Final Report

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Intersection Sight Distance for Unprotected Left-turn Traffic

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By

Essam Radwan, Ph.D., P.E.
Professor of Engineering
CATSS Executive Director

Xuedong Yan, Ph.D.
Research Associate

Center for Advanced Transportation Systems Simulation
University of Central Florida
Orlando, FL 32816
Phone: (407) 823-0808
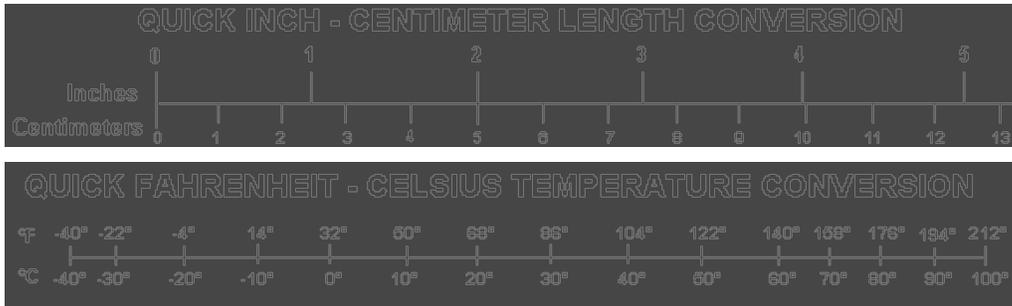Fax: (407) 823-4676

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METRIC CONVERSION TABLE

METRIC/ENGLISH CONVERSION TABLES

ENGLISH TO METRIC	METRIC TO ENGLISH
LENGTH (Approximate) 1 inch (in) = 2.5 centimeters (cm) 1 foot (ft) = 30 centimeters (cm) 1 yard (yd) = 0.9 meter (m) 1 mile (mi) = 1.6 kilometers (km)	**LENGTH (Approximate)** 1 millimeter (mm) = 0.04 inch (in) 1 centimeter (cm) = 0.4 inch (in) 1 meter (m) = 3.3 feet (ft) 1 meter (m) = 1.1 yards (yd) 1 kilometer (km) = 0.6 mile (mi)
AREA (Approximate) 1 square inch (sq in, in2) = 6.5 square centimeters (cm2) 1 square foot (sq ft, ft2) = 0.09 square meter (m2) 1 square yard (sq yd, yd2) = 0.8 square meter (m2) 1 square mile (sq mi, mi2) = 2.6 square kilometers (km2) 1 acre = 0.4 hectare (ha) = 4,000 square meters (m2)	**AREA (Approximate)** 1 square centimeter (cm) = 0.16 square inch (sq in, in) 1 square meter (m) = 1.2 square yards (sq yd, yd) 1 square kilometer (km) = 0.4 square mile (sq mi, mi) 10,000 square meters (m) = 1 hectare (ha) = 2.5 acres
MASS - WEIGHT (Approximate) 1 inch (in) = 2.5 centimeters (cm) 1 foot (ft) = 30 centimeters (cm) 1 yard (yd) = 0.9 meter (m) 1 mile (mi) = 1.6 kilometer (km)	**MASS - WEIGHT (Approximate)** 1 gram (gm) = 0.036 ounce (oz) 1 kilogram (kg) = 2.2 pounds (lb) 1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons
VOLUME (Approximate) 1 teaspoon (tsp) = 5 milliliters (ml) 1 tablespoon (tbsp) = 15 milliliters (ml) 1 fluid ounce (fl oz) = 30 milliliters (ml) 1 cup (c) = 0.24 liter (l) 1 pint (pt) = 0.47 liter (l) 1 quart (qt) = 0.96 liter (l) 1 gallon (gal) = 3.8 liters (l) 1 cubic foot (cu ft, ft 3) = 0.03 cubic meter (m3) 1 cubic yard (cu yd, yd3) = 0.76 cubic meter (m3)	**VOLUME (Approximate)** 1 milliliter (ml) = 0.03 fluid ounce (fl oz) 1 liter (l) = 2.1 pints (pt) 1 liter (l) = 1.06 quarts (qt) 1 liter (l) = 0.26 gallon (gal) 1 cubic meter (m) = 36 cubic feet (cu ft, ft) 1 cubic meter (m) = 1.3 cubic yards (cu yd, yd)
TEMPERATURE (Exact) $[(X-32)(5/9)]$ °F = Y °C	**TEMPERATURE (Exact)** $[(9/5)\, Y + 32]$ °C = X °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches: 0 1 2 3 4 5
Centimeters: 0 1 2 3 4 5 6 7 8 9 10 11 12 13

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F: -40° -22° -4° 14° 32° 50° 68° 86° 104° 122° 140° 158° 176° 194° 212°
°C: -40° -30° -20° -10° 0° 10° 20° 30° 40° 50° 60° 70° 80° 90° 100°

For more exact and/or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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16. Abstract

During the permitted left-turn green phase at intersections on divided highways, if the median of the major road is relatively wide, the simultaneously-turning vehicles in the opposite left-turn lane frequently block the driver's view. This situation may contribute not only to a serious safety problem because of drivers' misjudging gaps among the opposing through traffic, but may also lead to needless delays for the left-turning traffic since those cautious drivers reject physically adequate gaps. To improve intersection sight distances and traffic operation for unprotected left-turn drivers at signalized intersections, this study aimed at developing geometric models to calculate sight distance for unprotected left-turning vehicles for different geometric configurations. These models can be used by traffic engineers to lay out intersection configurations or renew the existing left-turn lane design to provide sufficient sight distance and enhance efficiency of the intersection traffic operation. Furthermore, to provide a better understanding of the relationship between highway visibility and traffic operation, a field study was conducted to investigate the influence of the sight-distance problem on left-turn gap-acceptance behaviors and traffic capacity. From field observations and data analysis, this study confirmed the serious negative effect of the sight-distance problem on both traffic safety and operation efficiency for unprotected left-turn traffic.

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EXECUTIVE SUMMARY

As the trend of urbanization and suburbanization keeps developing in the United States, new arterial and collector roads, especially in suburban areas, tend to be constructed with four or more lanes and dividing medians. As roadways and medians widen, turning left from the major road becomes increasingly complicated, and medians also increase the likelihood of sight-distance restrictions due to the opposing left-turn vehicles. Left-turn sight distance is an important geometric design factor for traffic turning left during the unprotected green phase at signalized intersections. Restricted visibility may cause the unprotected left-turn drivers to unintentionally accept a small gap to make a left turn because they can't see the opposing-through vehicles concealed in the view-blocked area. Accepting a very small gap could contribute to potential traffic conflicts and even serious angle collisions. Moreover, inadequate sight distance may cause cautious drivers to reject physically adequate gaps because they need more time to make sure that the opposing through lanes are clear, which can lead to needless delays for the left-turning traffic.

The first task of this study was to develop geometric models to calculate available sight distances for left-turning vehicles. These models would assist traffic engineers to identify a better intersection location along the major road when a curve exists, lay out intersection geometric design, or evaluate the sight-distance problem of an existing intersection configuration. For a more comprehensive and practical application to intersection design, this study introduced six types of geometric models to calculate left-turn sight distances for intersections with different

configurations. They include intersections with only a linear highway segment, with only a curve highway segment, or with a combination of curved and linear segments.

The second task involved a field study to investigate the influence of the sight-distance problem on left-turn gap-acceptance behaviors and intersection capacity. The results showed that sight obstruction due to the opposite turning vehicles may contribute to significant increments of the critical gap for both left-turn and U-turn drivers. With the sight-distance problem, the drivers' left-turn follow-up time is also significantly increased compared to those without the problem. The larger critical gap and follow-up time could result in an extra traffic delay and a capacity reduction. A capacity model showed that the capacity reduction rate increases with the increase of the opposing through volume and the volume-to-capacity ratio for the opposing left-turn traffic. On the other hand, when the available gaps are relatively small, the left-turn or U-turn drivers with the sight-distance problem are more likely to accept a very small gap compared to those drivers with unrestricted sight distance. Video analysis did show that more traffic conflicts happened because the left-turn or U-turn drivers with the sight-distance problem accepted smaller gaps. Moreover, the in-depth analysis of a coincidental left-turn crash occurring during the video session at an intersection provided evidence that opposing vehicle sight obstruction can contribute to the unsafe operation at such intersections. The field study in this project provided a better understanding of the relationship between highway visibility and traffic safety and operation.

Based on the findings of this study, it is strongly recommended to check the potential sight-distance problem for intersections with a wide median, particularly one at which gap-acceptance crashes frequently occur or where the efficiency of the permitted left-turn phase is abnormally

low during peak hours. Once the sight-distance problem is identified for an existing intersection, offsetting left-turn lanes based on the geometric models developed in this study would be an effective method to improve drivers' sight distance. If opposing through traffic volumes are relatively high, it is recommended that an exclusive-only phase be used instead of the permitted one.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 Background

During the permitted left-turn green phase at intersections on divided highways, drivers in the left-turn lane need to accept proper gaps or lags in the opposing through traffic to complete turn movements. The gap acceptance maneuvers are complex and require a minimum sufficient sight distance. However, if the median of the major road is relatively wide, the simultaneously turning vehicles (V1 and V2) in the opposite left-turn lane frequently block the driver's view (see Figure 1-1). This situation may cause the sight-restricted drivers to unintentionally accept a small gap to make a left turn because they can't see the opposing through vehicles hiding in the view-blocked area (V3). Accepting a very small gap could contribute to potential traffic conflicts and even serious angle collisions. Moreover, the inadequate sight distance may cause cautious drivers to reject physically adequate gaps because they need more time to make sure that the opposing through lanes are clear, which can lead to needless delays for the left-turning traffic.

V1: Left turning vehicle
V2: Opposite left turning vehicle
V3: Opposing-through vehicle that the left-turn driver can't see
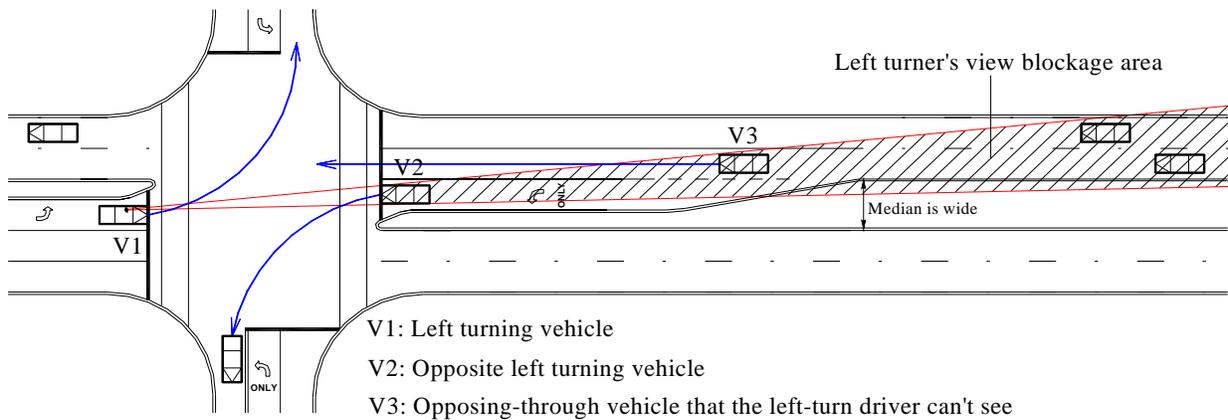
Figure 1-1: Restricted left-turn sight distance due to the opposing left-turning vehicle

The AASHTO (2001) manual pointed out that the typical poor visibility of opposing through traffic usually occurs at signal intersections with medians wider than 18 feet. To avoid the sight-distance problem for left-turners, the AASHTO design guide recommended two methods to highway designers. One is a parallel offset left-turn lane; the other is a tapered offset left-turn lane. However, AASHTO did not provide the specific design guideline nor present the related geometric design model. In addition, AASHTO criteria are provided only for linear-approach intersections but not considered for intersections located on or near a horizontal curve. The presence of a horizontal curve on the intersection approaches may represent an additional risk for left-turners beyond that of a typical intersection with linear approaches. In particular, traffic environments combined with a horizontal curve, a signalized intersection, and high traffic volumes contribute to a relatively complex situation for the driver. The insufficient left-turn sight distance due to a horizontal curve may result in a high accident rate at signalized intersections.

