 and 3.20, for obstruction on the outside and inside of the curve, respectively. The graphs were developed assuming that the required sight distance is equal to ten times the distance of intersection from the PC ($d = 10\ d_1$). Any other value can be calculated by interpolation between design graphs in Figure 3.19 and 3.20 and the design graphs in Figure 3.18. Note that the obstruction distance M_1 is measured from the tangent or curve with respect to the location of the obstruction corner (within the tangent or curve). The vertical lines in Figures 3.19 and 3.20 represent PC. The curves in the design graphs to the left of the vertical lines, provide obstruction distance M_1 from the tangent ($x_2 \leq d_1$), and the curves to the right of the vertical lines provide obstruction distance M_1 from the horizontal curve ($x_2 > d_1$).

Table 3.1 Geometric Data Required as Input to Mathematical Model

Input Data	Symbol
Radius of horizontal curve	R
Lane width on major-road	w_{major}
Lane width on minor-road	w_{minor}
Total number of lanes on major road	n
Median width of major-road	M_{major}
Total width of minor-road	W_{minor}
Driver's eye height	h_d
Height of approaching vehicle on the major-road	h_o
Length of vertical curve	L
First grade of vertical curve	g_1
Second grade of vertical curve	g_2
Distance between vehicle on minor-road and edge of major-road	D
Grade of minor-road	g_m
Intersection angle (skew)	θ
Distance of intersection from *PC*	d_1
Distance from *PVC* to the path of the minor-road vehicle	P

Table 3.2 Design values of M_1 and M_{1T} at M_2 for major-road design speed = 40 km/h on two-lane intersections (Case 1(b): obstruction on the inside of horizontal curve, $d = 10d_1$)

R	Obstruction distance M_2 (m)					
	0	4[a]	8[a]	12[a]	16[a]	20[a]
(a) Obstruction distance M_1 (m)						
100	5.37	5.26	4.97	4.51	3.88	3.09
200	5.15	4.92	4.61	4.22	3.74	3.18
300	5.08	4.81	4.49	4.11	3.68	3.20
400	5.04	4.75	4.43	4.06	3.65	3.20
500	5.02	4.72	4.39	4.03	3.63	3.21
700	5.00	4.68	4.35	3.99	3.61	3.21
(b) Obstruction distance M_{1T} (m)						
100	-[b]	5.27	5.15	5.02	4.90	4.78
200	-	4.93	4.69	4.44	4.20	3.96
300	-	4.81	4.54	4.26	3.98	3.70
400	-	4.76	4.46	4.17	3.87	3.58
500	-	4.72	4.42	4.11	3.81	3.50
700	-	4.68	4.37	4.05	3.73	3.42

[a] Perpendicular distance from the tangent M_{1T}, is required.
[b] M_{1T} is not required, use M_1

Table 3.3 Design values of M_1 and M_{1T} at M_2 for major-road design speed = 60 km/h on two-lane intersections (Case 1(b): obstruction on the inside of horizontal curve, $d = 10d_1$)

R	Obstruction distance M_2 (m)					
	0	4	8[a]	12[a]	16[a]	20[a]
(a) Obstruction distance M_1 (m)						
200	5.41	5.38	5.26	5.06	4.78	4.42
300	5.30	5.21	5.05	4.84	4.58	4.26
400	5.25	5.12	4.95	4.73	4.48	4.19
500	5.22	5.07	4.88	4.67	4.42	4.14
600	5.20	5.03	4.84	4.62	4.38	4.10
700	5.18	5.01	4.81	4.59	4.35	4.08
(b) Obstruction distance M_{1T} (m)						
200	-[b]	-	5.27	5.14	5.01	4.88
300	-	-	5.06	4.89	4.73	4.56
400	-	-	4.95	4.77	4.59	4.40
500	-	-	4.88	4.69	4.50	4.31
600	-	-	4.84	4.64	4.45	4.25
700	-	-	4.81	4.61	4.41	4.20

[a] Perpendicular distance from the tangent M_{1T}, is required.
[b] M_{1T} is not required, use M_1

Table 3.4 Design values of M_1 and M_{1T} at M_2 for major-road design speed = 80 km/h on two-lane intersections (Case 1(b): obstruction on the inside of horizontal curve, $d = 10d_1$)

R	Obstruction distance M_2 (m)					
	0	4	8	12[a]	16[a]	20[a]
(a) Obstruction distance M_1 (m)						
200	5.60	5.70	5.73	5.66	5.52	5.29
300	5.45	5.47	5.42	5.33	5.17	4.97
400	5.38	5.35	5.27	5.16	5.00	4.80
500	5.34	5.28	5.18	5.06	4.90	4.70
600	5.31	5.23	5.12	4.99	4.83	4.64
700	5.29	5.20	5.08	4.94	4.78	4.59
(b) Obstruction distance M_{1T} (m)						
200	-[b]	-	-	5.67	5.59	5.52
300	-	-	-	5.33	5.22	5.11
400	-	-	-	5.16	5.03	4.91
500	-	-	-	5.06	4.92	4.79
600	-	-	-	4.99	4.85	4.71
700	-	-	-	4.94	4.79	4.65

[a] Perpendicular distance from the tangent M_{IT}, is required.
[b] M_{IT} Not required, use M_I

Table 3.5 Design values of M_1 and M_{1T} at M_2 for major-road design speed = 100 km/h on two-lane intersections (Case 1(b): obstruction on the inside of horizontal curve, $d = 10d_1$)

R	Obstruction distance M_2 (m)					
	0	4	8	12	16[a]	20[a]
(a) Obstruction distance M_1 (m)						
300	5.57	5.67	5.72	5.71	5.64	5.52
400	5.48	5.52	5.52	5.48	5.40	5.27
500	5.43	5.43	5.40	5.34	5.25	5.13
600	5.39	5.37	5.33	5.25	5.15	5.03
700	5.37	5.33	5.27	5.19	5.08	4.95
800	5.35	5.30	5.23	5.14	5.03	4.90
(b) Obstruction distance M_{1T} (m)						
300	-[b]	-	-	-	5.64	5.57
400	-	-	-	-	5.40	5.31
500	-	-	-	-	5.25	5.15
600	-	-	-	-	5.15	5.04
700	-	-	-	-	5.08	4.97
800	-	-	-	-	5.03	4.91

[a] Perpendicular distance from the tangent M_{1T}, is required.
[b] M_{1T} Not required, use M_1

Table 3.6 Design values of M_1 and M_{1T} at M_2 for major-road design speed = 40 km/h on two-lane intersections (Case 1(b): obstruction on the outside of horizontal curve, $d = 10d_1$)

R	Obstruction distance M_2 (m)					
	0	4[a]	8[a]	12[a]	16[a]	20[a]
(a) Obstruction distance M_1 (m)						
100	4.51	3.93	3.49	3.21	3.08	3.11
200	4.72	4.26	3.87	3.56	3.33	3.18
300	4.79	4.37	3.99	3.67	3.41	3.19
400	4.83	4.42	4.06	3.73	3.44	3.20
500	4.85	4.46	4.09	3.76	3.47	3.20
700	4.87	4.49	4.14	3.80	3.49	3.20
(b) Obstruction distance M_{1T} (m)						
100	-[b]	3.93	3.39	2.86	2.32	1.77
200	-	4.26	3.81	3.37	2.93	2.49
300	-	4.37	3.96	3.55	3.13	2.72
400	-	4.42	4.03	3.63	3.24	2.84
500	-	4.45	4.07	3.69	3.30	2.92
700	-	4.49	4.12	3.75	3.37	3.00

[a] Perpendicular distance from the tangent M_{IT}, is required.
[b] M_{IT} Not required, use M_I

Table 3.7 Design values of M_1 and M_{1T} at M_2 for major-road design speed = 60 km/h on two-lane intersections (Case 1(b): obstruction on the outside of horizontal curve, $d = 10d_1$)

R	Obstruction distance M_2 (m)					
	0	4	8[a]	12[a]	16[a]	20[a]
(a) Obstruction distance M_1 (m)						
200	4.77	4.34	3.99	3.72	3.52	3.41
300	4.88	4.51	4.20	3.95	3.74	3.59
400	4.93	4.60	4.31	4.06	3.85	3.68
500	4.96	4.65	4.37	4.13	3.91	3.73
600	4.98	4.69	4.42	4.17	3.96	3.77
700	5.00	4.71	4.45	4.21	3.99	3.79
(b) Obstruction distance M_{1T} (m)						
200	-[b]	-	3.99	3.67	3.34	3.02
300	-	-	4.20	3.91	3.62	3.33
400	-	-	4.31	4.03	3.76	3.48
500	-	-	4.37	4.11	3.84	3.57
600	-	-	4.42	4.15	3.89	3.63
700	-	-	4.45	4.19	3.93	3.67

[a] Perpendicular distance from the tangent M_{1T}, is required.
[b] M_{1T} Not required, use M_1

Table 3.8 Design values of M_1 and M_{1T} at M_2 for major-road design speed = 80 km/h on two-lane intersections (Case 1(b): obstruction on the outside of horizontal curve, $d = 10d_1$)

R	Obstruction distance M_2 (m)					
	0	4	8	12[a]	16[a]	20[a]
(a) Obstruction distance M_1 (m)						
200	4.74	4.29	3.92	3.62	3.41	3.27
300	4.88	4.53	4.22	3.97	3.77	3.62
400	4.95	4.64	4.37	4.14	3.94	3.79
500	5.00	4.71	4.46	4.24	4.05	3.89
600	5.02	4.76	4.52	4.31	4.12	3.96
700	5.04	4.79	4.56	4.36	4.17	4.01
(b) Obstruction distance M_{1T} (m)						
200	-[b]	-	-	3.62	3.36	3.10
300	-	-	-	3.97	3.73	3.50
400	-	-	-	4.14	3.92	3.70
500	-	-	-	4.24	4.03	3.82
600	-	-	-	4.31	4.11	3.90
700	-	-	-	4.36	4.16	3.96

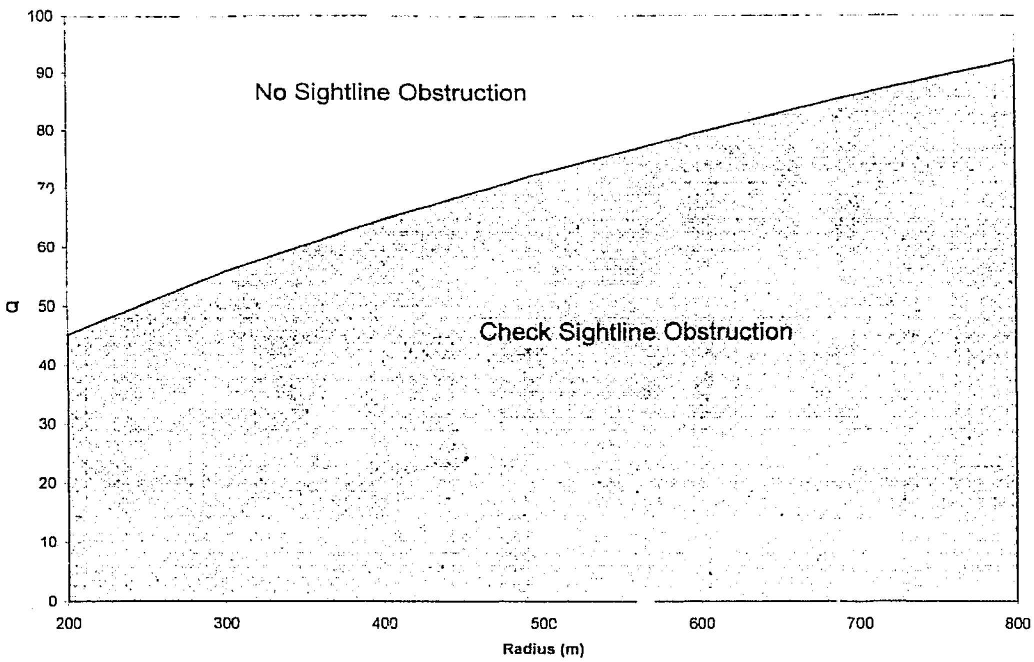
[a] Perpendicular distance from the tangent M_{1T}, is required.
[b] M_{1T} Not required, use M_1

Table 3.9 Design values of M_1 and M_{1T} at M_2 for major-road design speed = 100 km/h on two-lane intersections (Case 1(b): obstruction on the outside of horizontal curve, $d = 10d_1$)

R	Obstruction distance M_2 (m)					
	0	4	8	12	16[a]	20[a]
(a) Obstruction distance M_1 (m)						
300	4.86	4.48	4.16	3.89	3.67	3.50
400	4.95	4.63	4.35	4.12	3.92	3.76
500	5.00	4.72	4.47	4.25	4.07	3.91
600	5.04	4.78	4.55	4.34	4.17	4.01
700	5.06	4.82	4.60	4.41	4.24	4.09
800	5.08	4.85	4.65	4.46	4.29	4.14
(b) Obstruction distance M_{1T} (m)						
300	-[b]	-	-	-	3.67	3.47
400	-	-	-	-	3.92	3.74
500	-	-	-	-	4.07	3.89
600	-	-	-	-	4.17	4.00
700	-	-	-	-	4.24	4.07
800	-	-	-	-	4.29	4.13

[a] Perpendicular distance from the tangent M_{1T}, is required.
[b] M_{1T} Not required, use M_1

(a).



(b).