For sight obstruction by apposite left-turn vehicles, the basic traffic scenario at an intersection on a horizontal curve is similar to that at an intersection with linear major approaches, as shown in Figures 1-2-a and 1-2-b. However, the curve presence may contribute to or mitigate the sight distance problem, depending on whether the driver is making a left-turn toward the outside or the inside of the curve. As shown in Figure 1-2-b, the sight distance for the left-turners toward the outside of the curve is very short. On the other hand, for left-turners toward the inside of the curve, the sharpness of the curve can even result in unrestricted sight distance, since the left-turners benefit from a left-turn lane offset toward the coming traffic. Furthermore, when intersections are located at a major highway that is close to the tangent points of the linear and

curved segments, the sight distance calculation models could be more complicated than the linear or the curve models.

a. Linear approach

b. Curve approach

c. Linear approach leading to a curve (left-turn toward outside)

d. Linear approach leading to a curve (left-turn toward inside)

e. Curve approach leading to a linear segment (left-turn toward outside)

f. Curve approach leading to a linear segment (left-turn toward inside)
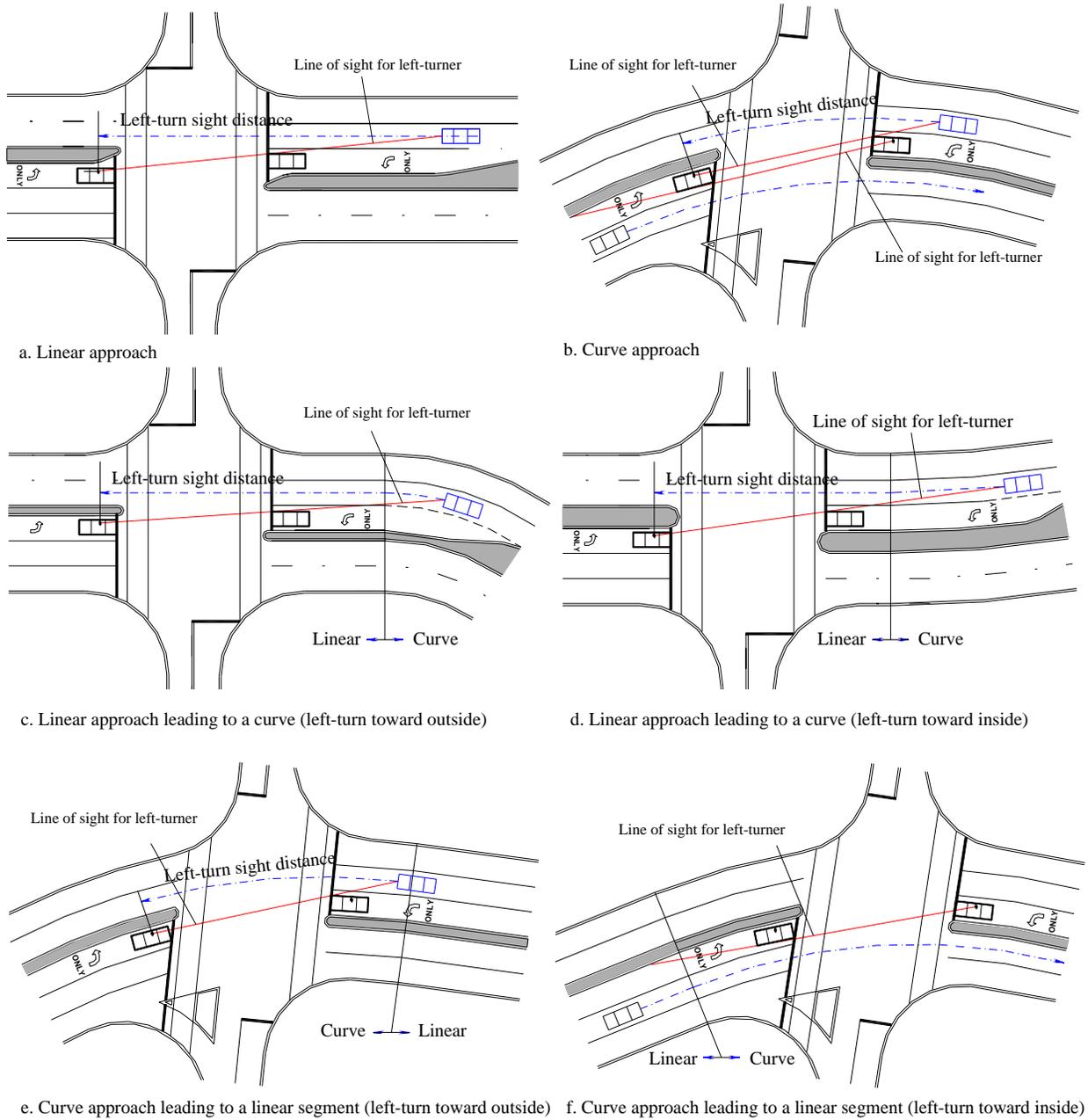
Figure 1-2: Intersection configurations and left-turn sight distance

The combination of the curve and linear segments may result in four different intersection configurations: linear approach leading a curve segment for a left turn toward the outside of the curve (Figure 1-2-c), linear approach leading a curve segment for a left turn toward the inside of the curve (Figure 1-2-d), curve approach leading a linear segment for a left turn toward the outside of the curve (Figure 1-2-e), and curve approach leading a linear segment for a left turn toward the inside of the curve (see Figure 1-2-f). Therefore, for a more comprehensive and practical application to intersection design, theoretical geometric models need to be developed to calculate sight distances for unprotected left-turning vehicles for different geometric configurations of signalized intersections.

1.2 Traffic Accident Analysis Based on GES Database

To address the necessity of developing unprotected left-turn sight-distance models and to investigate the influence of the restricted visibility due to opposing left-turn vehicles on drivers' behavior and traffic operation, we conducted a traffic-accident analysis based on the General Estimates System of National Sampling System (GES). The GES obtains its data from a nationally representative probability sample selected from the estimated 6.2 million police-reported crashes that occur annually. The GES is used to identify highway-safety problem areas, provide a basis for regulatory and consumer information initiatives, and form the basis for cost and benefit analyses of highway-safety initiatives. In the GES database, a weight variable is provided that can be used to produce the national estimates, and the Vision Data Set contains information on circumstances that may have obscured the driver's vision. In this analysis, we extracted those traffic accidents related to driver vision problems from the 2002–2004 GES

4

databases (see Figure 1-3). The data show that the most common type of traffic accidents that were related to the driver's restricted visibility occurred because of parked vehicles (28 percent on average), followed by moving vehicles (21 percent).
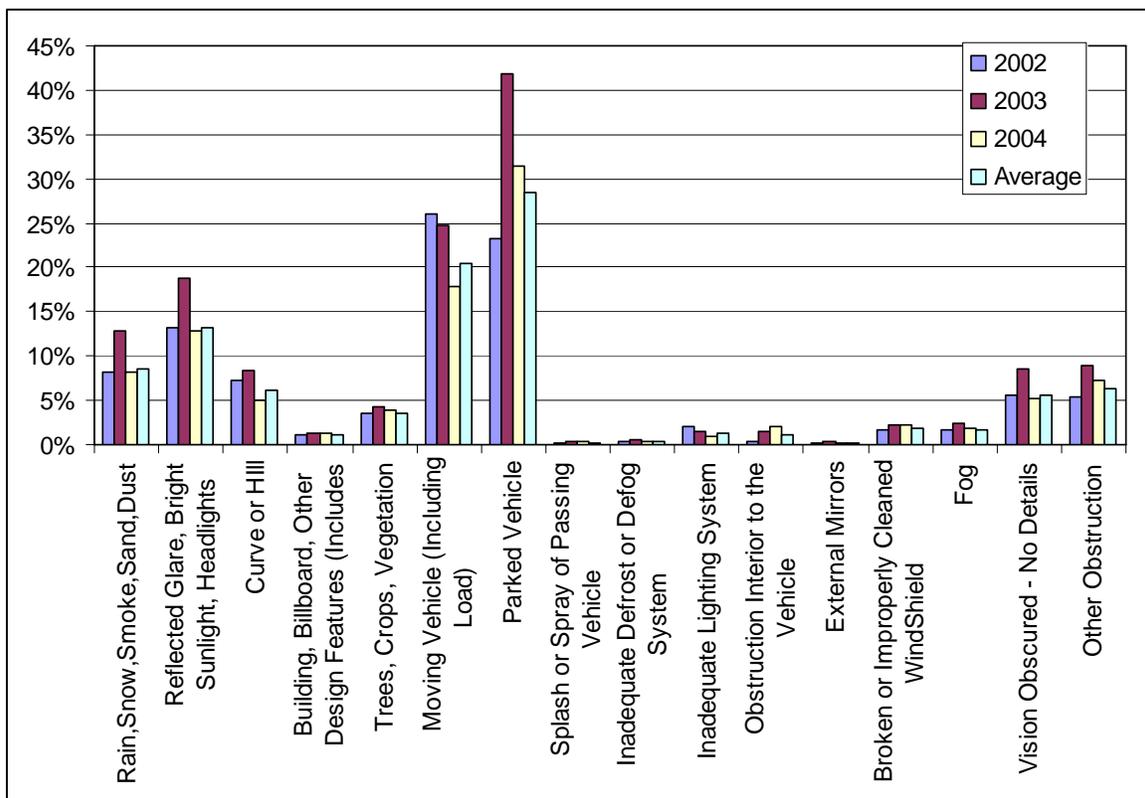
Figure 1-3: Circumstances that may have obscured the driver's vision

In those accidents related to restricted sight distances because of moving vehicles, it was found that the drivers turning left are most likely to be involved in accidents (42.6 percent), followed by going-straight drivers (37.4 percent), as shown in Table 1-1. For those accidents involving left-turn drivers, 41.8 percent of accident types are crashes between left-turn vehicles and opposing straight vehicles, which represent 10,530 crashes nationwide. Typically, 48.2 percent of the crashes occurred at signalized intersections, and 28.2 percent of left-turn drivers received a violation charge of "failed to yield the right of way."

Although the GES database does not specifically indicate that the moving vehicles that restricted the left-turn driver's sight distance at signalized intersection were opposing left-turn vehicles, those crashes most closely display the traffic scenarios analyzed in this study. Therefore, based on the GES database analysis, it is worthwhile to research this safety issue and seek effective countermeasures to reduce the incidence of unprotected left-turn crashes due to restricted sight distance at signalized intersections.

Table 1-1: Vehicle Maneuver Prior to Critical Traffic Event from 2004 Dataset

P_CRASH1	Frequency	Percent	Cumulative frequency	Cumulative percent
Going straight	231	37.44	231	37.44
Decelerating in traffic lane	5	0.81	236	38.25
Accelerating in traffic lane	1	0.16	237	38.41
Starting in traffic lane	32	5.19	269	43.60
Stopped in traffic lane	1	0.16	270	43.76
Passing or overtaking another vehicle	14	2.27	284	46.03
Leaving a parking position	1	0.16	285	46.19
Turning right	22	3.57	307	49.76
Turning left	263	42.63	570	92.38
Making a U-turn	3	0.49	573	92.87
Backing up (other than for parking position)	3	0.49	576	93.35
Negotiating a curve	5	0.81	581	94.17
Changing lanes	21	3.40	602	97.57
Merging	1	0.16	603	97.73
Successful avoidance maneuver to a previous critical event	7	1.13	610	98.87
Other (specify)	2	0.32	612	99.19
Unknown	5	0.81	617	100.00

1.3 Research Objectives

At signalized intersections with a permitted left-turn phase, the larger size median design without offsetting left-turn lanes is not uncommon in the United States because of simplicity and ease of design. Another possible reason that traffic engineers did not pay more attention to this issue is

that there is a lack of literature specifically investigating the adverse effect of restricted sight distances on left-turn traffic.

To improve intersection sight distances and traffic operation for unprotected left-turn drivers at signalized intersections, the first objective of this study was to develop geometric models to calculate sight distance for unprotected left-turning vehicles for different geometric configurations of signalized intersections. These models can be used by traffic engineers to lay out an intersection's configuration or renew an existing intersection's left-lane design to ensure sufficient sight distance for safe left-turn maneuvers by drivers and enhance efficiency of intersection traffic operation. Furthermore, to provide a better understanding of the relationship between highway visibility and traffic operation, the second objective of this project was to conduct a field study to investigate the influence of the sight-distance problem on left-turn traffic operation and safety.

CHAPTER 2. LITERATURE REVIEW

2.1 Left-turn Sight-distance Problem

American communities continue to expand, resulting in further urbanization and suburbanization. New arterial and collector roads, especially in suburban areas, tend to be constructed with four or more lanes and dividing medians (Melcher 2003). As roadways and medians widen, turning left from the major road becomes increasingly complicated, and the existence of medians also increases the likelihood of sight-distance restrictions due to the opposing left-turn vehicles. A number of related studies had shown that sight-distance problems at intersections usually result in a higher accident rate (Mitchell 1972; Hanna, et al. 1976; David and Norman 1979). McCoy et al. (1992) reported that in California, signalized intersections with opposing left-turn lanes were found to have significantly more accidents than intersections without opposing left-turn lanes, which were attributed primarily to sight-distance obstructions caused by opposing left-turn vehicles.

AASHTO (2001) reported that the typical poor visibility of opposing through traffic usually occurs at intersections with medians wider than 18 feet. A related study suggested the use of protected only-left-turn phases when medians are wider than 18 feet (Reilly, et al. 1980). To avoid the sight-distance problem for left-turners, the AASHTO design guide recommended two methods to highway designers. One is a parallel offset left-turn lane (see Figure 2-1); the other is a tapered offset left-turn lane (see Figure 2-2). Both of these designs can reduce the width of the medial separators, maximize the offset between the opposing left-turn lanes, and place vehicles

waiting to make a left-turn as far to the left as practical. The advantages of offsetting left lanes are improving visibility, decreasing the probability of left-turn accidents, and maintaining the design capacity of left-turn traffic. The tapered offset is especially helpful to the left-turn maneuver of longer vehicles, such as logging trucks. However, AASHTO did not provide a specific design guideline nor present a related geometric design model. It is also the case that sight-distance problems can occur with medians narrower than 18 feet (McCoy, et al. 1992), although AASHTO did not give any suggestions for such cases.
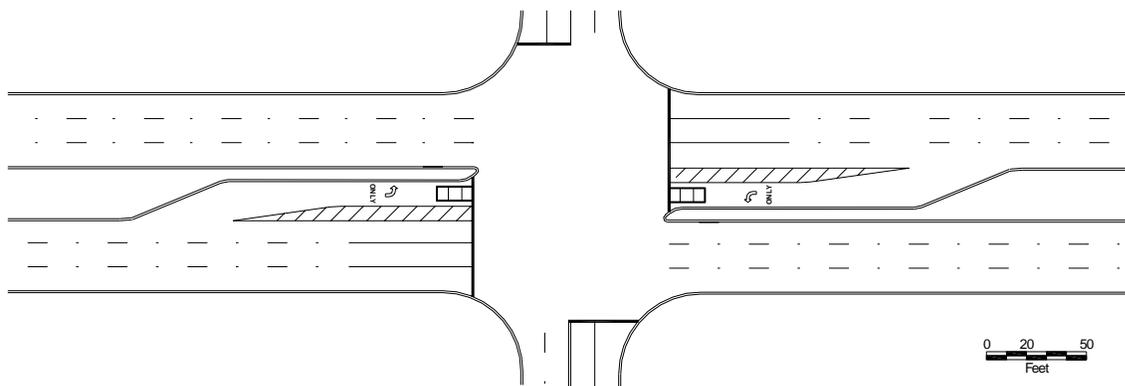
Figure 2-1: Signalized intersection with parallel offset left-turn lanes
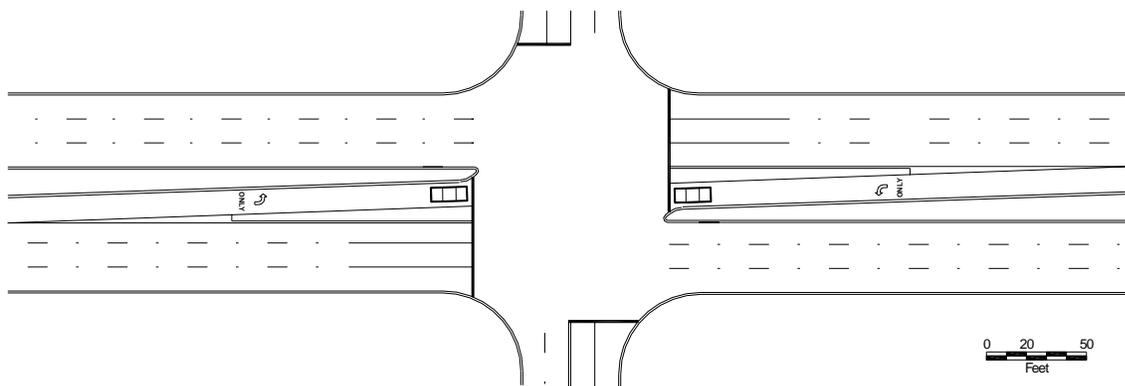
Figure 2-2: Signalized intersection with tapered offset left-turn lanes

9

The current AASHTO criteria are provided only for linear-approach intersections. However, the presence of a horizontal curve on the intersection approaches represents an additional risk for left-turners beyond that of a typical intersection with linear approaches. Specifically, traffic environments combined with a horizontal curve, a signalized intersection, and high traffic volume contribute to a relatively complex situation for the driver. The insufficient left-turn sight distance due to a horizontal curve may result in a high accident rate at signalized intersections.

More attention in prior studies was paid to sight obstruction on the inside of curves, which can be objects such as cut slopes, walls, buildings, bridge piers, and longitudinal barriers. For example, Easa et al. (2004) presented a mathematical model for the analysis of stop-controlled intersection sight distance on 3-D highway alignments that allows the major road to have vertical and horizontal curves with skewed angle, and the minor road to have a longitudinal grade. However, the mathematical model is applicable only to the case where the obstruction is located inside the horizontal curve of the major road, and, additionally, the model focuses only on intersections with stop control on the minor road, which is classified as Case B in the AASHTO.

Very few studies were found related to opposing left-turn vehicle as sight obstruction to the left-turn vehicle at an intersection located on a horizontal curve, although several researchers developed geometric models to calculate available left-turn sight distance for such cases at linear-approach intersections.

2.2 Previous Left-turn Sight-distance Models

Joshua and Saka (1992) developed geometric models for parallel left-turn lanes to calculate available left-turn sight distance and evaluate the improvement effect related to the offset value between opposing parallel left-turn lanes. Joshua and Saka's model was based on the sight-distance model of the 1994 AASHTO manual, but the section on Intersection Sight Distance has been completely revised in the 2001 AASHTO manual, which is based on a time-gap-acceptance methodology. Researchers in this study have found a strong correlation between left-turn offset distance from the left-edge of a left-turn lane to the right-edge of the opposite left-turn lane and the available sight distance for left-turn traffic. However, it was suggested that the value of the offset beyond zero should not be used, as it will lead to unsafe conditions.

McCoy et al. (1992) developed the related models to compute left-turn sight distance and provided guidelines for the required offset between opposite left-turn lanes to improve the sight-distance problem (Tarawneh and McCoy 1997). Furthermore, using McCoy's sight-distance model, researchers at the University of Nebraska-Lincoln tested the effect of offsetting the opposing left-turn lanes by simply widening the lane line between the left-turn lanes and the adjacent through lanes (McCoy, et al. 1999). It was found that significantly higher percentages of left-turn vehicles at the study sites had adequate sight distances after the lane lines were widened. McCoy's work paid more attention to departure positions of left-turn vehicles, in which the left-turn vehicles are permitted to enter the intersection before they execute the turn maneuver. He developed the left-turn sight-distance model based on a field observation for the lateral and longitudinal positioning of the left-turn vehicles, but the model is limited to configurations of intersections because the vehicle-positioning data used to develop the models were collected

only at 90-degree intersections of four-lane divided roadways with 12-foot left-turn lanes in 16-foot median and 4-foot medial separators. From the perspective of traffic operation, some aggressive left-turn drivers might encroach into the pedestrian crossing and even move inside the intersection to maximize available sight distance and minimize the left-crossing time. However, this aggressive driving behavior may contribute to their illegal traffic performance at signalized intersections. If they do not succeed making the left-turn during the first permitted left-turn phase, they may run a red light, or block the going-straight traffic along the minor road or the pedestrian flow to cross the major road. In addition, another study (Tarawneh and McCoy 1996) found that older drivers are less likely than younger drivers to position their vehicles within an intersection when making a left turn. Likewise, women drivers are less likely than men to position their vehicles within an intersection when making a left turn.