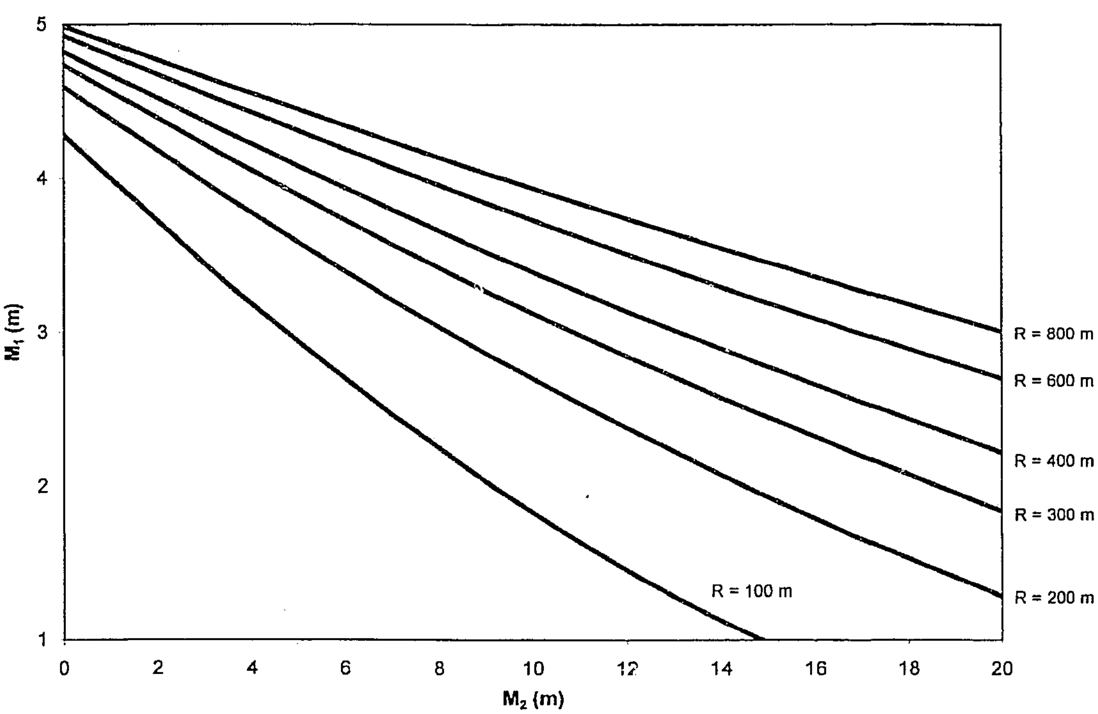
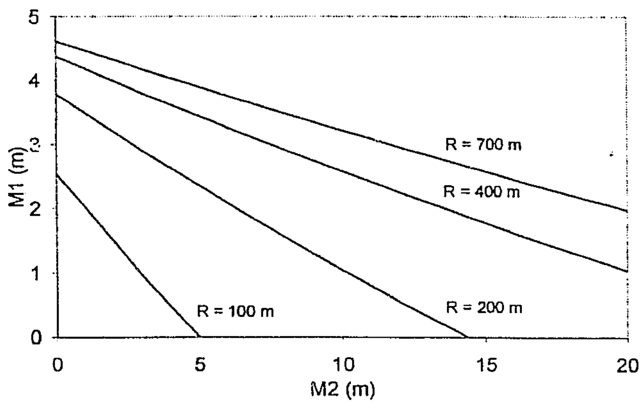
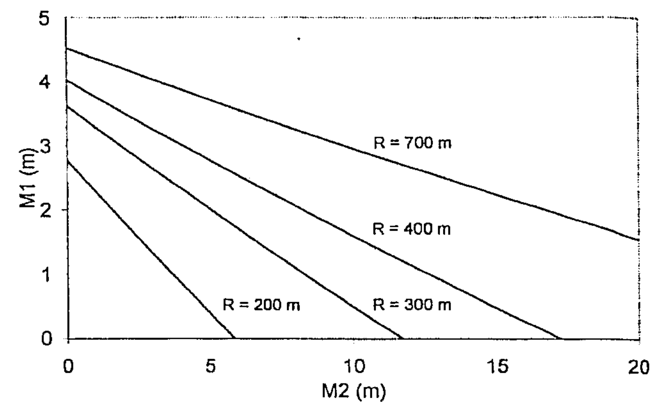


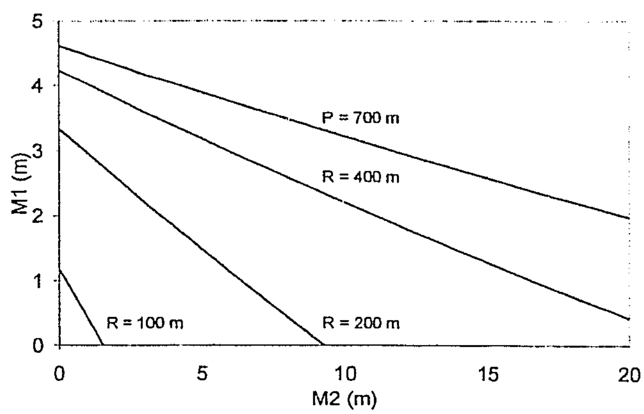
Figure 3.12 Initial check when obstruction is outside the curve: (a) check and (b) design Graph independent of major-road design speed



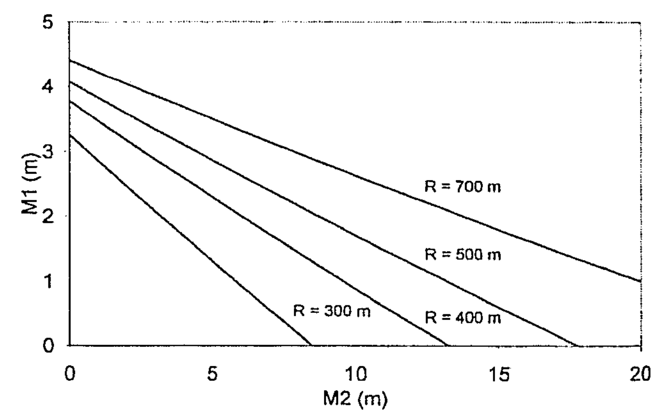
(Major-road design speed = 40 km/h)



(Major-road design speed = 80 km/h)

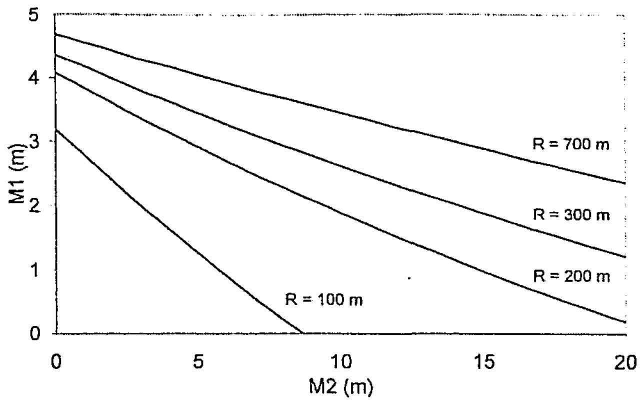


(Major-road design speed = 60 km/h)

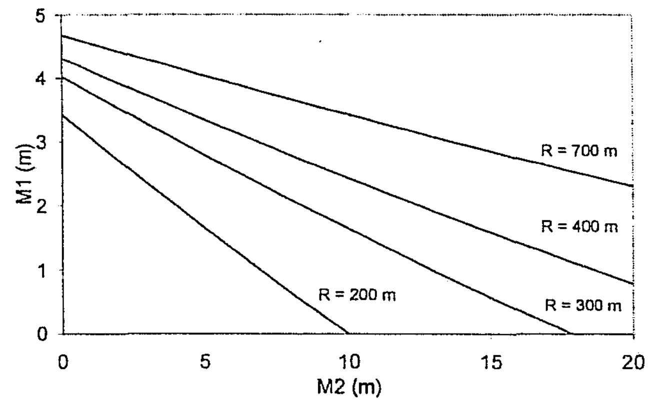


(Major-road design speed = 100 km/h)

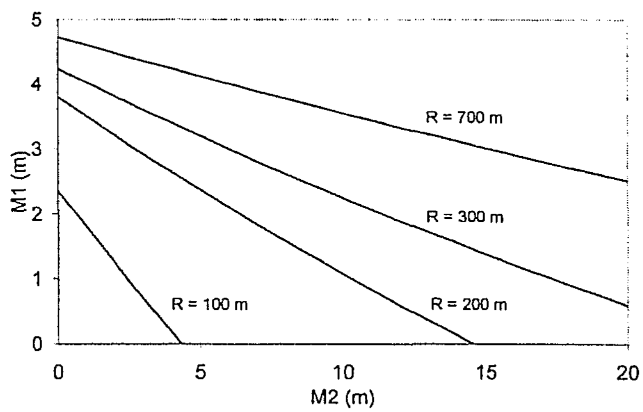
Figure 3.13 Design graphs for M_1 and M_2 for two-lane intersections on horizontal curves, Case 1(a) – Obstruction on the outside of horizontal curve ($d \leq d_1$) (Lane width = 3.6 m, major-road design speed = 40-100 km/h)



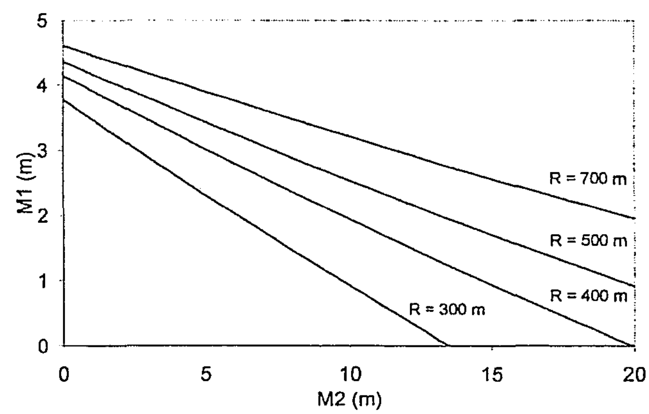
(Major-road design speed = 40 km/h)



(Major-road design speed = 80 km/h)

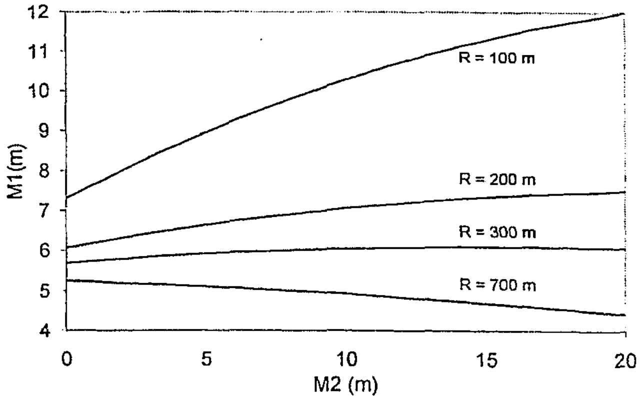


(Major-road design speed = 60 km/h)

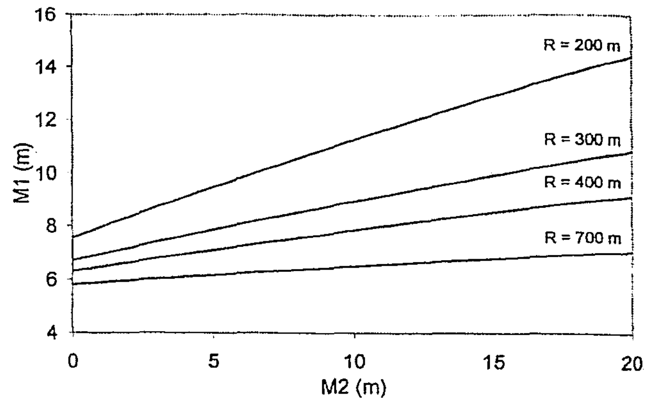


(Major-road design speed = 100 km/h)

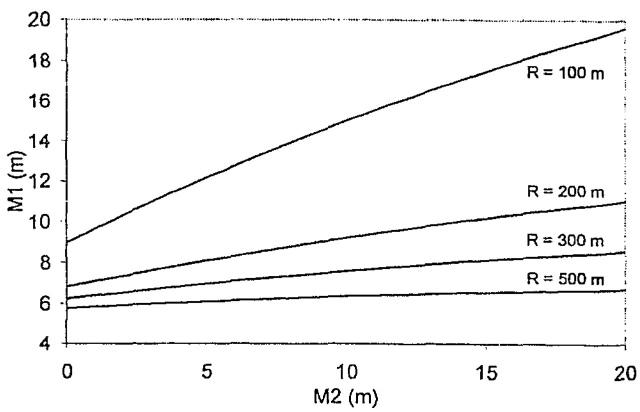
Figure 3.14 Design graphs for M_1 and M_2 for two-lane intersections on horizontal curves, Case 1(b) – Obstruction on the outside of horizontal curve ($d = 2d_1$) (Lane width = 3.6 m, major-road design speed = 40-100 km/h)



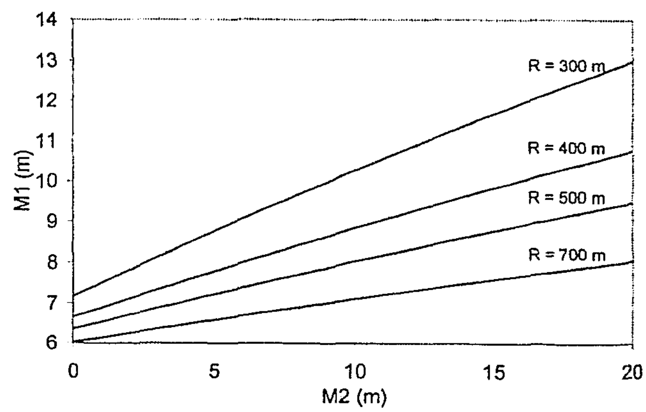
(Major-road design speed = 40 km/h)



(Major-road design speed = 80 km/h)