2.3 Required Sight Distance and Available Sight Distance

Based on previous research (Harwood, et al. 1996; Harwood, et al. 2000), procedures for determining appropriate intersection sight distance based on time-gap acceptances are provided by AASHTO for various levels of intersection control and the maneuvers to be performed. There are six scenarios (A to F) in the manual, and the one that pertains to this paper is defined as Case F, left-turns from the major road. The 2001 AASHTO manual recommended that the required intersection sight distance for left turns from a major road should be based on critical gap acceptance as shown in Equation 2-1, which is equal to the distance traversed by the conflicting vehicle at the design speed of the major road in the critical gap duration time accepted by the

left-turner. For the curved road, it should be the curve length of the centerline in the near opposing through lane along which the opposing through vehicles will traverse.

$$ISD = 1.47*V*G \; , \hspace{4cm} \text{(2-1)}$$

where ISD = required sight distance for a left-turn from the major road (ft)

V = major road design speed (mph)

G = critical gap size for a left turn from the major road (sec)

In the 2001 AASHTO manual, the recommended values of critical gap sizes for passenger cars, single-unit trucks, and combination trucks turning left across an opposing through lane are 5.5, 6.5, and 7.5 seconds, respectively. For each additional through lane that must be crossed, 0.5 seconds is added for passenger cars and 0.7 seconds for trucks. Although trucks and buses need larger critical gaps to make left turns, it is supposed that there is no sight-distance problem for them for two reasons. When trucks and buses make left turns and the opposite left-turn vehicle is a passenger car, the car's relatively lower vehicle body height will not block the truck or bus driver's view. Additionally, the probability of two large vehicles making opposing left-turns at the same time should be very small.

To check the required sight distance for an intersection, the available sight distance needs to be calculated. Available sight distance is defined as the distance along the centerline of the near opposing through lane from the left-turn driver's eye position to the point at which his/her line of sight intersects the centerline of the near opposing through lane. The minimum sight distance

should be no less than the required sight distance for a safe intersection design; otherwise the sight distance for left turns is insufficient and there is a potential for accidents between left-turn vehicles and opposing-through vehicles. Furthermore, based on the aforementioned gap-acceptance method, the minimum sight distance can also be put into Equation 2-1 to calculate a safe operation speed for opposing through vehicles on the major road. A safe intersection design should ensure that the safe operation speed is not less than the design speed.

2.4 Unprotected Left-turn Traffic Operations

A previous study developed theoretical models to analyze the effect of the dynamic sight-distance problem on unprotected left-turn capacity (Saka, 1998). It focused on the momentary impedance caused by leading left-turn vehicles with larger size (non-compact cars) that are in the line of sight of the drivers in the follow-up vehicles. The situation prevents the driver in the follow-up vehicle from making an unimpeded evaluation of the gaps in the conflicting traffic stream; consequently the driver may fail to accept gaps that are normally acceptable. The model analysis results indicated that the dynamic sight-distance problem can result in larger critical gaps and hence significantly reduce the left-turn traffic capacity at unsignalized intersections or signalized intersections with permitted left-turn phasing.

Unprotected left-turn capacity estimations are also based on gap-acceptance theory. In the gap-acceptance theory used in the current HCM manual (HCM 2000), the critical gap and follow-up time are key factors in determining the potential unprotected left-turn capacity. The critical gap is the minimum gap that all drivers in the minor stream are assumed to accept at all similar

locations. It is further assumed that a number of left-turn drivers will be able to continuously enter the intersection in very long gaps. Usually, headways between the continuously left-turning vehicles in the long gaps are referred to as the follow-up time. Besides the conflicting volume, increasing critical gap and follow-up time lead to a lower left-turn capacity. According to the current HCM, at signalized intersections with a permitted left-turn phase, the critical gap accepted by left-turn drivers is 4.5 sec and the average follow-up time between continuous left-turn cars is 2.5 sec. Moreover, these values are independent of the number of opposing through lanes to be crossed by drivers. From a traffic-safety perspective, it is reasonable that the critical gap size used by AASHTO sight-distance design policies should be more conservative than operational criteria in the HCM.

The techniques used to estimate gap-acceptance parameters (critical gap and follow-up time) fit into essentially two different groups (Lieu, et al. 1999). The first group of techniques is based on a linear regression analysis between the number of drivers that accept a gap and the gap size. Kyte et al. (1994) illustrated the method developed by Siegloch that provides a direct link between gap-acceptance theory and the definitions of these parameters. In this method, the mean values were plotted with gap size in seconds as the X-axis and the number of acceptances as the Y-axis. The resulting regression line that best fits these points is used to calculate the critical gap and the follow-up time. The value t_0 is obtained as the X-axis intercept. The slope of the regression line is the reciprocal of the follow-up time (t_f). The critical gap (t_g) is the sum of t_0 plus one-half of t_f. The linear regression method is straightforward for further traffic-capacity analysis. However, it disregards the analysis of the probability distribution of gap acceptance. Further, to use this method as a queue acceptance model, the minor road must be saturated with

queued traffic; otherwise, the regression approach cannot be used. Maher and Dowse (1983) also illustrated an example that is similar to the Siegloch method. The difference is that the Maher and Dowse example did not include the gap data with zero acceptances.

The other group of techniques estimates the distribution of follow-up time and the critical-gap distribution independently. The follow-up time is the mean headway between queued vehicles that move through the intersection during the longer gaps in the major stream. To obtain the follow-up time, headways between the queued minor stream vehicles are measured. If a minor stream vehicle was not in a queue then the preceding headway would not be included. On the other hand, a wide variety of procedures for the estimation of the critical gap have been used, including the maximum likelihood method (Miller 1972; Troutbeck 1992, Tian, et al. 1999). Several probability density functions have been used to describe the distribution of gaps. Troutbeck (1992) used a log-normal distribution for the critical gaps. This distribution is skewed to the right and has non-negative values, as would be expected in these circumstances. Brilon (1995) used a hyper-Erlang distribution, Miller (1972) assumed a Gamma distribution, and Cassidy et al. (1995) assumed a Gumbel distribution. Similar results were reported between the two approaches—linear regression and distribution estimation. The Probit or logistic regression (logit) techniques are also acceptable, particularly for estimating the probability that a gap will be accepted (Abou-Henaidy, et al. 1994).

Fitzpatrick (1991) compared three methods (Greenshield, Raff, and logit) to measure the critical gap in his study. It was found that the logistic regression model is appropriate for a situation in which drivers have a series of opportunities for which one of two discrete choices is made. In the

16

logistic regression method, the critical gap is defined as the median of accepted gaps that are accepted by 50 percent of the drivers.

U-turn operation in left-turn lanes during the permitted left-turn phase can also be considered as a gap-acceptance behavior. In the literature, there is no related study that analyzes the characteristics of U-turn gap acceptance at signalized intersections. Only one paper explored the U-turn critical gap at median openings based on Ruff's method and logit model (Yang, et al. 2001). This study showed that the critical gap of U-turns ranged from 5.8 sec to 7.4 sec with respect to varied geometric and traffic conditions, and the distance between signalized intersection and U-turn site greatly affected the behavior of drivers making U-turns.

CHAPTER 3. GEOMETRIC MODEL OF SIGHT-DISTANCE CALCULATION FOR LINEAR-APPROACH INTERSECTIONS

This chapter presents geometric models for both parallel and tapered left-turn lanes to calculate available left-turn sight distances for unprotected left-turn traffic at signalized intersections with only linear approaches. The study included evaluation of the sight improvement effects of the two offset methods and an analysis of the relationship between available sight distance and related intersection geometric parameters. Based on intersection configurations and reasonable assumed values, this chapter also presents an evaluation of the effect of opposite larger-size vehicles on the sight distance and provides corresponding guidelines of an offsetting left-turn lane method to satisfy required sight distances for different major road design speeds.

3.1 Geometric Model for Parallel Offset Left-turn Lanes

3.1.1 Intersection geometric features assumed for left-turn maneuver

A typical 90-degree angle of intersection with four straight and level approaches is shown in Figure 3-1. For the major road divided by a median, there is one left-turn lane and three through lanes with a 12-foot lane width on both sides of the intersection. For the minor road divided by a median, three lanes with an 11-foot lane width are assumed. There are also 10-foot pedestrian crossings across the major approaches, and the distance from the stop bar of the major road to the edge of the minor road is calculated to be 25 feet (10' + 10' + 5'). In the opposing left-turn lanes, both vehicles try to make a left turn at the same time, and the sight view of each driver is blocked by the other.
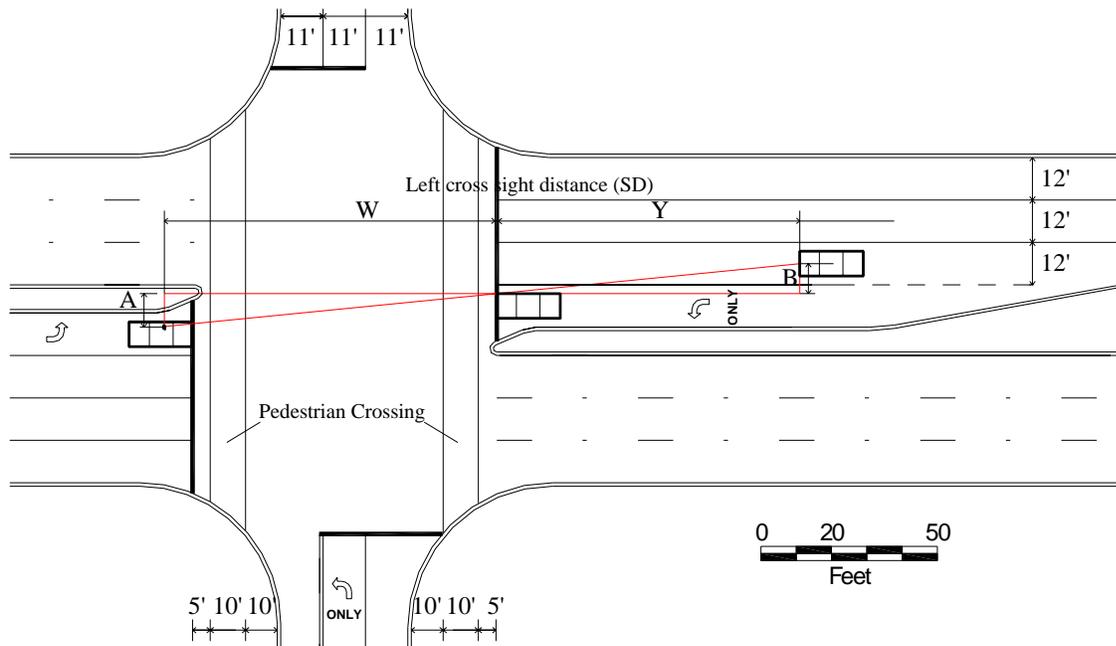
Figure 3-1: Intersection geometric features for parallel left-turn lanes and available sight distance

3.1.2 Formula to calculate available sight distance for parallel left-turn lanes

According to the definition used by McCoy et al. (1992), the available sight distance is the distance from the left-turn driver's eye to the point at which his/her line of sight intersects the centerline of the near opposing through lane. As shown in Figure 3-1 and Equation 3-1, the available sight distance is:

$$SD = W + Y, \tag{3-1}$$

where

SD = available sight distance (ft)

W = the distance from the left-turn driver's eye to the stop bar of the opposing through

lanes (ft)

Y = the distance from the stop bar of the opposing through lanes to the front of the opposing through vehicle (ft)

According to the similar triangle rule, we get Equation 3-2:

$$\frac{Y}{W} = \frac{B}{A} \quad \Rightarrow \quad Y = \frac{B \cdot W}{A}, \tag{3-2}$$

where

A = the distance from the left-turn driver's eye to the right edge of the opposing left-turning vehicle (ft)

B = the distance from the right edge of the opposing left-turning vehicle to the centerline of the nearest opposing through lane (which is also the centerline of the opposing through vehicle (ft))

Combining Equations 3-1 and 3-2, we get Equation 3-3:

$$SD = W + \frac{B \cdot W}{A} \tag{3-3}$$

Equations 3-4, 3-5, and 3-6 show how to calculate the terms A, B, and W, separately.

$$A = n + g + e - (m - n - g - V_w)$$

$$A = 2n + 2g + e + V_w - m$$

$$A = 2n - m + 12.5 \tag{3-4}$$

$$B = L_t / 2 + (m - n - g - V_w)$$

$$B = m - n - 3 \tag{3-5}$$

$$W = V_f + D$$

$$W = 8 + D \tag{3-6}$$

As shown in Figure 3-2 where

n = the width of the median nose (ft)

g = the distance from the left side of the left-turn vehicle to the left-lane line (ft) [2 ft can be assumed for design purposes, according to the AASHTO]

e = the distance from the eye of the driver to the left side of the vehicle (ft) [1.5 ft is assumed]

L_t = the width of the opposing through lane (ft) [12 ft is assumed]

m = the width of the median (ft)

V_w = the width of the opposing left-turn vehicle (ft) [7 ft is assumed]

V_f = the distance from the eye of the driver to the front of the vehicle (ft) [8 ft is assumed according to the AASHTO]

D = the distance between stop bars of the opposing left lanes, which is composed of the width of pedestrian corridors and the width of the minor road (ft)
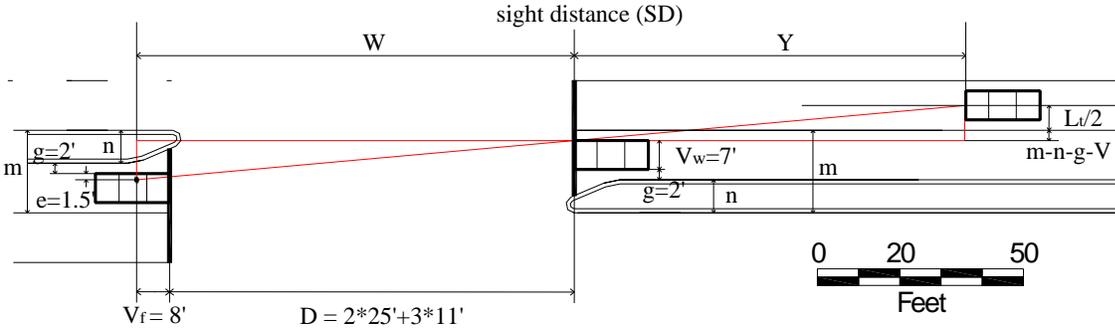
Figure 3-2: Parameter descriptions of the formula for parallel left-turn lanes

Substituting Equations 3-4, 3-5, and 3-6 into Equation 3-3, a detailed available sight-distance model is shown in Equation 3-7. Equation 3-8 is a simplified sight-distance model using the assumed parameter values and considering intersection features, as follows:

$$SD = V_f + D + \frac{(L_t/2 + m - n - g - V) \cdot (V_f + D)}{2n + 2g + e + V - m} \tag{3-7}$$

$$SD = 8 + D + \frac{(m - n - 3) \cdot (8 + D)}{2n - m + 12.5} \tag{3-8}$$

3.1.3 Evaluation of sight-distance problem for left turn

From Equation 3-8, it can be seen that the main factors of available sight distance are median width (m), the width of the median nose (n), and the distance between stop bars of the opposing left-turn lanes (D). Of those, term D is positively related to the sight distance. Simply put, the wider the intersection, the larger the sight distance available for left turners. To emphasize the severity of the sight-distance problem, a wider intersection is conservatively assumed here, as shown in the Figures 3-1 and 3-2, which is equal to the width of the two pedestrian corridors plus the width of the minor road that contains three lanes, totaling 83 feet.

22

Terms of m and n are correlated with each other. For the traditional intersection design, especially with median width of less than 19.5 feet, there is no offset method used for opposing left-turn lanes, so the median width is equal to the width of the median nose plus the left-turn lane width. Table 3-1 shows a series of results of available sight distance (ASD) according to equitation, supposing that the left-turn lane width (LW) is 12 feet. For the 12-foot median for only the left-turn lane, the available sight distance is 1,729 feet and there is no sight-distance problem. For the 14-foot median, sight distance is 419 feet, but according to the AASHTO design criteria, a 445-foot design value is required for 55 mph design speed. For the 16-foot median, a 273-foot sight distance is available, but a 285-foot design value is required for 35 mph design speed. When the median is 20 feet, the available sight distance is only 187 feet, which cannot support intersections that have design speeds higher than 20 mph. According to Equation 2-1, the corresponding major road design speed can be derived from those available sight distances for which left turners can safely cross the opposing through traffic (see Figure 3-3). The figure shows that the wider the median size, the lower the design speeds provided. When the median width is 13.5 feet, the major road speed should be no more than 60 mph. As the median width increases to 20 feet, the safe major road speed decreases to 23 mph.

Table 3-1: Calculated Available Sight Distance for Traditional Parallel Opposing Left-turn Lanes

m	N	LW	D	ASD
(ft)	(ft)	(ft)	(ft)	(ft)
12	0	12	83	1,729
13	1	12	83	637
14	2	12	83	419
15	3	12	83	325
16	4	12	83	273
17	5	12	83	240
18	6	12	83	217
19	7	12	83	200
20	8	12	83	187
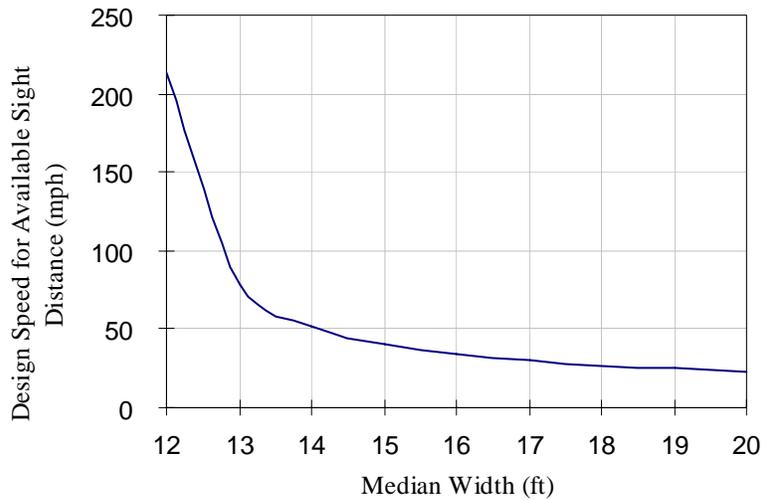
Figure 3-3: Relationship between safe major road design speed and median width

Therefore, compared to the required sight distances for left turns from the AASHTO design criteria for traditional left-turn lane design, the available sight distance may be insufficient even for a 14-foot narrow median at 55 mph major-road design speed. The sight-distance calculation model demonstrated that the left-turn sight-distance problem can also occur at medians narrower than the 18-foot figure documented by AASHTO.

3.1.4 Sight-distance improvement by offsetting left-turn lanes

The parallel offset design for left-turn lanes is designed to improve the sight distance because there are dividers in both sides of the left lane. As shown in Figure 3-4, one is a narrowed median nose in the left side of the lane and the other is a concrete island or pavement marking in the right side. Offset value (O) is defined as the distance from the outer edge of the left-turn lane to the inner edge of the opposing left-turn lane. Thus, the median width (m) is equal to the width of the median nose (n) plus the left-turn lane width (LW) and the right divider (r). So the m term

is equal to n + LW + r and n is equal to O + r. Substituting terms O and r into Equation 3-9, sight-distance improvement by offsetting left-turn lanes can be evaluated as:

$$SD = 8 + D + \frac{(m - O - r - 3) \cdot (8 + D)}{2O + 2r - m + 12.5} \qquad (3\text{-}9)$$
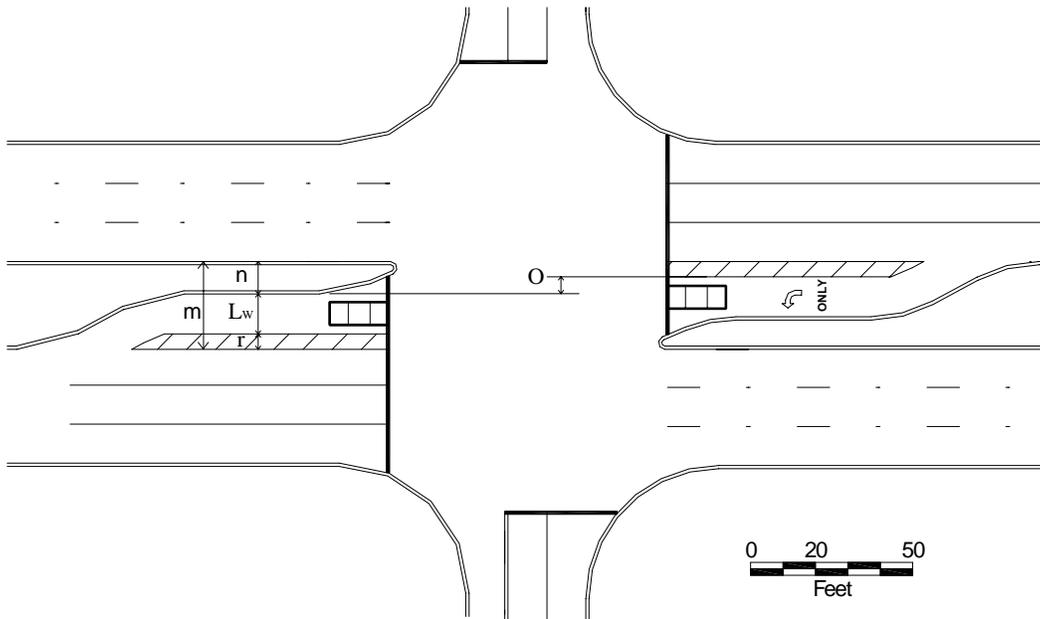
Figure 3-4: Parameter descriptions for offset parallel left-turn lanes

The value of the offset is negatively related to the sight distance. The smaller the O and the more opposing left-turn lanes move toward each other, the larger the sight distance available. Joshua and Saka (1992) indicated that the minimum value of the offset can be zero feet but cannot be negative in practical design, which would result in unsafe conditions, even though negative offsets can create unrestricted sight distance. Assuming that the width of the left-turn lane (LW) is 12 feet and D is equal to 83 feet as the intersection geometric features were described before, a series of sight distances can be calculated according to the different offset values (see Table 3-2).

When the offset is 0 to 1 foot, the effect of sight-distance improvement is very apparent, which can provide major road design speeds higher than 70 mph, as shown in Figure 3-5. For the 2-foot offset, the sight distance cannot provide design speeds higher than 65 mph. For the 3-foot offset, the benefit from the offset becomes comparatively weak and the provided-for design speed cannot exceed 50 mph. In Table 3-2, the related widths of dividers (n and r) in both sides of the left-turn lane are also listed as the references for intersection design. For other concrete intersection geometric features, different values of m, r, O, and D can be substituted into Equation 3-9 to search for the proper offset and create sufficient sight distance for the major road design speed.