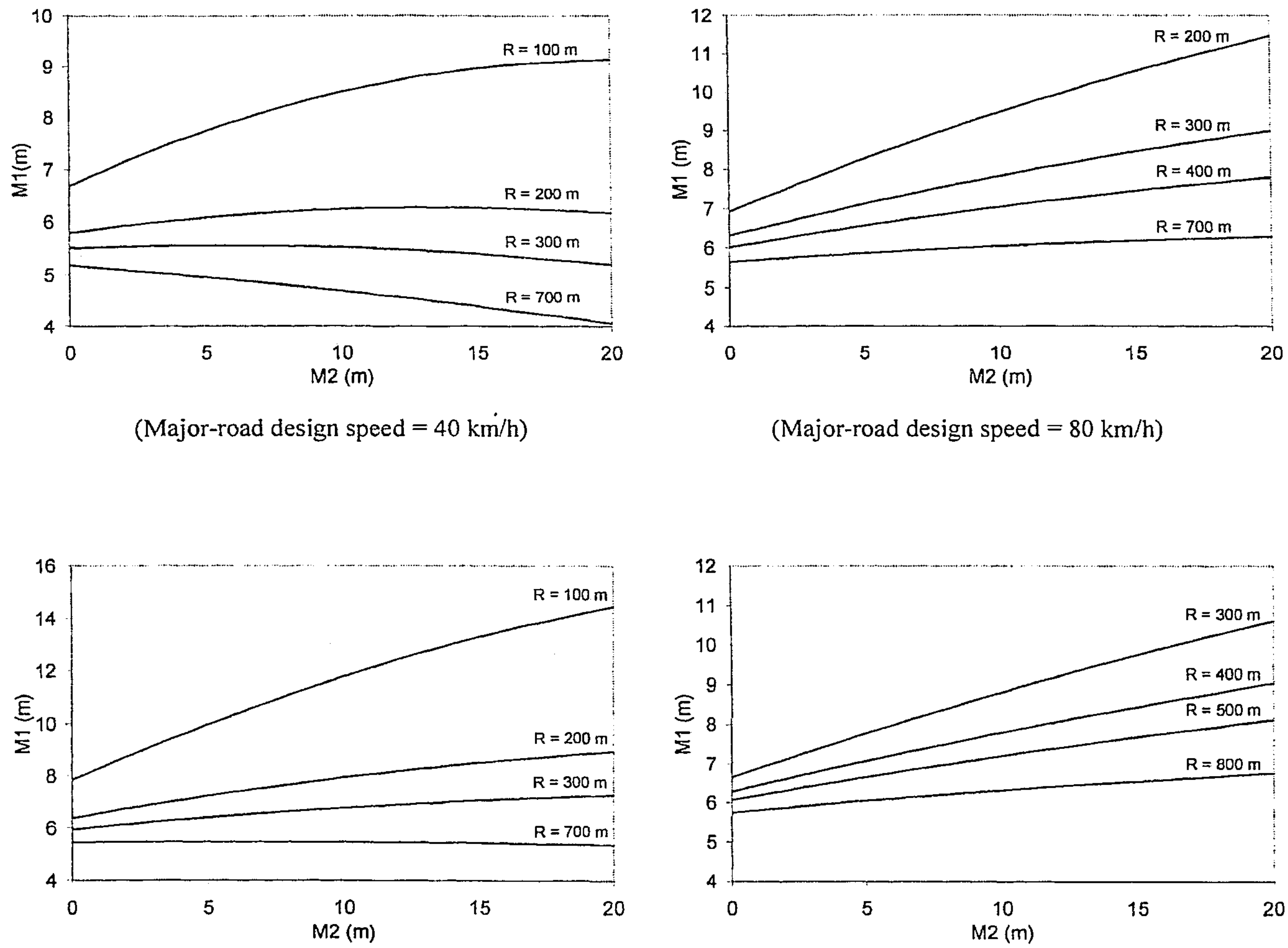


(Major-road design speed = 60 km/h)



(Major-road design speed = 100 km/h)

Figure 3.15 Design graphs for M_1 and M_2 for two-lane intersections on horizontal curves, Case 1(a) – Obstruction on the inside of horizontal curve ($d \leq d_1$) (Lane width = 3.6 m, major-road design speed = 40-100 km/h)



(Major-road design speed = 40 km/h)

(Major-road design speed = 80 km/h)

(Major-road design speed = 60 km/h)

(Major-road design speed = 100 km/h)

Figure 3.16 Design graphs for M_1 and M_2 for two-lane intersections on horizontal curves, Case 1(b) – Obstruction on the inside of horizontal curve ($d = 2d_1$) (Lane width = 3.6 m, major-road design speed = 40-100 km/h)

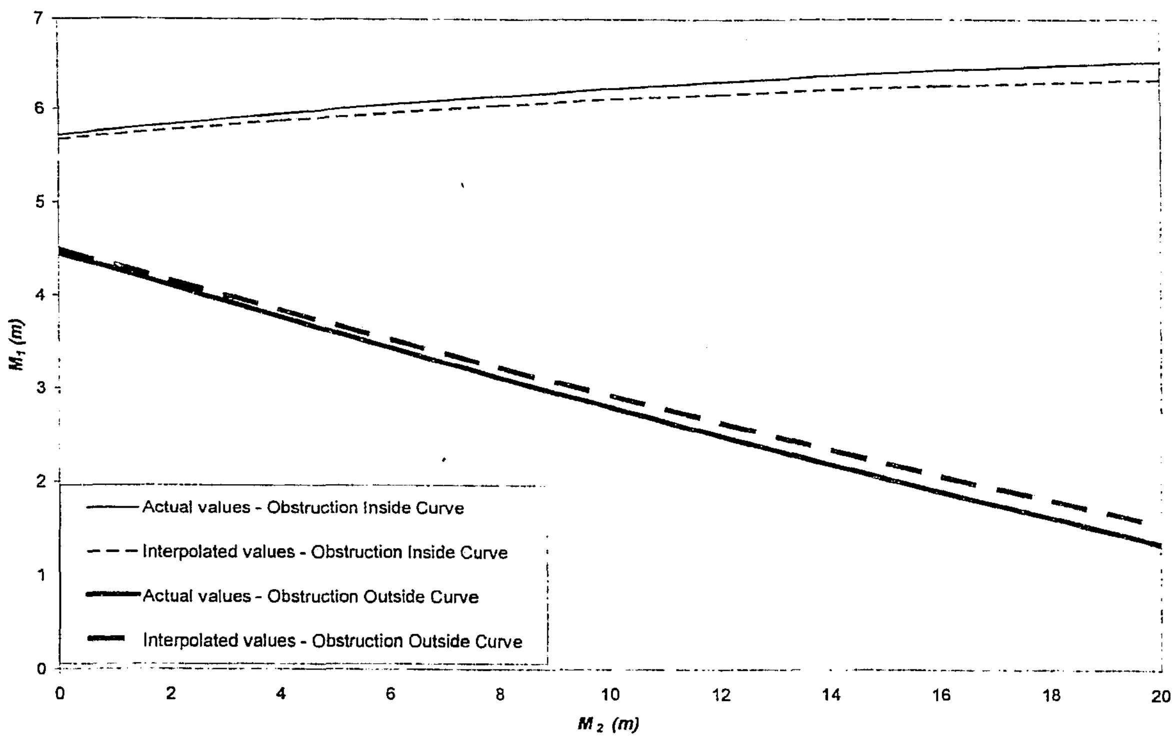


Figure 3.17 Interpolated vs. Actual values of M_1 at different M_2, Case 1 (b) – Values shown for Obstruction on inside and outside of curve (R = 500m, major road design speed = 60km/h, d = 1.33 d_1)

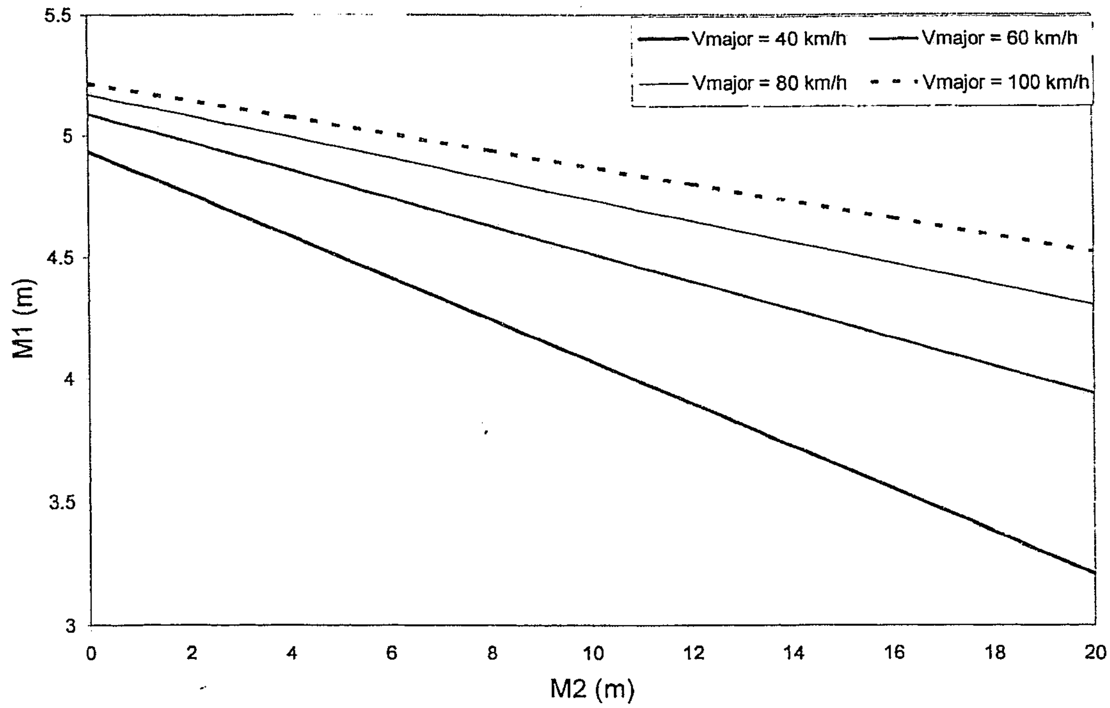
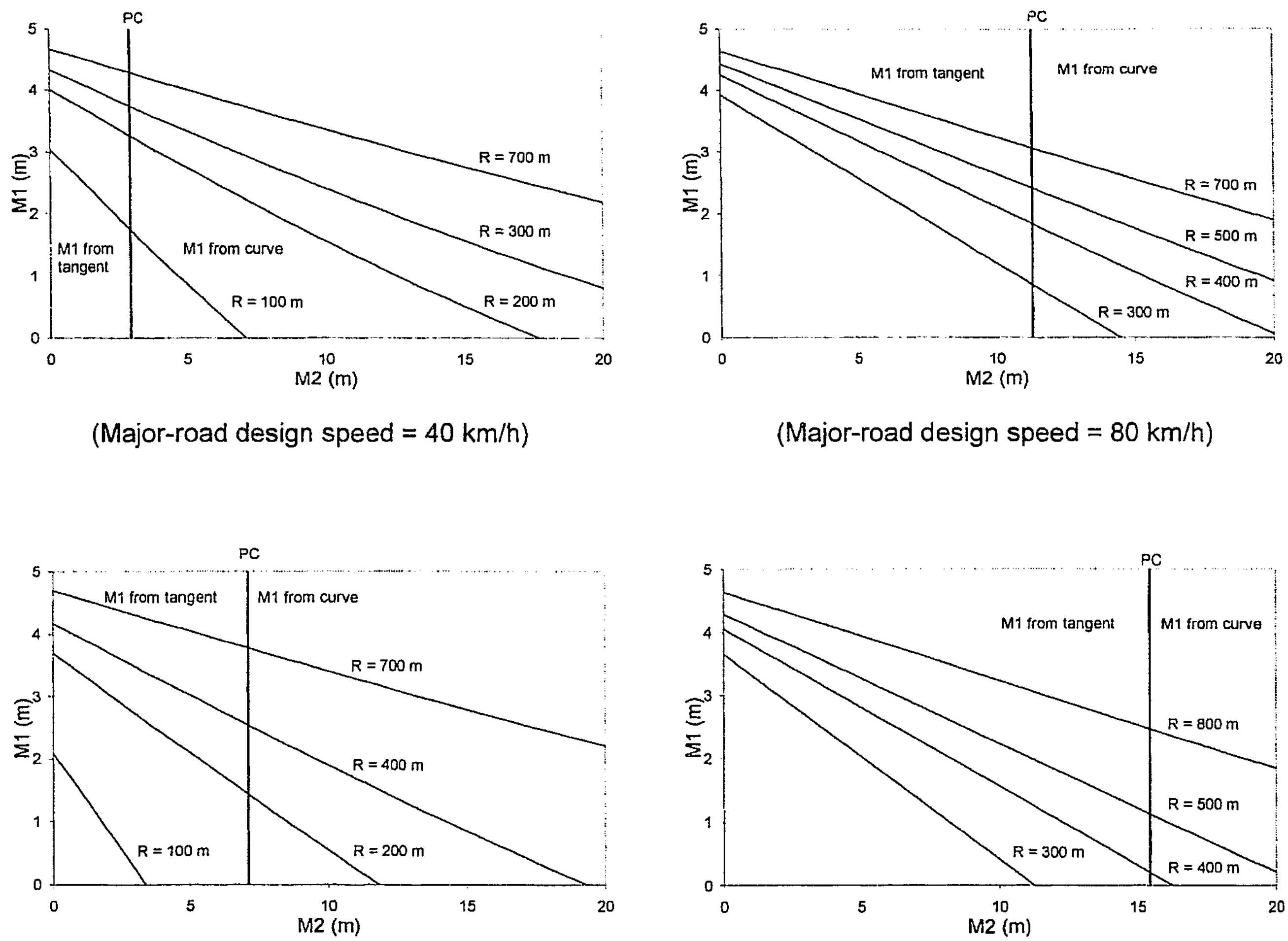


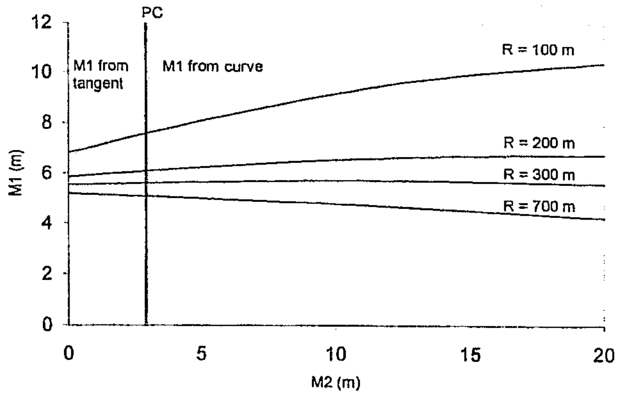
Figure 3.18 Design graphs for M_1 and M_2 when intersection and object lie on the tangent of major-road horizontal curve, Case 2 - Obstruction on the inside or outside ($d < d_1$) (Lane width = 3.6 m, major road design speed = 40 - 100 km/h)