Table 3-2: Calculated Sight Distance for Parallel Offset Opposing Left-turn Lanes

Offset (O) = 0 ft, n = r					Offset (O) = 1 ft, n = r + 1				
R	m	n	D	ASD	r	m	n	D	ASD
(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)
1	14	1	83	1,911	0.5	14	1.5	83	667
1.5	15	1.5	83	2,002	1	15	2	83	698
2	16	2	83	2,093	1.5	16	2.5	83	728
2.5	17	2.5	83	2,184	2	17	3	83	758
3	18	3	83	2,275	2.5	18	3.5	83	789
3.5	19	3.5	83	2,366	3	19	4	83	819
4	20	4	83	2,457	3.5	20	4.5	83	849
Offset (O) = 2 ft, n = r + 2					Offset (O) = 3 ft, n = r + 3				
R	m	n	D	ASD	r	m	n	D	ASD
(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)
0	14	2	83	419	--	14	--	83	--
0.5	15	2.5	83	437	0	15	3	83	325
1	16	3	83	455	2	16	3.5	83	338
1.5	17	3.5	83	473	0.5	17	4	83	351
2	18	4	83	491	1	18	4.5	83	364
2.5	19	4.5	83	510	1.5	19	5	83	377
3	20	5	83	528	2	20	5.5	83	390

Note: (--) means that data are not applicable.
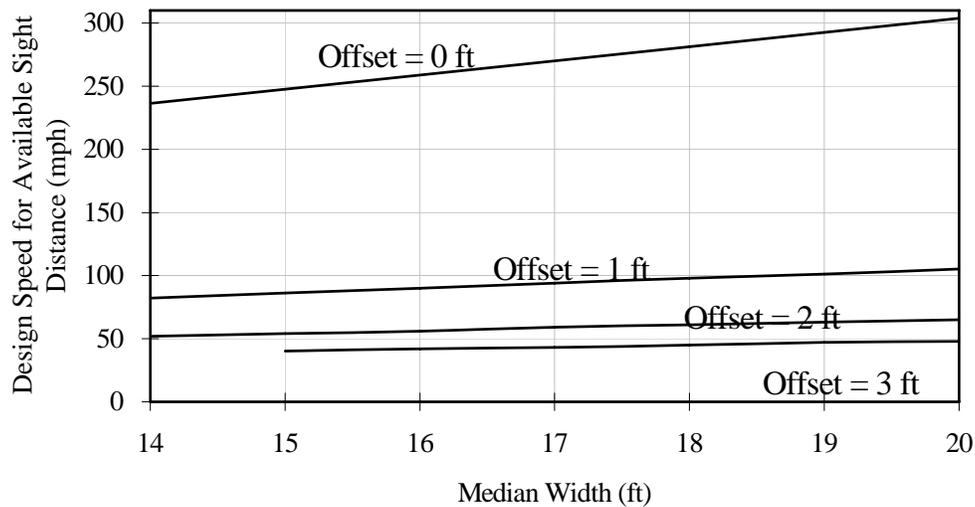
Figure 3-5: Effect of sight-distance improvement of offset parallel left-turn lanes

3.2 Geometric Model for Tapered Offset Left-turn Lanes

3.2.1 Formula to calculate available sight distance for tapered left-turn lanes

Until now, no related literature about a geometric model analyzed and evaluated the effect of sight-distance improvement by the method of tapered offset left-turn lanes. In fact, the model for tapered offset is a little different from the parallel one, since the blockage points of the driver's view may shift from the right front corner of the opposing left-turn vehicle to the right back corner, due to the rotation of the vehicle's position. This concept is illustrated in Figure 3-6. As far as this model is concerned, it can still be resolved by the similar triangle rule to get Equation 3-10 if the right front corner of the opposing left-turn vehicle blocks the driver's view, or by Equation 3-11, if the right back corner blocks the view.

27

$$SD = W + \frac{B_1 \cdot W}{A - B_1} \tag{3-10}$$

$$SD = W + V_L + \frac{B_2 \cdot (W + V_L)}{A - B_2} \tag{3-11}$$

as shown in Figure 3-6, where

SD = available sight distance (ft)

W = the distance from the left-turn driver's eye to the stop bar of the opposing through lanes (ft)

V_L = the length of the opposing left-turn vehicle (ft) [20 ft is assumed]

A = the distance from the left-turn driver's eye to the centerline of the nearest opposing through lane (which is also the centerline of the opposing through vehicle (ft))

B_1 = the distance from the right front corner of the opposing left-turn vehicle to the centerline of the nearest opposing through lane (which is also the centerline of the opposing through vehicle (ft))

B_2 = the distance from the right back corner of the opposing left-turn vehicle to the centerline of the nearest opposing through lane (which is also the centerline of the opposing through vehicle (ft))
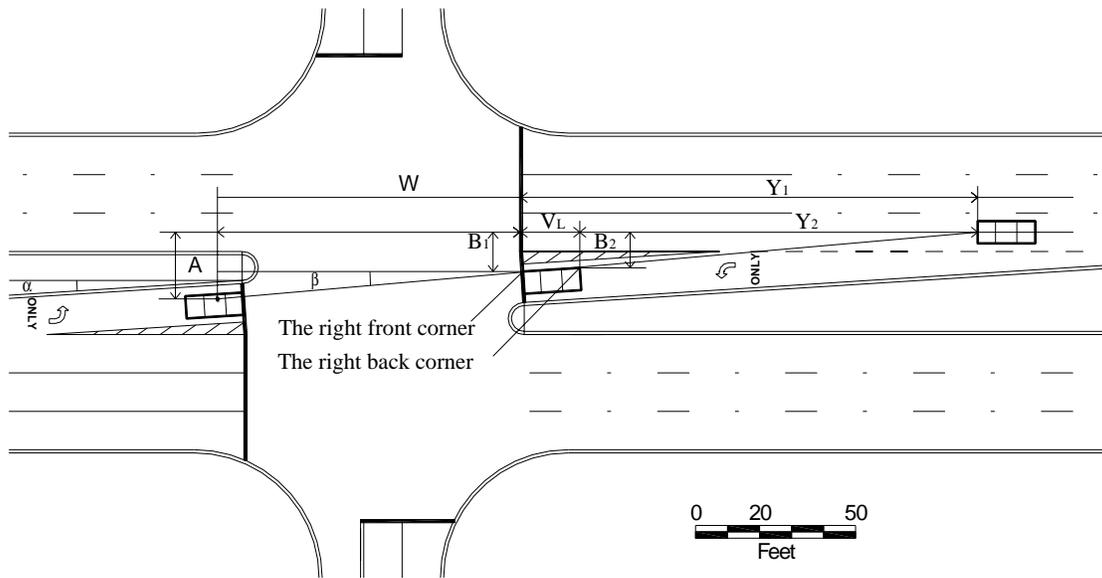
Figure 3-6: Intersection geometric features for tapered left-turn lanes and available sight distance

For the above Equations 3-10 and 3-11, it is necessary to note that W, the sight distance in advance of the opposing left-turn vehicle, can be approximately calculated by Equation 3-6, since the no-more-than-one-foot error of W due to the very small angle rotation of the left-turn vehicles would have a negligible effect on sight-distance calculation. For the same reason, V_L can be approximately assumed as the length of the opposing left-turn vehicle. For the other terms, Equations 3-12, 3-13, and 3-14 show how to calculate A, B_1, and B_2.

$$A = m + L_t / 2 - d$$

$$T = (m - n) / \cos \alpha$$

$$b_1 = V_f * tg\alpha$$

$$n = m - S * tg\alpha$$

$$d = (T - g - e - b_1) * \cos \alpha$$

29

$$A = m + L_t / 2 - d$$

$$A = m + L_t / 2 - [S * tg\alpha / \cos\alpha - g - e - V_f * tg\alpha] * \cos\alpha \qquad (3\text{-}12)$$

$$B_1 = L_t / 2 + d_1$$

$$T = (m - n) / \cos\alpha$$

$$d_1 = (T - g - V_w) * \cos\alpha$$

$$B_1 = L_t / 2 + [S * tg\alpha / \cos\alpha - g - V_w] * \cos\alpha \qquad (3\text{-}13)$$

$$B_2 = L_t / 2 + d_2$$

$$b_2 = V_L * tg\alpha$$

$$d_2 = (T - g - V_w - b_2) * \cos\alpha$$

$$B_2 = L_t / 2 + [S * tg\alpha / \cos\alpha - g - V_w - V_L * tg\alpha] * \cos\alpha \qquad (3\text{-}14)$$

All above parameters are shown in Figure 3-7, where

n = the width of the end of the median nose (ft)

m = the width of the median (ft)

g = the distance from the left side of the left-turn vehicle to the left lane line (ft) [2 ft can be

assumed for design purposes, according to the AASHTO]

e = the distance from the eye of the driver to the left side of the vehicle (ft) [1.5 ft is

assumed]

L_t = the width of the opposing through lane (ft) [12 ft is assumed]

V_W = the width of the opposing left-turn vehicle (ft) [7 ft can be assumed for design purposes, according to the AASHTO]

V_L = the length of the opposing left-turn vehicle (ft) [20 ft is assumed]

V_f = the distance from the eye of the driver to the front of the vehicle (ft) [8 ft is assumed according to the AASHTO]

S = storage length of left-turn lane (ft)

α = taper angle (degrees)
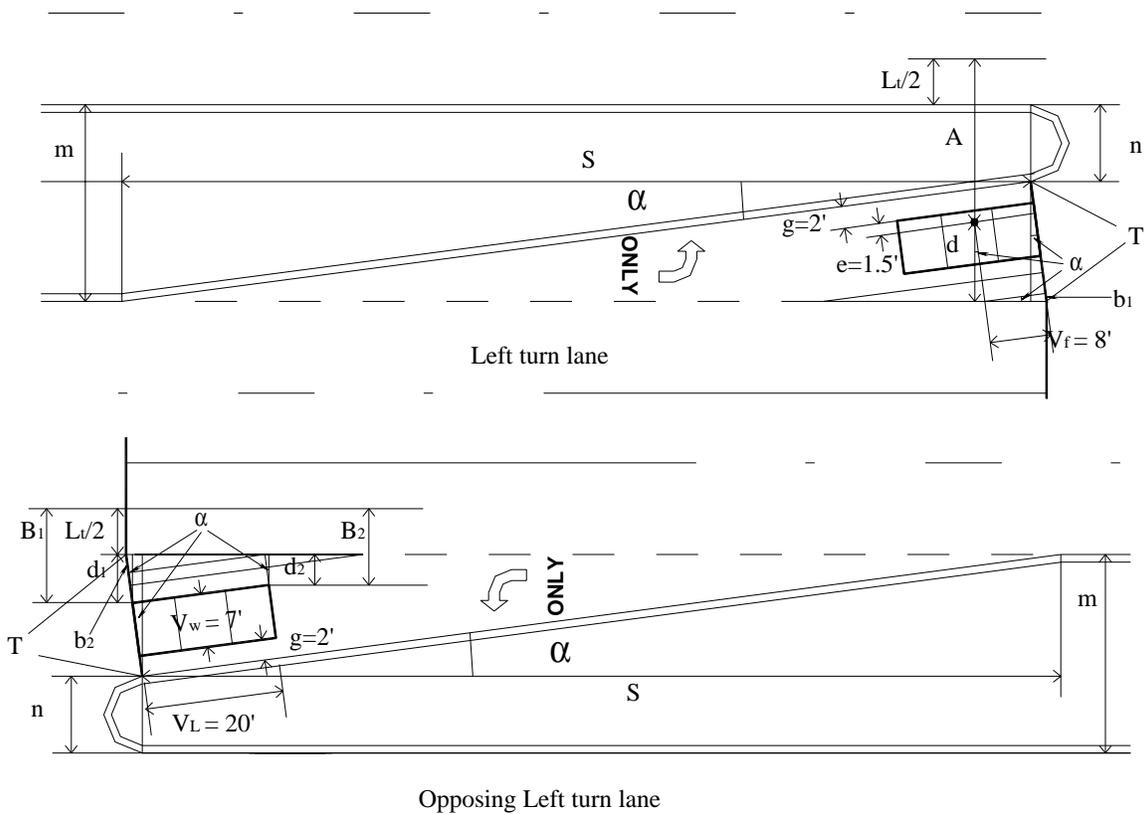
Figure 3-7: Parameter descriptions of the formula for tapered left-turn lanes