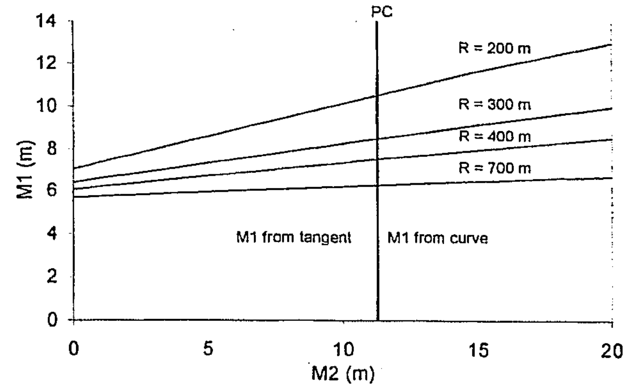
(Major-road design speed = 40 km/h) (Major-road design speed = 80 km/h)

(Major-road design speed = 60 km/h) (Major-road design speed = 100 km/h)

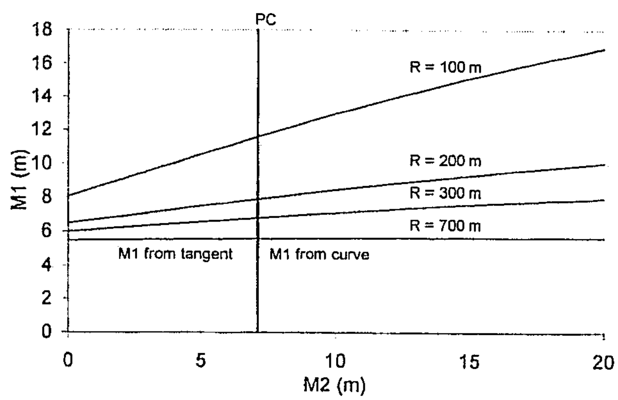
Figure 3.19 Design graphs for M_1 and M_2 for two-lane intersections on the tangent of major-road horizontal curve, Case 2– Obstruction on the outside of horizontal curve ($d = 10\ d_1$) (Lane width = 3.6 m, major road design speed = 40 - 100 km/h)



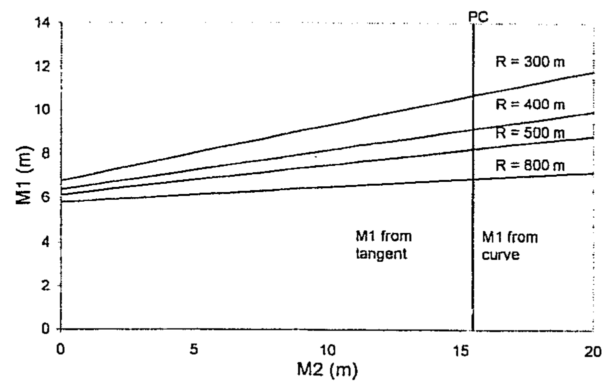
(Major-road design speed = 40 km/h)



(Major-road design speed = 80 km/h)



(Major-road design speed = 60 km/h)



(Major-road design speed = 100 km/h)

Figure 3.20 Design graphs for M_1 and M_2 for two-lane intersections on the tangent of major-road horizontal curve Case 2– Obstruction on the inside of horizontal curve ($d = 10\ d_1$) (Lane width = 3.6 m, major road design speed = 40 - 100 km/h)

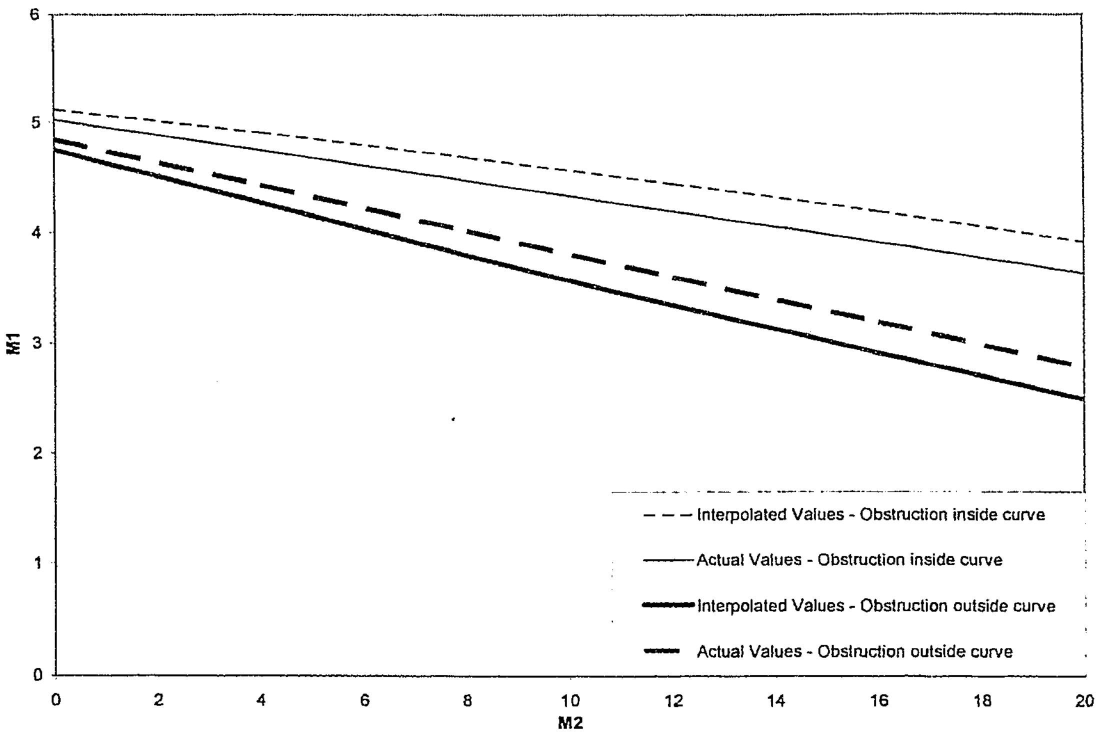


Figure 3.21 Interpolated vs. Actual values of M_1 at different M_2 , Case 2 – Values shown for Obstruction on inside and outside of Curve (R = 500m, major road design speed = 40km/h, d = 1.8 d_1)

Chapter 4: MODEL DEVELOPMENT: II. LEFT-TURN SIGHT DISTANCE AT 3D SIGNALIZED INTERSECTIONS

4.1. INTERSECTION GEOMETRY

To check the intersection sight distance, where the intersection is located on a horizontal curve, the following geometric characteristics are assumed (Figure. 4.1): (a) the major-road has a horizontal curve and (b) there is no vertical curvature. The presented model is applicable to skewed and non-skewed intersections, but a 90-degree intersection angle is assumed for simplicity (implications for skewed geometry are discussed later).

4.2. MATHEMATICAL MODEL

Throughout this chapter, the left-turn vehicle making the turn is referred to as the *observer*, the oncoming through vehicle as the *object*, and the opposite left-turn vehicle, which obstructs the sight line of the observer, as the *obstruction*. The centerline of the inside opposing through lane is used as the reference line for calculating the available sight distance, based on previous research (McCoy et al. 1992).

The positions of both vehicles (observer and obstruction) within the intersection are determined based on their lateral and longitudinal distances from the reference points. Let the lateral and longitudinal distances be measured along the lines perpendicular to the tangent to the horizontal curve and to the minor-road, respectively. Then, the lateral position refers to the lateral distance measured from the extension of the left edge of the lane from which a vehicle is turning, and the longitudinal position refers to the longitudinal distance measured from the extension of the left edge of the lane on the cross minor street, into which it is turning. The vehicle positioning variables used in the model are shown in Figure. 4.2.

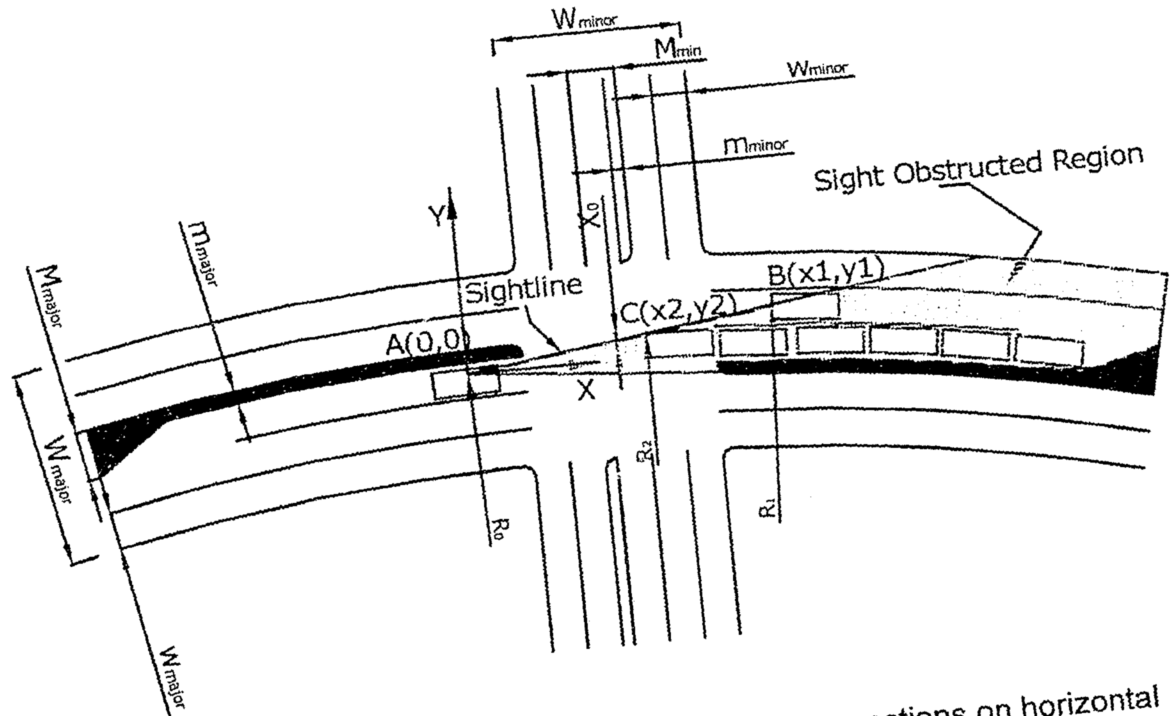


Figure 4.1 Left-turn intersection sight distance at intersections on horizontal curves

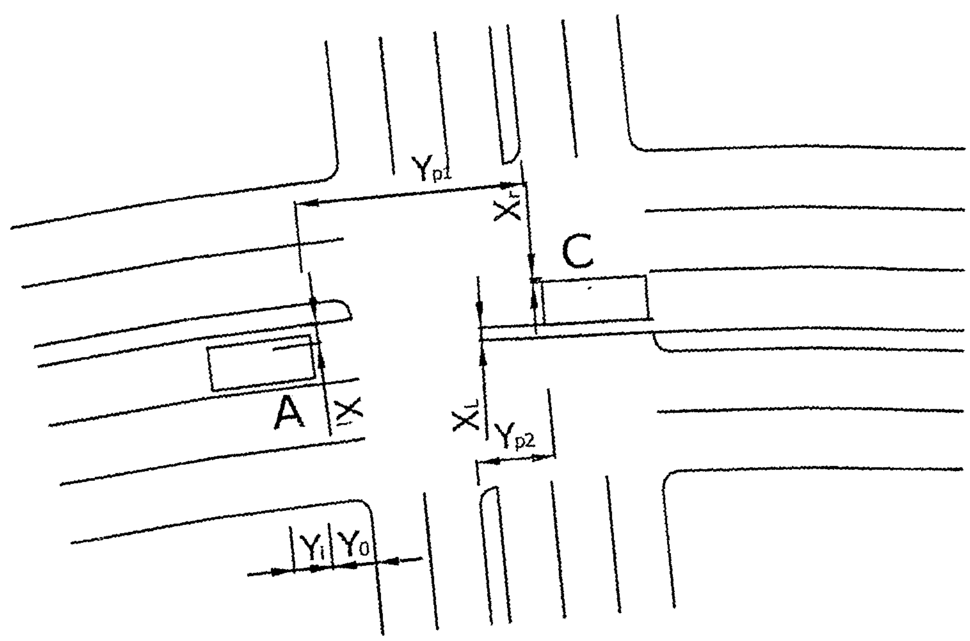


Figure. 4.2 Vehicle positioning

The lateral positions of the observer (to driver's eye) and obstruction (to the front left-corner) are denoted by X_i and X_L, respectively, whereas the longitudinal positions of observer (from the front) and object (from the front right corner) are given by Y_{p1} and Y_{p2}. The left-turn lane offset Xo is the lateral distance from the left edge of the lane occupied by the observer to the right edge of the lane occupied by the obstruction, at the center of the minor-road (Figure. 4.1). X_o is considered negative if the latter edge is to the left of the former, and vice versa. The minimum required left-turn lane offset is the offset that would enable an unobstructed view of the object by the observer when the former is at a distance equal to the required sight distance from the point of conflict.

Analytical geometry was used to determine the minimum offset required for unobstructed sightline for left-turn vehicles. The concept used for the analysis is similar to the analysis of stop-control intersection sight distance on 3D highway alignments (Easa et al. 2004). The model involves several tasks including determination of the required sight distance, establishing coordinates of sightline and obstruction, and checking sightline obstruction.

The required sight distance is calculated using Equation (2.1) and the time gap is determined using Table 2.2.

4.2.1. Establishing Coordinates of Object and Obstruction

The widths of the major and minor roads are given by

$$W_{major} = M_{major} + 2n_{major}\, w_{major} \tag{4.1}$$

$$W_{minor} = M_{minor} + 2n_{minor}\, w_{minor} \tag{4.2}$$

where W_{major} M_{major}, w_{major}, and n_{maj} = total width, median width, lane width, and number of lanes in one direction for the major-road (similarly for the minor-road variables).

The road surface under the driver's eye of the left-turn vehicle (observer) is considered as the point of origin for the global Cartesian coordinates with the *y*-axis being parallel to the minor-road. The coordinates of Point A (driver's eye) are $(0, 0, h_d)$. The radius of the arc on which the origin A lies is is given by (Figure. 4.1)

$$R_0 = R + \frac{M_{major}}{2} - m_{major} - X_i \tag{4.3}$$

where R = radius of horizontal curve along the centerline of the major-road (m), m_{major} = width of medial separator along major-road (m), and X_i = Lateral distance of driver's eye from the left edge of the left-turn lane (m). The coordinates of Point B (object) are (x_1, y_1) and the radius of the horizontal-curve path for the object (along the centerline of the inside lane) is (Figure. 4.1)

$$R_1 = R + \frac{M_{major} + w_{major}}{2} \tag{4.4}$$

The object travels a distance d' on the curve before it reaches the centerline of the minor-road given by

$$d' \cong ISD_a + \frac{(w_{\min or} + M_{\min or})}{2} \tag{4.5}$$

where ISD_a = available sight distance measured from the front of the object to the point of conflict, which is the same as for the crossing maneuver presented in AASHTO (2001). For the observer to perform a safe left-turn maneuver, the available sight distance should be at least equal to the minimum required sight distance given by Equation (2.1). Hence, substituting ISD_a for d in Equation (4.5), gives

$$d' \cong d + \frac{(w_{\min or} + M_{\min or})}{2} \tag{4.6}$$

The central angle for this arc with length d' is calculated as:

$$\phi = \frac{180d'}{\pi R_1} \tag{4.7}$$

ϕ = central angle (in degrees) for the curved path with length d'. From Figure 4.3, the x-coordinate of Point C is given by

$$x_1 = R_1 \sin\phi + Y_i + Y_0 + \frac{W_{min\,or}}{2} \tag{4.8}$$

where Y_O, distance from the front of the vehicle to the edge of the minor-road (m), is given by

$$Y_0 = Y_{p1} - \left(\frac{W_{min\,or} + M_{min\,or}}{2}\right)$$

and Y_i = distance from driver's eye to the front of the vehicle (m).

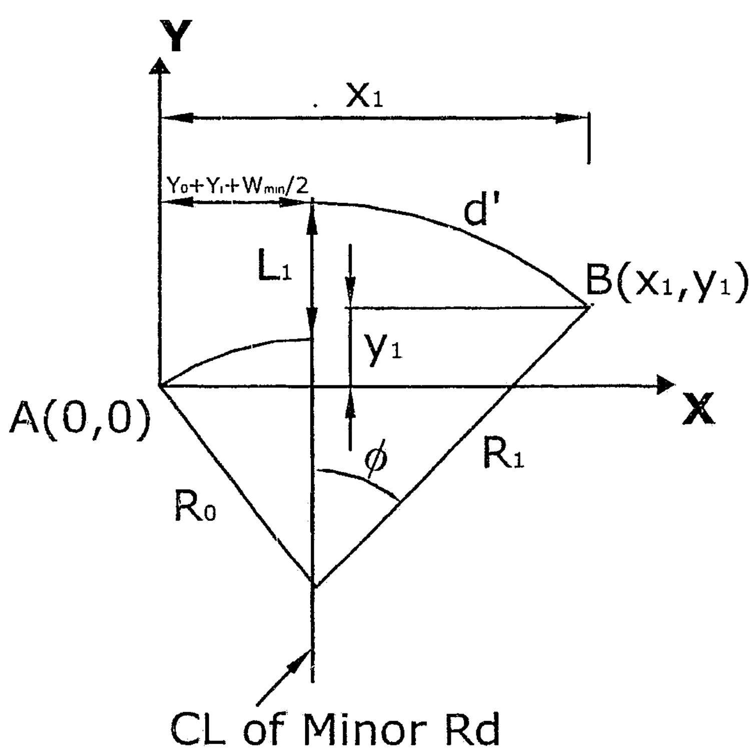


Figure. 4.3 Coordinates of object

Similarly, the y-coordinate can be obtained as

$$y_1 = L_1 - R_1(1-\cos\phi) + \left(R_0 - \sqrt{R_0^{\,2} - \left(Y_0 + Y_i + \frac{W_{\min or}}{2}\right)^2}\right) \tag{4.9}$$

where

$$L_1 = \frac{w_{major}}{2} + m_{major} + X_i$$

To establish the coordinates of the obstruction, it is assumed that the observer's sightline to the object is obstructed by the front-right corner of the opposing left-turning vehicle stopping at the opposite left-turn lane. Note that this assumption is appropriate as the sightline around the obstruction might be obstructed in the presence of a larger vehicle, or a queue of left-turn vehicles (Figure. 4.1). The coordinates of Point B (obstruction) are (x_2, y_2) and the corresponding radius is given by

$$R_2 = R + \frac{M_{major}}{2} - m_{major} - X_0 - X_r \tag{4.10}$$

where X_r = lateral distance of front right corner of obstruction from the right edge of the left-turn lane from which it is turning (m). It is given by

$$X_r = w_x - V_w - X_L \tag{4.11}$$

where w_x = width of left-turn lane (m) and V_w = vehicle width (m), which equals 2.13 m for passenger cars (AASHTO 2001). Also,

$$X_o = M_{major} - 2m_{major} - w_x \tag{4.12}$$

Then, from Figure. 4.4, the x-coordinate of Point C is given by

$$x_2 = \frac{W_{\min or} - M_{\min or}}{2} + Y_i + Y_0 + Y_{p2} \tag{4.13}$$

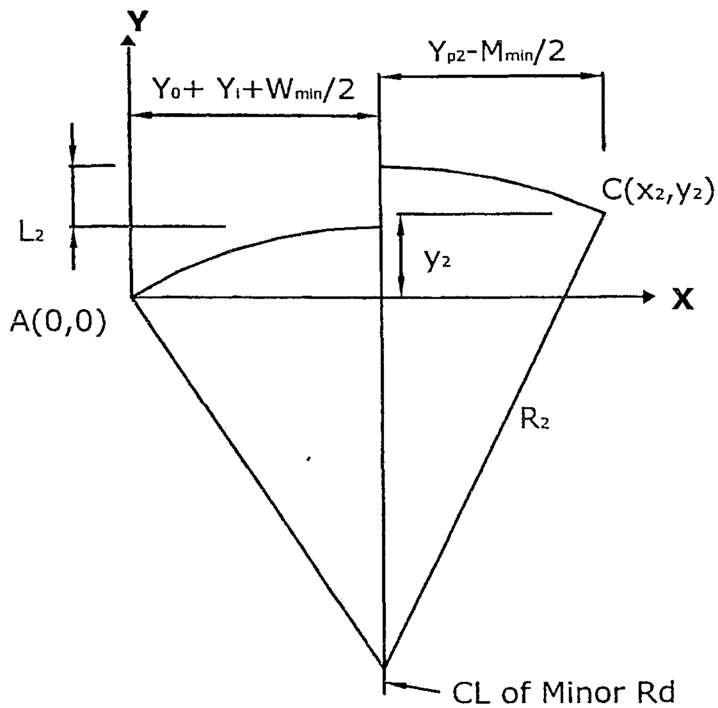


Figure. 4.4 Coordinates of obstruction

Similarly, the y-coordinate y_2 is given by

$$y_2 = L_2 - \left(R_2 - \sqrt{R_2^2 - \left(Y_{p2} - \frac{M_{\min or}}{2} \right)^2} \right) + \left(R_0 - \sqrt{R_0^2 - \left(Y_0 + Y_i + \frac{W_{\min or}}{2} \right)^2} \right) \tag{4.14}$$

where $L_2 = X_i - X_0 - X_r$

4.2.2. Checking Sightline Obstruction

To ensure that the sightline to the object is not obstructed, the slopes of the sightlines to the object and obstruction are compared. The slope of the sightline to the object is given by $\tan \alpha = y_1/x_1$, while the slope of the sightline to the obstruction is given by $\tan \beta = y_2/x_2$ (Figure. 4.5).

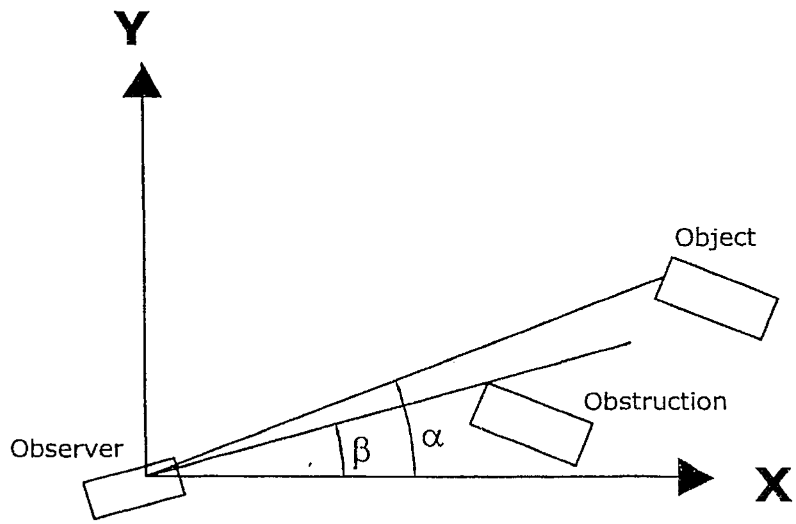


Figure. 4.5 Slopes of sightlines to the object and obstruction

The sightline to the object is not obstructed if

$$\tan\beta \le \tan\alpha$$

or

$$y_2/x_2 \le y_1/x_1 \qquad (4.15)$$

Substituting variables and solving for X_0, Equation (4.15) may be written as

$$X_0 = A - X_r - \sqrt{\left(\frac{y_1}{x_1}x_2 + A - X_i - R_0 + \sqrt{R_0^2 - \left(Y_0 + Y_i + \frac{W_{\min or}}{2}\right)^2}\right)^2 + \left(Y_{p2} - \frac{M_{\min or}}{2}\right)^2}$$

(4.16)

where

$$A = R + \frac{M_{major}}{2} - m_{major}$$

and x_1, y_1, x_2, and y_2 are obtained using Equations. (4.8), (4.9), (4.13), and (4.14). For a given geometric configuration and design speed on the major-road, use Equations. (4.1) to (4.9), (4.13), and (4.14) to calculate x_1,y_1, x_2 and y_2, respectively. Check the condition given in Equation (4.15). If it is not satisfied, use Equation (4.16) to calculate the minimum required offset which provides unobstructed sightline to the object for the given conditions.

The required median width to accommodate the required offset can be calculated by using the required offset in Equation (4.12) and solving for the median width. It should be noted that if the right of way is limited or the methodology is applied to an existing intersection where it is not possible to increase the width of the major-road, the designer might have to reduce the through-lane width to accommodate the required median.

To simplify the analysis, the preceding mathematical model was translated to an Excel worksheet (Appendix. C). The calculations of offset and median requirements for intersections on horizontal curves can be performed for any geometric configuration (e.g. curvature of major-road, and number of lanes and lane widths of the minor and major roads). Different design speeds along the major-road, and longitudinal and lateral positioning of vehicles based on field observations may also be used.

4.2.3. Major-Road Surface Obstruction

Similar to the procedure used to check the major-road surface obstruction in chapter 3, coordinate z_1 of object is given by

$$z_1 = \frac{rx_1^{\,2}}{2} - g_t x_1 + h_o \tag{4.17a}$$

(Observer and Object on curve)

$$z_1 = \frac{rP^2}{2} - g_t P - g_1(x_1 - P) + h_0 \tag{4.17b}$$

(Observer on curve & Object before PVC)

$$z_1 = g_1(P + L) + \frac{rL^2}{2} + g_2(x_1 - L - P) - h_0 \tag{4.17c}$$

(Observer before PVC and Object beyond PVT) where g_t = slope of the vertical curve at the minor-road vehicle path, r = rate of change of grade of vertical curve, and h_0 = height of the approaching vehicle on major-road. The variable r and g_t are given by

$$r = \frac{g_2 - g_1}{L} \tag{4.18}$$

$$g_t = g_1 + r P \tag{4.19}$$

where g_1 and g_2 = first and second grades of the vertical curve in decimal, L = length of vertical curve (m), and P = distance from the point of vertical curvature (PVC) to the Observer (m).

As both the observer and object lie on the major-road, the assumption of observer at the centerline of the major-road is quite reasonable in this case. Similar to ISD analysis for stop-control intersection presented earlier, three cases are addressed: (a) Observer and object are within the vertical curve, (b) Observer on curve and approaching vehicle on tangent i.e. before PVC. This case exists when there is a vertical curve and x_1 calculated for any case of 'off-road obstruction' is greater than P. Note that the approaching vehicle is considered to be on the first grade for the development of analysis. This assumption is made to avoid the confusion of using positive or negative sign of x_1. (a) Observer on First tangent and Object on Second tangent. From Figures 3.9, 3.10 and 3.11, the coordinate z at any point x on the curve is given by

$$z = \frac{rx^2}{2} - g_t x \tag{4.20}$$

The sightline 'S' to the approaching vehicle is a straight line with a start point at the driver's eye $(0,h_d)$ and an end point at the top of the approaching vehicle (x_1,z_1). Comparing slopes using equation of a straight line, we have

$$\frac{z - h_d}{x - 0} = \frac{z_1 - h_d}{x_1 - 0} \tag{4.21}$$

Substituting for z_1 and z from (4.17a), (4.17b), (4.17c) and (4.20) in (4.21), then

$$\frac{rx_1}{2}x^2-(\frac{rx_1^{\,2}}{2}+h_o-h_d)x-h_dx_1=0 \qquad (4.22a)$$

(Observer and Object on curve)

$$\frac{rx_1}{2}x^2+\left(g_1(x_1-P)+g_tP-h_0+h_d-g_tx_1-\frac{rP^2}{2}\right)x-h_dx_1=0 \qquad (4.22b)$$

(Observer on curve & Object before PVC)

$$\frac{rx_1}{2}x^2+\left(g_1(P+L)+\frac{rL^2}{2}+g_2(x_1-L-P)-h_0-h_d+g_tx_1\right)x-h_dx_1=0 \qquad (4.22c)$$

(Observer before PVC and Object beyond PVT)

The major-road surface obstructs the sightline only if Equation (4.22a), (4.22b) or (4.22c) has a solution within the range,

$$0\le x\le x_1$$

4.3. MODEL VERIFICATION

For the purpose of verification, the radius of the horizontal curve was set to a very large value (i.e. R $\cong\infty$), which means that the horizontal curve virtually becomes a straight line. The results for minimum required left-turn lane offsets were then compared with the guidelines for intersections located on a straight highway section (Easa and Ali 2004). The results for the desired offsets, defined as the offsets that provide unobstructed sight distance regardless of the required sight distance (McCoy et al. 1992), were also compared. For this purpose, the radius of horizontal curve and the required sight distance along the major-road were set to a very large value (representing straight major-road with very large required sight distance). The developed methodology was then applied and the offsets were calculated. The values of the required offset that satisfies this infinite sight distance represent the desirable offset. The desired offset for infinite radius (straight major-road) was found to be 0.61 m, which is the same value established for straight highway sections when the opposing vehicle is a passenger car (McCoy et al. 1992). The results for the case of opposing truck were also found to be accurate. It should be noted that the calculations for the purpose of verification were performed using the vehicle positioning and other input data used in the existing guidelines.