Substituting Equations 3-12, 3-13, and 3-14 and assuming values into Equations 3-10 and 3-11, Equations 3-15 and 3-16 can be derived to calculate the available sight distance for tapered offset

left-turn lanes. Equation 3-15 is applied to the case in which the right front corner of the opposing left-turn vehicle blocks the driver's view, and Equation 3-16 is applied to the case that the right front corner of the opposing left-turn vehicle blocks the driver's view.

$$SD = V_f + D + \frac{(L_t / 2 + S*tg\alpha - g*\cos\alpha - V_w *\cos\alpha) \cdot (V_f + D)}{m - 2S*tg\alpha + 2g*\cos\alpha + e*\cos\alpha + V_w *\cos\alpha + V_f *\sin\alpha}$$

$$SD = 8 + D + \frac{(6 + S*tg\alpha - 9*\cos\alpha) \cdot (8 + D)}{m - 2S*tg\alpha + 12.5*\cos\alpha + 8*\sin\alpha} \tag{3-15}$$

$$SD = V_f + D + V_L + \frac{(L_t / 2 + S*tg\alpha - g*\cos\alpha - V_w *\cos\alpha - V_f *\sin\alpha) \cdot (V_f + D + V_L)}{m - 2S*tg\alpha + (2g + e + V_w)*\cos\alpha + (V_f + V_L)*\sin\alpha}$$

$$SD = D + 28 + \frac{(6 + S*tg\alpha - 9*\cos\alpha - 20*\sin\alpha) \cdot (D + 28)}{m - 2S*tg\alpha + 12.5*\cos\alpha + 28*\sin\alpha} \tag{3-16}$$

As shown in Figure 3-7, β is defined as the angle between the driver's sight line passing the right front corner of the opposing left-turn vehicle and the parallel line to the major road. If $\beta \geq \alpha$, it can be concluded that the right front corner of the opposing left-turn vehicle blocks the driver's view; otherwise ($\beta < \alpha$), the right back corner of the opposing left-turn vehicle blocks the driver's view. Since $tg\beta = (A - B_1)/W$ (approximately), values of β and α can be compared in order to check which one of Equations 3-15 and 3-16 should be used.

3.2.2 Sight-distance improvement by tapered left-turn lanes

Evaluations using the tapered offset model focus only on medians wider than 18 feet, because the taper angle for the narrow median would be too small and would be adverse to traffic operation. In the following case, the same value as the parallel offset case, 83 feet, is assumed for term D, and 250 feet is assumed for storage length, S. Calculation results using Equation 16 (since $\beta < \alpha$) are presented in Table 3-3, showing a sequence of sufficient sight distance for larger medians with tapered offset left-turn lanes. For 18- to 23-foot medians, a 4-degree taper angle is appropriate to create adequate sight distance even for 80 mph major road speed. For 24- to 27-foot medians, a 4.5-degree taper angle is needed. For 28- to 30-foot medians, at least a 5-degree taper angle should be used. It can be concluded that as the sight-distance problem deteriorates with the increase of the median width, the larger taper angle is needed.

Table 3-4 shows the sensitivity analysis of the relationship between taper angle and available sight distance. If the value of m is held at 30 feet, the value of S at 250 feet, and the value of D at 83 feet, then when α is gradually increased in 0.5-degree increments, the corresponding available sight distances grow increasingly bigger, especially when α is larger than 4.5 degrees. Another sensitivity analysis showed that storage length S also contributes to the larger sight distance, as shown in Table 3-4. If the value of m is held at 30 feet, D at 83 feet, and α at 5 degrees, then increasing S in 10-foot increments will yield available sight distances that extend very rapidly, especially when S exceeds 230 feet.

In Tables 3-3 and 3-4, most analyses of sight distance for tapered offset left-turn lanes involved Equation 3-16. The reason is that the assumed intersection width (83 feet) is very wide, which

causes a very small β, even a negative value because of the taper effect. If in some cases D is comparatively smaller, Equation 3-15 may be used to calculate sight distance. Therefore, using these models, it is possible for traffic engineers to lay out the tapered offset lanes to satisfy the sight-distance requirement of left turners, through balancing the relationship between parameters m, S, D, n, and α.

Table 3-3: Suggested Taper Angle Corresponding to Median Width for Sufficient Sight Distance

m	S	D	n	α	β	SD
18.0	250.0	83.0	0.5	4.0	-2.5	Unlimited
19.0	250.0	83.0	1.5	4.0	-1.8	Unlimited
20.0	250.0	83.0	2.5	4.0	-1.2	Unlimited
21.0	250.0	83.0	3.5	4.0	-0.6	3,278.8
22.0	250.0	83.0	4.5	4.0	0.0	1,108.1
23.0	250.0	83.0	5.5	4.0	0.7	702.6
24.0	250.0	83.0	4.3	4.5	-1.4	Unlimited
25.0	250.0	83.0	5.3	4.5	-0.8	5,574.6
26.0	250.0	83.0	6.3	4.5	-0.2	1,395.8
27.0	250.0	83.0	7.3	4.5	0.5	839.0
28.0	250.0	83.0	6.1	5.0	-1.6	Unlimited
29.0	250.0	83.0	7.1	5.0	-1.0	12,943.3
30.0	250.0	83.0	8.1	5.0	-0.4	1,769.8

Table 3-4: Relationship Between the Taper Angle and Available Sight Distance

m	S	D	n	α	β	SD
30.0	250.0	83.0	16.9	3.0	10.4	146.1
30.0	250.0	83.0	14.7	3.5	7.7	181.4
30.0	250.0	83.0	12.5	4.0	5.1	254.7
30.0	250.0	83.0	10.3	4.5	2.4	427.5
30.0	250.0	83.0	8.1	5.0	-0.4	1,769.8
30.0	250.0	83.0	5.9	5.5	-3.1	Unlimited
30.0	250.0	83.0	3.7	6.0	-5.8	Unlimited
30.0	250.0	83.0	1.5	6.5	-8.5	Unlimited

3.3 Effect of Opposite Large-Size Vehicles on Left-turn Sight Distance

3.3.1 Geometric sight-distance models for large-size vehicles

A truck or bus presented in the opposite left-turn lane with its larger dimensions would aggravate sight obstruction further. According to the AASHTO manual, the design width of passenger cars, including passenger cars of all sizes, sport/utility vehicles, minivans, vans, and pick-up trucks, can be assumed to be 7 feet; for a single unit truck, design width is 8 feet; for an intercity bus, design width is 8.5 feet. However, AASHTO did not present the effect of large-size vehicles on sight distance. The following models focus mainly on the sight-distance problem on a passenger car's driver making a left-turn when confronted by an opposing truck or bus turning left.

Figure 3-8 illustrates the restricted sight distance by trucks or buses as opposite left-turn vehicles. According to the intersection features and left-turner's behavior, several parameters can be assumed when calculating terms A, B, and W. For passenger cars as opposite left-turn vehicles, 2 feet is assumed for the distance from the left side of the left-turn vehicle to the left lane line; this distance is represented by the term g in Figure 3-2. For trucks or buses, it is assumed that the left lateral distance is equal to the right lateral distance. Figure 3-8 shows related parameter descriptions and how to calculate terms A and B for trucks or buses. By substituting those geometric parameters into Equation 3-3, we can obtain more detailed available sight-distance models, which are shown in Equation 3-17 for buses or trucks as opposite left-turn vehicles.
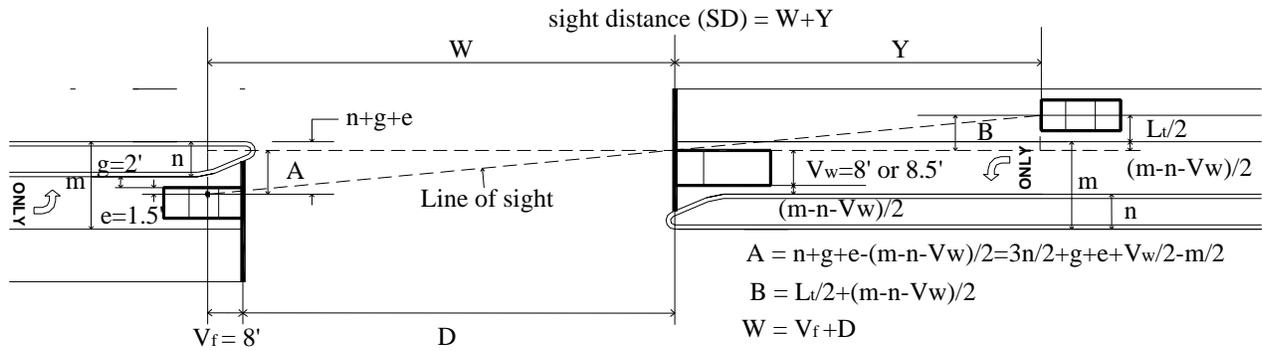
Figure 3-8: Parameter descriptions of the formula for parallel left-turn lanes for trucks or buses as opposing left-turn vehicles

$$SD \; = \; V_f + D + \frac{(L_t + m - n - V_w) \cdot (V_f + D)}{3n + 2g + 2e + V_w - m}$$
(3-17)

D is positively related to the sight distance, which includes the pedestrian crossing widths of the major road and the minor road widths of intersections. Simply put, as the number of minor road lanes increase, the intersection gets wider, resulting in a larger sight-distance available for left-turners. Four typical assumed minor road types are shown in the Figure 3-9. The corresponding Ds for them are 72, 83, 94, and 110 feet, respectively. All major roads of those intersections have the same geometric features, which are that they are all divided by a median and have only one left-turn lane and two through lanes in each direction with a 12-foot lane width. It is also assumed that the far left edge of the median curb is aligned with the opposing left-turn lane line. For minor roads, Figures 3-9-a, 3-9-b, and 3-9-c show the number of lanes increasing by one lane, from 2 lanes to 4 lanes, with a lane width of 11 feet. Figure 3-9-d shows a divided minor road of the intersection that has four 11-foot lanes and a 16-foot median. There are also 10-foot pedestrian crossings to cross the major approaches in those intersections, and the distance from

the stop bar of the major road to the edge of the minor road is supposed to be 25 feet (10' + 10' + 5').