4.4. EVALUATION PROCEDURE

Whether the major-road is a straight highway or it has a horizontal curve, the guidelines developed in this chapter can be applied directly. Note that for straight major-road ($R = \infty$). To calculate the required offset for an intersection where left-turns are permitted from major-road, the procedure is as under:

1. Calculate the required sight distance d using Equation (2.1)
2. Calculate the total widths of major and minor roads, W_{major} and W_{minor} using Equations (4.1) and (4.2), respectively.
3. Calculate the radii of the curved paths of observer (under driver's eye) and object R_0, and R_1 using Equations (4.3) and (4.4), respectively.
4. Calculate total curved path d' using Equation (4.6).
5. Calculate the central angle ϕ of the arc with length d' using Equation (4.7).
6. Calculate x_1 and y_1 using Equations (4.8) and (4.9), respectively.
7. Calculate the current offset Xo, using Equation (4.12).
8. Calculate the radii of the curved paths of the right corner of obstruction R_2 using Equations (4.10).
9. Calculate x_2 and y_2 using Equations (4.13) and (4.14), respectively.
10. Check for sightline obstruction using Equation (4.15), if $y_1/x_1 \geq y_2/x_2$.
11. If $y_1/x_1 < y_2/x_2$, the sightline to the object is obstructed. Calculate the required minimum offset for which the sightline becomes unobstructed is using Equation (4.16).
12. The required median width to accommodate the required offset can be calculated using the required minimum offset calculated above and solving for the median width in Equation (4.12).

4.5. DESIGN AIDS

Using the analytical model, design aids were established to determine the intersection sight distance for different intersection configurations. Two cases of minor-road are presented. Case 1 considers a four-lane divided minor-road, while Case 2 considers a two-lane undivided minor-road. The following AASHTO recommended values were used in developing the design aids:

- The distance from driver's eye to the front of vehicle, Y_i is 2.4 m
- The width of design vehicle (passenger car), V_w is 2.13 m
- The lane width of the major and minor roads, w_{major} and w_{minor}, is 3.6 m
- The median width of the major and minor roads, M_{major} and M_{minor}, is 4.8 m with a medial separator of 1.2 m (m_{minor} or m_{major}).

Both the observer and obstruction were considered to be at the center of the occupied lanes and hence the lateral positions were determined accordingly. Two longitudinal positions of the obstruction are used for Case 1 (a) when the obstruction is located at the edge of the minor-road, (b) when the obstruction moves into the intersection covering a distance equal to the lane width. For Case 2, the obstruction is assumed to be located at the edge of the minor-road. Note that unlike straight intersections, the offset requirements for intersections on horizontal curves (when the obstruction vehicle is positioned into the intersection) are less critical than when it is stopped behind the stop line in most cases. This happens when y_1 is negative (the object vehicle is to the right of the observer due to curvature). Recall that it is assumed here that the observer cannot view the object from the right side of the obstruction as his sightline might be obstructed by other left-turn vehicles in the queue. As the radius becomes flatter, y_1 increases (becomes less negative) and eventually becomes positive. As a result, the offset requirements for the case when the obstruction vehicle is positioned become more critical.

Easy-to-use design aids are presented in Figures. 4.7 and 4.8. The design aids were developed for design speeds of 40, 60, 80 and 100 km/h. By plotting the point for a given radius and design speed, the designer can check sightline obstruction. If the point lies below the corresponding curve, the sightline is obstructed, and vice versa. The designer can then determine the required minimum offset by extending the point vertically up till it hits the corresponding curve. Then, a horizontal line drawn to the left will give the required minimum offset that provides an unobstructed sightline. Alternatively, the designer can extend the point vertically down to determine the speed that provides unobstructed sightline for the given conditions.

Table 4.1 Design guidelines for Left-Turn Lane Offset for Case 1(a) [a]

Radius of Horizontal Curve, R (m)	Left-turn Lane Offset Xo (m)			
	Speed of Major-Road V_{major} (km/h)			
	40	60	80	100
300	1.57	3.15	- [b]	-
500	0.67	1.74	2.68	3.56
700	0.28	1.14	1.86	2.52
900	0.06	0.81	1.41	1.94
1100	-0.07	0.59	1.12	1.58
1300	-0.17	0.45	0.92	1.32
1500	-0.24	0.34	0.77	1.14

[a] n_{majo}, n_{minor} = 2 and M_{major}, M_{minor} = 4.88 m.

[b] values for radii less than or equal to the minimum radius are not included.

Table 4.2 Design guidelines for Left-Turn Lane Offset for Case 1(b) [a]

Radius of Horizontal Curve, R (m)	Left-turn Lane Offset Xo (m)			
	Speed of Major-Road V_{major} (km/h)			
	40	60	80	100
300	1.50	2.83	- [b]	-
500	0.70	1.60	2.39	3.12
700	0.36	1.08	1.68	2.23
900	0.16	0.79	1.29	1.74
1100	0.04	0.60	1.04	1.42
1300	-0.04	0.47	0.87	1.21
1500	-0.11	0.38	0.74	1.05

[a] n_{major}, n_{minor} = 2 and M_{major}, M_{minor} = 4.88 m.

[b] values for radii less than or equal to the minimum radius are not included.

Table 4.3 Design guidelines for Left-Turn Lane Offset for Case 2 [a]

Radius of Horizontal Curve, R (m)	Left-turn Lane Offset Xo (m)			
	Speed of Major Road V_{major} (km/h)			
	40	60	80	100
300	0.97	1.72	-[b]	-
500	0.53	1.05	1.50	1.90
700	0.34	0.77	1.11	1.42
900	0.23	0.61	0.89	1.14
1100	0.17	0.50	0.76	0.97
1300	0.12	0.43	0.66	0.85
1500	0.09	0.38	0.59	0.77

[a] $n_{major} = 2$, $n_{minor} = 1$, $M_{major} = 4.88$ m, and $M_{minor} = 0$.

[b] values for radii less than or equal to the minimum radius are not included.

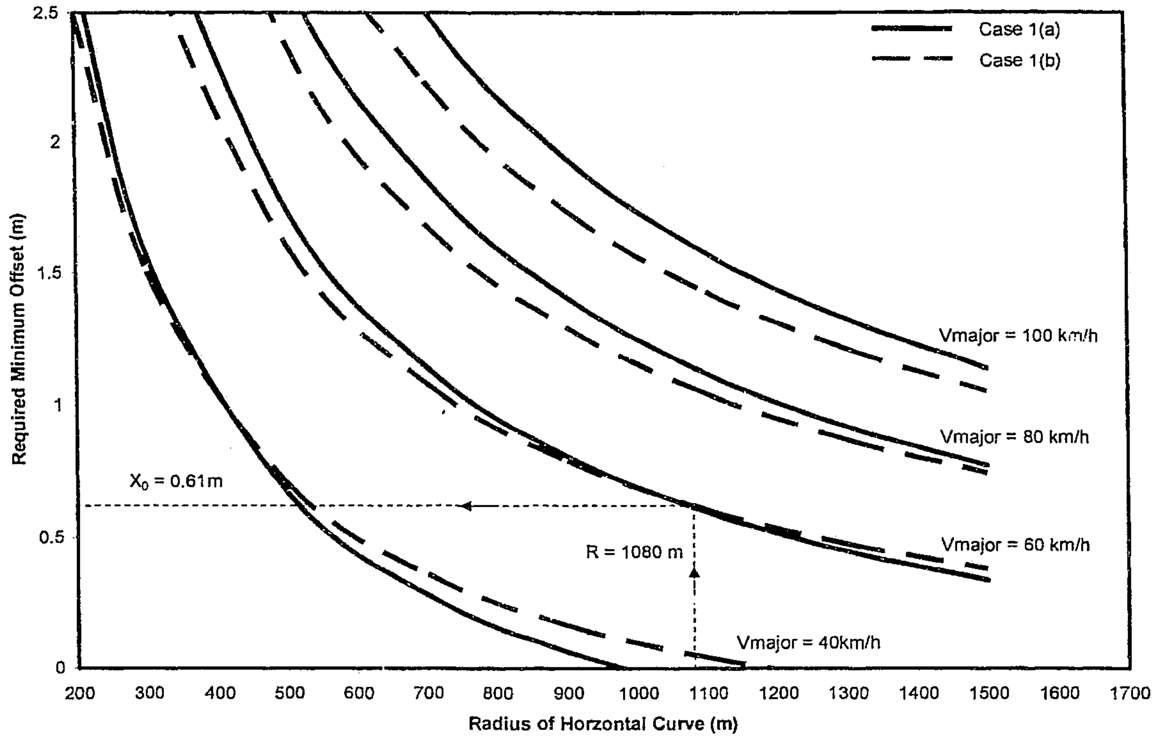


Figure. 4.6 Required minimum left-turn lane offsets for Case 1(a) and Case 1(b) (n_{major}, n_{minor} = 2, M_{major}, M_{minor} = 4.88 m)

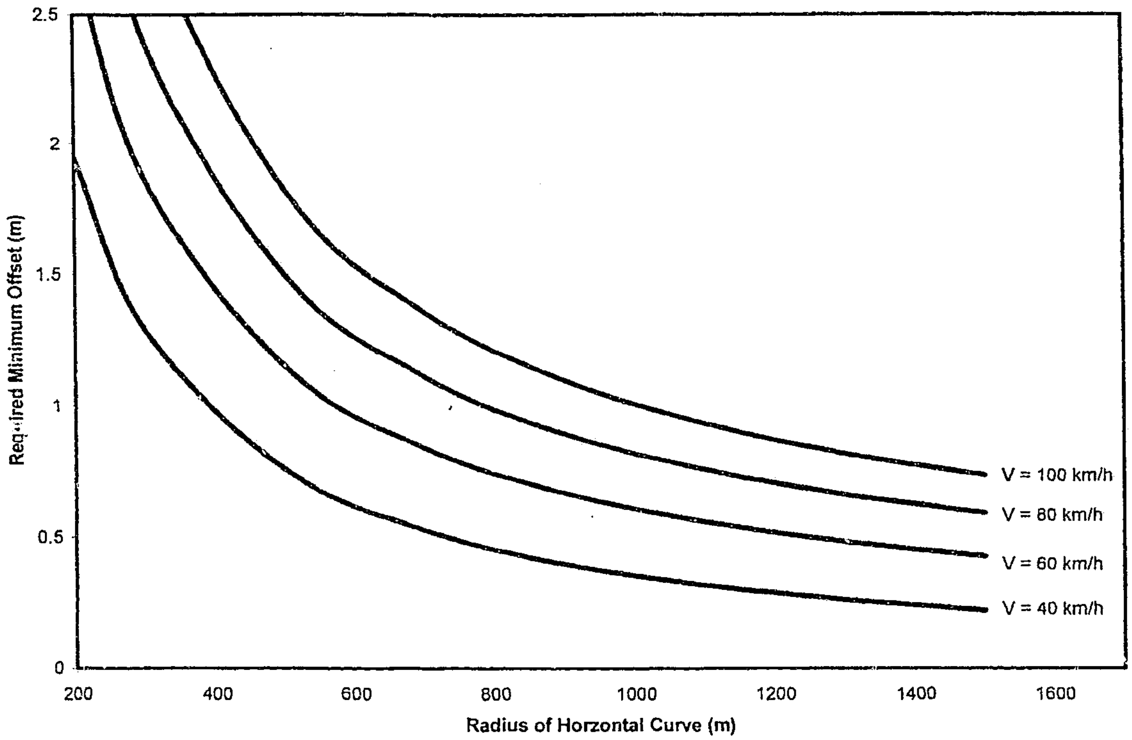


Figure. 4.7 Required minimum offset for two-lane undivided minor-road for Case 2 ($n_{major} = 2$, $n_{minor} = 1$, $M_{major} = 4.88m$ and $M_{minor} = 0$)

Chapter 5: APPLICATION

5.1. PRACTICAL APPLICATION FOR STOP-CONTROL INTERSECTION

The application of the methodology is shown on an existing intersection (Dundas St. and Pembroke St.). Dundas st. constitutes the major-road while Pembroke st. is the minor-road. The intersection is located in downtown Toronto. Pembroke St. operates one-way southbound and is a residential street which crosses Dundas St. (a major highway). The minor-road approach is stop-control. The satellite image of the intersection is shown in Figure 5.1. GIS ArcView was used to establish the location of object and observer based on the presented methodology. The detailed procedure is discussed in the following sections.

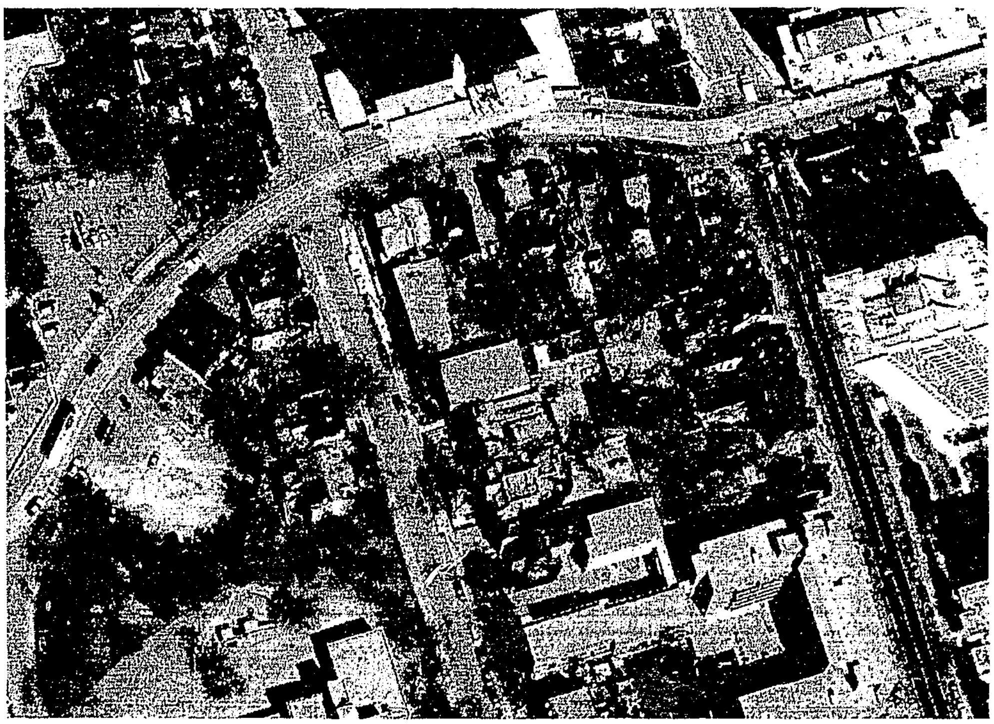


Figure 5.1 Aerial view of the modeled intersection

5.1.1. Data Collection

The intersection is located in zone NBV of Toronto. Ortho image of this zone was acquired through the geospatial database of Ryerson Library. In addition, geometric drawing of the intersection was obtained from the Toronto Works and Emergency Department.

5.1.2. Model Application

The radius of the horizontal curve at the centerline of the major-road was obtained from the geometric drawing. The center of the radius was then fixed. A line from the origin of the radius was drawn through the intersection of major and minor-road (intersection of the centerlines of major and minor roads). A line along the centerline of minor-road was also drawn. Recall that the skew of the intersection is measured from the line perpendicular to the tangent to the horizontal curve. The minor-road does not pass through the center and hence a skew of 9^0 exists at the intersection. (Figure. 5.2)

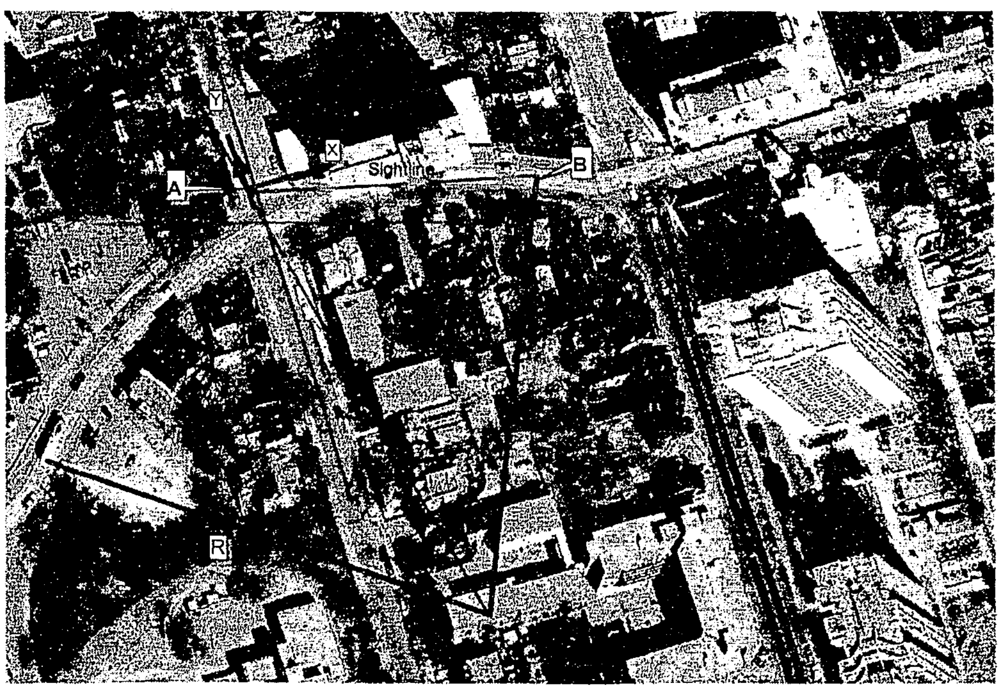


Figure 5.2 Establishment of center of curve and sightline

Point. A in Figure. 5.2 represent the point of origin of the Cartesian coordinates with the x and y-axis being perpendicular and along the minor-road respectively. Point B represents the position of the object according to the required sight distance. Note that position of the object is only shown for the vehicle approaching from left. Position of the vehicle approaching from right can be fixed in the similar manner. The details of the geometric inputs are given in Table 5.1 below:

Variables	Values
R	142 m
w_{major}	3.6 m
w_{minor}	3.6 m
V_{major}	40 km/h
D	5.4 m
M_1(Left-side)	4.2 m
M_2(Left-side)	6.6 m
M_1(Right-side)	2.4 m
M_2(Right-side)	6.3 m
θ	9^0 (clockwise)

Table 5.1 Input data

- Using Equation (2.1), the required sight distance d is 83.4 m
- Using Equation (3.1), radius of horizontal-curve path of approaching vehicle for vehicle approaching from left and right is

R_n = 142 + (3.6 x 4)/2 - 3.6/2 = 147.4 m (vehicle approaching from left)

R_n = 142 – (0)/2 - 3.6/2 = 140.2 m (vehicle approaching from right)

As minor-road vehicle path is more than 83.4 m from PC, the major-road vehicle also lies within the curve, therefore it is Case 1(a).

- Using Equations (3.4a) and (3.4b) x_2 for vehicle approaching from left and right is given by:

x_2 = 6.6 + (7.2 – 3.6/2) = 12m (vehicle approaching from left)

x_2 = 6.3 + 3.6/2 = 8.1m (vehicle approaching from right)

- Using Equation (3.8a), x_1 for vehicle approaching from left and right is given by:

x_1 = 81.7 m (vehicle approaching from left)

x_1 = 74.5 m (vehicle approaching from right)

- Using Equation (3.9a), (3.10a) and (3.10b), y_1 for vehicle approaching from left and right is given by:

y_1 = -17.6 m (vehicle approaching from left)

y_1 = -53.2 m (vehicle approaching from right)

- Using Equation (3.15), required minimum value of M_1 for the existing M_2 is given by

M_1 = 1.1 m (vehicle approaching from left)

$M_1 = 1$ m (vehicle approaching from right)

As M_1 calculated is less than M_1 available, hence sightlines to the vehicles approaching from the left and right are not obstructed.

5.1.3. Results and Discussion

It should be noted that the above calculations are based on D = 5.4m. It was observed at the intersection that the driver's eye of the minor-road vehicle stopped exactly on the stop line is more than 5.4 m away form the edge of the major-road. Using greater value of D will results in larger values of required M_1 for the existing M_2. For example, a value of D = 7.5m results in M_1 values of 2.9 and 2.8 m for vehicle approaching from left and right respectively. In this case, the available M_1 for the right side i.e. for vehicle approaching from right is less than the required minimum value.

It should also be noted that there are often parked vehicles on the North West corner of the intersectiont although the area is restricted for parking. The presense of these vehicles significantly reduces the available sight distance for the minor-road vehicles. These vehicles, however, were not considered in the analysis.

5.2. HYPOTHETICAL EXAMPLE FOR STOP-CONTROL INTERSECTIONS

A hypothetical example with general geometry is used to illustrate the application of the presented design aids and mathematical model in detail. Both major and minor roads are two-lane undivided with lane widths of 3.6m each. The design speed along major-road is 50 km/h and all maneuvers are permitted from the minor-road. As the major-road is a two lane highway, therefore the required time gap for critical case (turning left maneuver) for a departing minor-road vehicle is 7.5 sec. The intersection is located in the middle of the curve i.e. equidistant from PC and PT and the skew is zero. The radius R of the curve is 600 m with a deflection angle Δ equal to 10°. The other geometric variables are based on AASHTO (2001) recommended values and are shown in Table 5.2. It is required to establish zones clear of obstruction on the inside and outside of the curve. The example was solved considering a vehicle approaching from the left, which is the most critical case.

5.2.1. Checking Off-Road Obstruction

Off-Road Obstruction (inside of curve)

1. Using Equation (2.1), the required sight distance d is 104.25m
2. Using Equation (3.1), radius of horizontal-curve path of approaching vehicle is $R_n = 600 - 3.6 + 1.8 = 598.2$ m
3. As the intersection is equidistant from PC and PT, therefore $\phi_1 = \Delta/2$ i.e. 5°.
4. Using ϕ_1, $d_1 = 52.2$ m
5. As $d > d_1$, therefore, it is Case 1(b).
6. Using Equation (3.13), $x_1 = 103.98$ m
7. Using Equation (3.14b), $y_1 = 0.39$ m
8. Using Equation (3.12), minimum required M_1 is determined assuming different values of M_2. For a range of M_2 (0 – 20 m), M_1 was found to be in the range of (5.38– 4.97 m).
9. As it is Case 1(b), check given in Equation (3.15) is required to see if calculation of M_{1T} is necessary. For $M_2 = 20$ m and $M_1 = 4.97$ m, using Equations (3.4a) and (3.6b), $x_2 = 25.4$ m and $q = 591.43$ m. Then, $q \sin\phi_1 = 51.55$ m. As $x_2 < q \sin\phi_1$, therefore calculation for M_{1T} is not required.

Off-Road Obstruction (outside of curve)

1. Using Equation (3.2a), radius of horizontal-curve path of approaching vehicle from the left is: $R_n = 600 + 3.6 - 1.8 = 601.8$ m
2. As the intersection is equidistant from PC and PT, therefore $\phi_1 = \Delta/2$ i.e. 5°.
3. Using ϕ_1, $d_1 = 52.52$ m

4. As $d > d_1$, therefore, it is Case 1(b).
5. Using Equation (3.13), x_1 = 104.01 m
6. Using Equation (3.14a), y_1 = -14 m
7. Using Equation (3.11), minimum required M_1 is determined assuming different values of M_2. For a range of M_2 (0 – 20 m), M_1 was found to be in the range of (4.67 – 2.31 m).

5.2.2. Checking Major-Road Obstruction

1. As x_1 calculated above is greater than P = 50 m, it implies that the object is on tangent. Using Equation (3.23b), z_1 = -2.98 m. (negative sign indicates that the object is below the observer).
2. Using Equation (3.26b) to check sightline obstruction against road surface, $-0.0042x^2+0.316x -112.32 = 0$, which does not produce any value of x within the range of $0 \leq x \leq x_1$. Hence road surface does not obstruction sightline.

It should be noted that the above check is made for the vehicle approaching from the left for the observer on the inside of the curve. To check road surface obstruction for the vehicle approaching from the left of the observer on the outside of the curve (or for vehicle approaching from the right of observer on the inside of curve), P should be subtracted from the length of vertical curve L and used instead of P in the given equations. Also, g_2 should be used as g_1 i.e. the positive grade.

Check for major-road obstruction for vehicle approaching from the left of observer on the outside of horizontal curve follows:

3. Now, P is given by L - P = 750-50 = 700 m, it implies that the object is within the curve. Using Equation (3.23a), z_1 = 4.39 m. (+ve sign indicates that the object is above the observer).
4. Using Equation (3.26a) to check sightline obstruction against road surface, $-0.0042x^2+0.433x -112.32 = 0$, which does not produce any value of x

within the range of $0 \le x \le x_1$. Hence road surface does not obstruction sightline.

5.3. HYPOTHETICAL EXAMPLE FOR LEFT-TURNS AT SIGNALIZED INTERSECTIONS

A hypothetical example with general geometry is used to illustrate the application of the presented design aids and mathematical model. Both major and minor roads are four-lane divided highways with median and lane widths of 4.8 m (3.6 m left-turn lanes and 1.2 m medial separator) and 3.6 m, respectively. The design speed along the major-road is 64 km/h. Other geometric variables for the assumed intersection are given in Table 5.3. It is required to check if there is adequate sight distance available. If inadequate, it is required to calculate the minimum left-turn lane offset X_o which will satisfy sight distance requirement. The procedures are as described next using the design aids and the mathematical model.

5.3.1. Using Design Aids

Using Figure. 4.7, enter on the horizontal axis at a radius of horizontal curve of 1080 m. Project a line vertically upward until it hits the curve corresponding to the design speed along the major-road (60 km/h for the current case). The required minimum offset can be obtained from the correspondent value on the vertical axis. For a radius of 1080 m and a design speed of 60 km/h, the required minimum offset that will provide unobstructed required sight distance is 0.61 m, identical to the offset previously obtained using the mathematical model. If the provision of this required offset is not feasible, the designer can reduce the speed along the major-road to satisfy sight distance requirements. For example, for the current scenario, reducing the design speed along the major-road from 60 km/h to 40 km/h reduces the required minimum offset to -0.06 m from 0.61m.

5.3.2. Using Mathematical Model

1. Using Equation (2.1), the required sight distance, d = 100.08 m.

2. Using Equations (4.1) and (4.2), the total widths of major and minor roads are, W_{major} = 19.52 m and W_{minor} = 19.52 m.
3. Using Equations (4.3) and (4.4), R_0 = 1080 m and R_1 = 1084.27 m. Note that when the object is positioned in the center of the occupied left-turn lane, the driver's eye is exactly above the centerline of the major-road ($R_0 = R$).
4. Using Equation (4.6), d' = 104.35 m
5. Using Equation (4.7), the central angle ϕ of the arc with length $d' = 5.51^{\circ}$.
6. Using Equations (4.8) and (4.9), x_1 = 116.99 m and y_1 = -0.67 m (the negative sign indicates that the object is below the observer)
7. Using Equations (4.10-4.14), x_2 = 22.57 m and y_2 = 1.70 m
8. Using Equation (4.15) to check for sightline obstruction, we have: $y_1/x_1 = -0.006$ and $y_2/x_2 = 0.075$
9. As $y_2/x_2 > y_1/x_1$, the sightline to the object is obstructed.
10. To satisfy sight distance requirements, the offset should be adjusted. The minimum value of the offset for which the sightline becomes unobstructed is calculated using Equation (4.16). For the current case, it is found that for an offset of 0.61 m the sightline is unobstructed. Therefore, the required minimum offset for the given intersection is 0.61 m.

Using Equation (4.12), the required median width to accommodate the required offset is 6.71 m. Note that the required median width of 6.71 m will increase the total width of the major-road W_{major} from 19.52 m to 21.35 m. If it is desired to keep the width of the major-road constant, the designer must reduce the width of the through lanes along the major-road near the intersection and recheck the offset and median width requirement. For the addressed case, it follows that:

- Reducing the lane width along the major-road to 3.19 m results in 19.51 m major-road width, which is almost equal to 19.52 m.
- Using Equations (4.16) and (4.12), the required offset X_o and median width M_{major} are 0.65m and 6.75 m, respectively.

Table 5.2 Input data (Example for Stop-control intersections)

Variable	**Value**
R	600 m
w_{major}	3.6 m
w_{minor}	3.6 m
W_{major}	7.2 m
W_{minor}	7.2 m
h_d	1.08 m
h_o	1.08 m
L	750 m
g_1	4%
g_2	-2%
D	5.4 m
θ	0°
g_m	0%
P	50 m

Table 5.3 Input data (Example for Left-Turns at Signalized Intersections)

Variables	Values
R	1080 m
V_{major}	60 km/h
w_x	3.66 m
m_{major}	1.22 m
m_{minor}	1.22 m
Y_{p1}	12.2 m
Y_a	19.52 m
Y_i	3.05 m
n_{major}	2
n_{minor}	2
V_w	2.13 m
M_{major}	4.88 m
M_{minor}	4.88 m
X_i	1.22 m
X_L	0.76 m

Chapter 6: SUMMARY AND CONCLUSIONS

6.1. SUMMARY

Sight Distance is an important element of design. It is evident from past research that provision of proper sight distance improves highway safety. Although the use of horizontal curves along with vertical alignment (combined 3D alignments) is usually not practiced on intersecting roadways, there are situations where highway intersections are built on 3D combined alignments in which case sight distance can be greatly reduced. Current design guidelines do not provide adequate guidelines to investigate sight distance adequacy on 3D alignments. Several sight distance models are developed in this thesis considering different cases of 3D alignments on intersections.

6.2. MAJOR FINDINGS

6.2.1. Stop-control Intersections

1. This research has presented new mathematical models for the analysis o sight distance at intersections under complex situations. Practical design aids are provided to determine the exact location of obstruction. The design aids presented can be used to evaluate sight distance for an existing or proposed intersection.
2. Although the cases of obstruction on the outside of the curve are less critical than that for straight roadways, guidelines are provided for those cases to illustrate the exact location of obstruction from the major and minor-road. Moving the obstruction closer to the major and minor roads means less right of way which in turn means cost saving.
3. For the case when the major-road vehicle is beyond PC (i.e. on tangent), the results become less critical for an obstruction on the inside and vice versa for an obstruction on the outside of curve.

4. The check presented for major-road surface obstruction can be used for any location of minor-road .nd/or major-road vehicle with respect to vertical alignment.

6.2.2. Left-turns at Signalized Intersections

1. Where an intersection and a median both exist on a curve, the preferred treatment should be to make the median continuous and deter the turns to nearby median openings on tangents. However, it might not always be feasible to do so, and hence for cases where the left-turns are present on horizontal curves, sight distance adequacy should be carefully checked.
2. The developed model was translated into an Excel worksheet to make it easier for the users. Given the model input (for geometric and other variables,), a step-by-step procedure was presented to calculate the required minimum left-turn lane offset, which is used to calculate the required minimum median width along major-road.
3. Since no actual data were available to determine the exact positioning of vehicles, the design graphs were developed assuming that the observer and obstruction are located at the center of the occupied lanes. This results in conservative values because drivers often position their vehicles at the intersection in a way that attempts to improve sight distance as much as possible. It is expected that actual vehicle positioning will result in reduced offset requirements.
4. Where the major-road is located on a vertical curve, the sightline may be obstructed. The adequacy of sight distance can be checked using basic vertical curve geometry presented. If the sightline is obstructed by the vertical curve, the vertical alignment can be improved or appropriated posted speed can be calculated.

6.3. RECOMMENDATIONS

Based on the research conducted in this thesis, the following recommendations are made:

1. The methodology developed considers the vertical obstruction caused by the road surface on crest vertical curves. Further research is required to explore the case of sag vertical curve where the sightline may be obstructed by an overpass. This case would be more critical for trucks and buses.
2. The check presented for major-road surface obstruction can be used for any location of the intersection and/or object with respect to the vertical alignment. This check, however, is approximate because it assumes that the vertical curve lies in a vertical plane (no horizontal curve exists). This approximation is reasonable since the minor-road vehicle is stopped close to the major-road. For the case where there is a median barrier along the major-road that may obstruct the sightline to a vehicle approaching from right, this approximation would not be appropriate. In such a case, it is recommended that the finite element method should be used (Easa et. al. 2004).
3. It should be noted that the skew of the intersection will have no effect on the total available sight distance (from the observer to the object) for the addressed case in chapter 4 since the observer, obstruction, and object are located on the major-road. In other words, the sightline to the object and obstruction will remain unaffected by the skew. However, the skew would affect the positioning of the left-turn vehicles. For such cases, it is strongly recommended that vehicle positioning should be observed prior to the application of the presented methodology. Also, the vehicles may need slightly larger or smaller time gaps (depending on the angle of the skew), and this may require adjustment to the AASHTO time gaps.

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APPENDIX A

NOTATION

APPENDIX A: NOTATION

D = Distance between the driver's eye of vehicle on the minor road and the edge of the major-road

d' = Total curved path (assumed to the centerline of minor-road) (m)

d = Required intersection sight distance (m)

d_1 = Distance of intersection from PC

g_1, = Grade of first tangent of the vertical curve

g_2 = Grade of second tangent of the vertical curve

g_m = Grade of the minor-road (positive for upgrade and negative for downgrade)

h_d = Driver's eye height on minor-road

h_d = Driver's eye height on minor-road

L = Length of vertical curve

M_1 = Distance between the obstruction and the edge of the major-road (perpendicular to the tangent to the curve)

M_{1T} = Distance between the obstruction and the edge of major-road (perpendicular to tangent segment)

M_2 = Distance between the obstruction and the edge of the minor-road

M_{major} = Median width along major-road (m)

M_{minor} = Median width along minor-road (m)

m_{major} = Width of medial separator along major-road (m)

m_{minor} = Width of medial separator along minor-road (m)

n_{major} = Number of through lanes along major-road (in one direction)

n_{minor} = Number of through lanes along minor-road (in one direction)

P = Distance from PVC to the path of the minor-road vehicle

PVC = Point of vertical curvature

PVT = Point of vertical tangency

r = Rate of change of grade of the vertical curve

R = Radius of horizontal curve (along the center of major-road) (m)

R_0 = Radius of the curved path of the observer (under driver's eye) (m)

R_1 = Radius of the curved path of the object (Centerline of inside lane) (m)

R_2 = Radius of the curved path under the right front corner of the obstruction (m)

R_n = Radius of the horizontal-curve path for approaching vehicle

V_{major} = Design Speed along major-road (km/h)

W_{major} = total width of major-road

W_{minor} = total width of minor-road

w_x = Width of left turn lanes (m)

w_{major} = Lane width along major-road (m)

w_{minor} = Lane width along minor-road (m)

X_i = Lateral position of observer (distance of driver's eye from the left edge of the left-turn lane from which it is turning) (m)

X_L = Lateral position of the obstruction (distance of the front left-corner of obstruction from the left edge of the left-turn lane from which it is turning) (m)

X_0 = Left-turn lane offset (m)

X_r = Lateral distance of front right corner of obstruction from the right edge of the left-turn lane from which it is turning (m)

Y_i = Distance from driver's eye to the front of the vehicle (m) = 2.4 m (AASHTO)

Y_0 = Distance from the front of the vehicle to the edge of the minor-road (m)

Y_{p1} = Longitudinal position of observer (distance from front of the vehicle to the left-edge of the lane into which it is turning)

Y_{p2} = Longitudinal position of obstruction (distance from front the right corner of the vehicle to the left-edge of the lane into which it is turning)

α = Angle between the sightline to the object and the x-axis

β = Angle between the sightline to the obstruction and the y-axis

θ = skew angle of the intersection

ϕ = Central angle of the curved path with length d' (degrees)

ϕ_1 = Central angle of the curved path with length d_1 (degrees)

ϕ_2 = Central angle of the curved path with length d_2 (degrees)

APPENDIX B

ANALYSIS WORKSHEETS – STOP-CONTROL INTERSECTIONS

APPENDIX B: ANALYSIS WORKSHEETS – STOP-CONTROL INTERSECTIONS

Case 1. Intersection lies on Curve and Object lies on curve/ tangent - Obstruction Outside the Curve			
INPUT DATA			
R	600	h_o	1.08
w_{maj}	3.6	D	5.4
w_{min}	3.6	θ	0
W_{maj}	7.2	t_g	7.5
W_{min}	7.2	V	40
h_d	1.08	u	0
d_1		**83.4**	
CALCULATIONS			
d	**83.4**	$\phi 1$	**7.944319907**
d_2	**0**	**x_1**	**83.17519441**
Rn	**601.8**	**y_1**	**-12.97556507**

Table for M_1 and M_2 for Vehicle approaching from Left

M_2	x2	M_1
0	5.4	**4.55758476**
4	9.4	**3.946741325**
8	13.4	**3.362286034**
12	17.4	**2.804295187**
16	21.4	**2.272841903**
20	25.4	**1.767996073**

Case 1. Intersection lies on Curve and Object lies on curve/ tangent - Obstruction Inside the Curve			
INPUT DATA			
R	600	h_o	1.08
w_{maj}	3.6	D	5.4
w_{min}	3.6	θ	0
W_{maj}	7.2	t_g	7.5
W_{min}	7.2	V	40
h_d	1.08	u	0
d_1		**83.4**	
CALCULATIONS			
d	**83.4**	$\phi 1$	**7.988077585**
d_2	**0**	**x_1**	**83.13008191**
Rn	**598.2**	**y_1**	**1.395669702**
Table for M_1 and M_2 for Vehicle approaching from Left			
M_2	**x2**	**M_1**	
0	5.4	**5.309339481**	
4	9.4	**5.22865093**	
8	13.4	**5.120905165**	
12	17.4	**4.986116973**	
16	21.4	**4.82430484**	
20	25.4	**4.635490933**	

Case 2. Intersection lies on Tangent and Object lies on tangent/curve - Obstruction Outside the Curve

INPUT DATA			
R	250	h_o	1.08
w_{maj}	3.6	D	5.4
w_{min}	3.6	θ	0
W_{maj}	7.2	t_g	7.5
W_{min}	7.2	V	40
h_d	1.08	u	0
d1		**20.85**	
CALCULATIONS			
d	**83.4**	$\phi 1$	**14.24014611**
d2	**62.55**	x_1	**82.78942545**
Rn	**251.8**	y_1	**-14.93700081**

Table for M_1 and M_2 for Vehicle Approaching from Left

M_2	$x2$	M_1
0	5.4	**4.425723347**
4	9.4	**3.704036937**
8	13.4	**2.982350527**
12	17.4	**2.260664117**
16	21.4	**1.539570521**
20	25.4	**0.857974155**

Case 2. Intersection lies ·· Tangent and Object lies on Tangent/curve - Obstruction Inside the Curve			
INPUT DATA			
R	500	h_o	1.08
w_{maj}	3.6	D	5.4
w_{min}	3.6	θ	0
W_{maj}	7.2	t_g	7.5
W_{min}	7.2	V	40
h_d	1.08	u	0
d1		**20.85**	
CALCULATIONS			
d	**83.4**	$\phi 2$	**7.193598973**
d2	**62.55**	x_1	**83.23579705**
Rn	**498.2**	y_1	**3.278516958**

Table for M_1 and M_2 for Vehicle Approaching from Left

M_2	$x2$	M_1
0	5.4	**5.187303153**
4	9.4	**5.029749933**
8	13.4	**4.872196714**
12	17.4	**4.714643494**
16	21.4	**4.556782757**
20	25.4	**4.378498398**

APPENDIX C

ANALYSIS WORKSHEET – LEFT-TURNS AT SIGNALIZED INTERSECTIONS

APPRENDIX C: ANALYSIS WORKSHEET – LEFT-TURNS AT SIGNALIZED INTERSECTIONS

Input Data	
Speed on Major Road 'V_{major}' =	48
Rad of Horz curve (Centerline of Maj Rd) R =	1500
Lane Width along Major Road w_{major} =	3.66
Lane Width along Minor Road w_{minor} =	3.66
Width of Left Turn Lane w_x=	3.66
Medial Seperator along Major Road m_{maj}=	1.22
Medial Seperator along Minor Road m_{min} =	1.22
No. of lanes in one direction along Major Road n_{maj} =	2
No. of lanes in one direction along Minor Road n_{min} =	2
Median Width on Major Road M_{maj} =	4.88
Median Width on Minor Road M_{min}' =	4.88
Distance from Driver's eye (Observer) to the front of vehicle Yi =	3.05
Longitudinal distance of Observer Veh Y_{P1}	12.2
Longitudinal distance of opp left turn veh Y_{P2}	12.2
Lat dist of driver's eye from left-edge of left-turn lane 'X_i' =	1.22
Lat post of opp left turn veh w.r.t left-edge of occupied lane 'X_L'	0.76
Vehicle width 'Vw=	2.13
Calculated Values	
$X_r = W_{x-} V_w - X_l$ =	0.77
Current Offset = $M_{maj} - 2m_{maj} - w_x$ =	-1.22
Total width of Major Road 'W_{major}' =	19.52
Total width of Minor Road 'W_{minor}' =	19.52
Dist. from front of Observer to the edge of Minor Road:Y_o=	0
Dist. from Observer's eye to the edge of Minor Road:Yi+Yo =	3.05
Time gap 't_g' =	6
R_0	1500
R_1	1504.27
Required Sight Distance 'd'	80.064
Distance upto the centerline of Min.Rd d'	84.334
Φ	3.212177514
x_1	97.09982902
L_1	4.27
y_1	1.961307188
x_2	22.57
Required Offset 'X_0'	0.017067409
Equating Current offset to Req and solving for Median width, Req M_{maj} =	6.117067409