a. Intersection with 2-lane minor road

c. Intersection with 4-lane minor road

b. Intersection with 3-lane minor road

d. Intersection with 4-lane minor road with 16 ft median
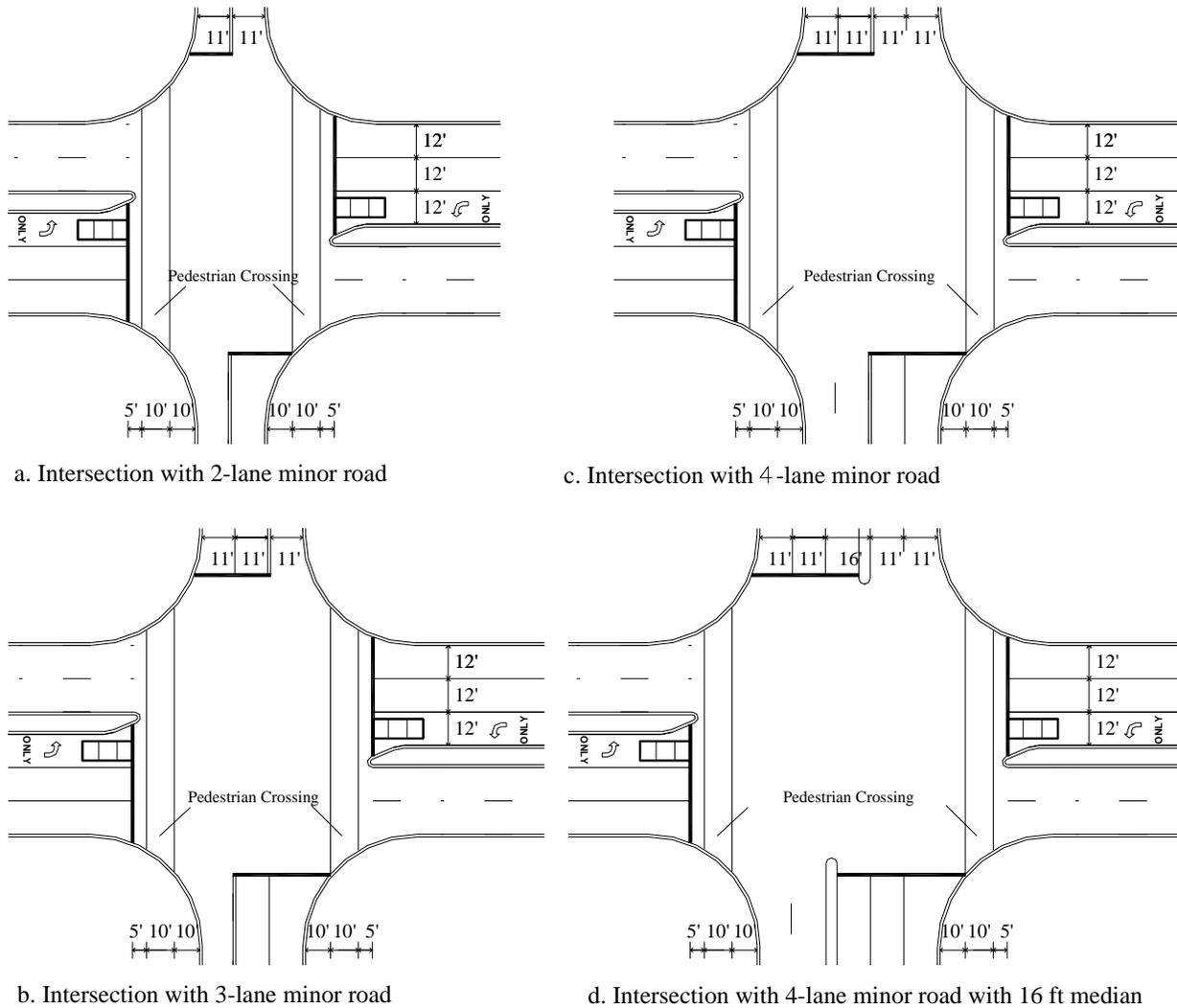
Figure 3-9: Intersection geometric features for parallel left-turn lanes and available sight distance

Figures 3-10-a, 3-10-b, and 3-10-c show available sight distances for different minor road types when passenger cars, trucks, and buses are present as the opposite left-turning vehicles separately, using Equations 3-7 and 3-17. The figures illustrate that as major road median widths increase, the available sight distances decrease very rapidly. The larger vehicle widths of trucks and buses would result in less sufficient left-turn sight distances compared to passenger cars.

When the median width is larger than 14 feet, all of the available sight distances for trucks and buses are less than 400 feet, which may be insufficient for higher major road speed, since 445 feet is required for 55 mph design speed according to AASHTO sight-distance design criteria. When the median width is 18 feet, all sight distances, including for passenger cars, are less than 300 feet, which can only provide 37 mph major road design speed, according to Equation 2-1. It is notable that for the 12-foot median that is composed of only one left-turn lane, if buses are using the opposite left-turning lane, the available sight distance for a 2-lane minor road intersection is 434 ft, which cannot satisfy the 445-foot requirement for 55 mph design speed. The sight-distance calculation models demonstrated that the left-turn sight-distance problem could frequently occur at medians narrower than the 18-foot dimension, especially when a truck or bus is present in the opposite left-turn lane.
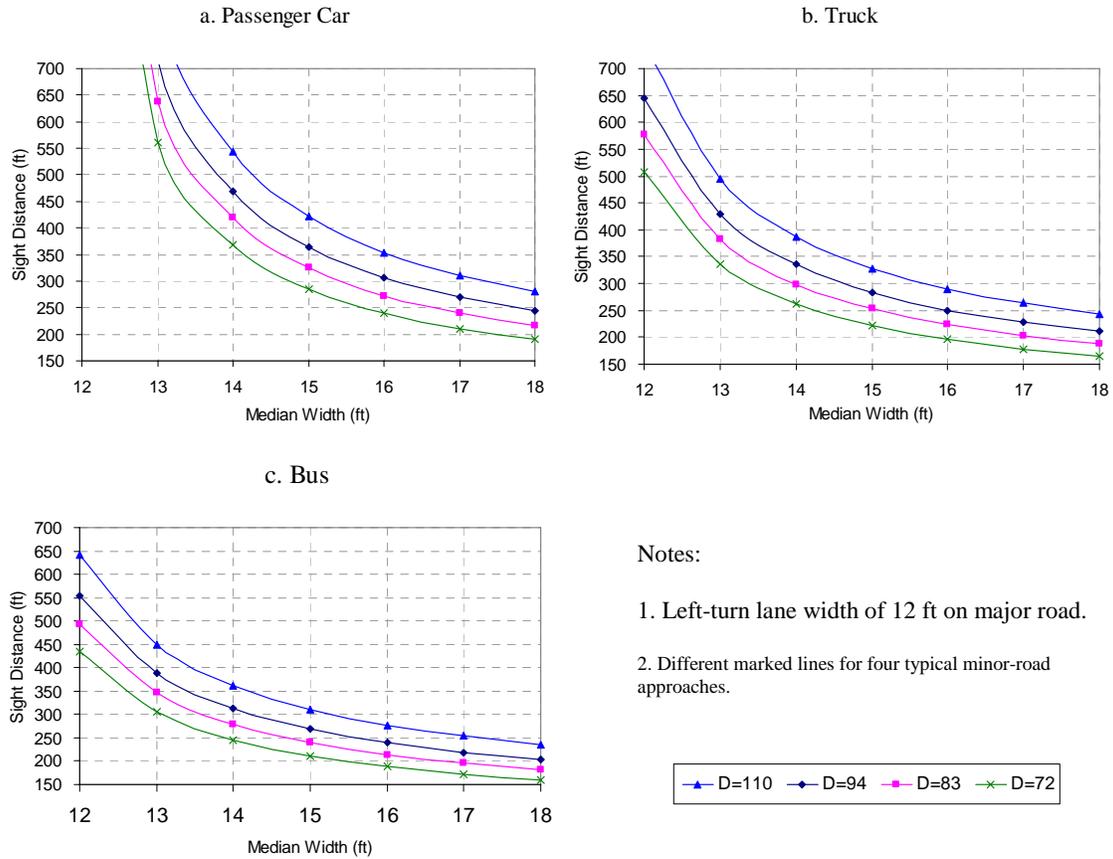
Figure 3-10: Available left-turn sight distances for different intersection configurations

3.3.2 Offset models to develop guideline to satisfy required sight distance

For the method of offsetting parallel left-turn lanes to improve left-turn sight distance as shown in Figure 3-11, there are medial separators in both sides of the left lane. Offset value (O) is defined as the distance from the left edge of the left-turn lane to the right edge of the opposing left-turn lane, which is equal to n-r. If the width of the median nose is larger than the width of the right separator (n > r), the offset is positive; if it is less (n < r), the value is negative. In the case of a negative offset, the blockage of the opposing vehicle to the left-turning vehicle does not become an issue anymore, and the sight distance becomes unrestricted.

$$A = n+g+e-(m-n-g-V_w)=2g+e+O-L_L+V_w$$
$$B = L_t/2+(m-n-g-V_w)=(m-O+L_t+L_L)/2-g-V_w$$
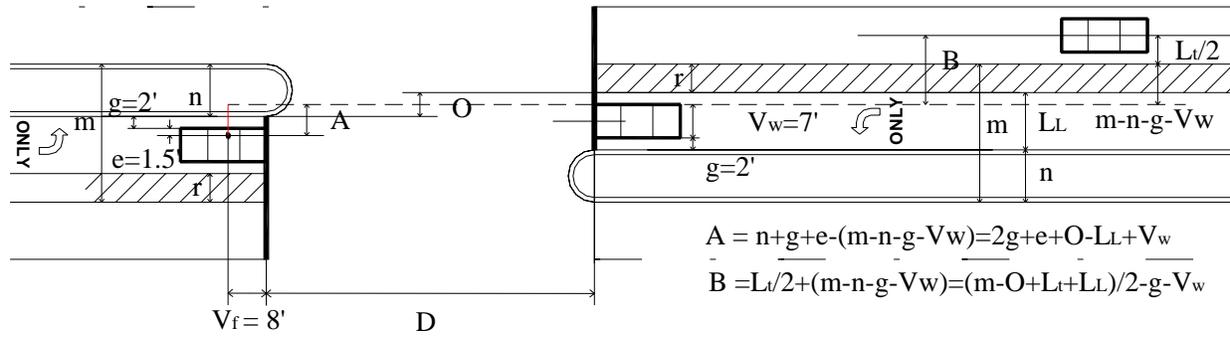
a. For passenger cars as opposing left-turn vehicles

$$A = n+g+e-(m-n+r-V_w)/2=g+e+(2O-L_L+V_w)/2$$
$$B = L_t/2+(m-n+r-V_w)/2=(m-O+L_t-V_w)/2$$
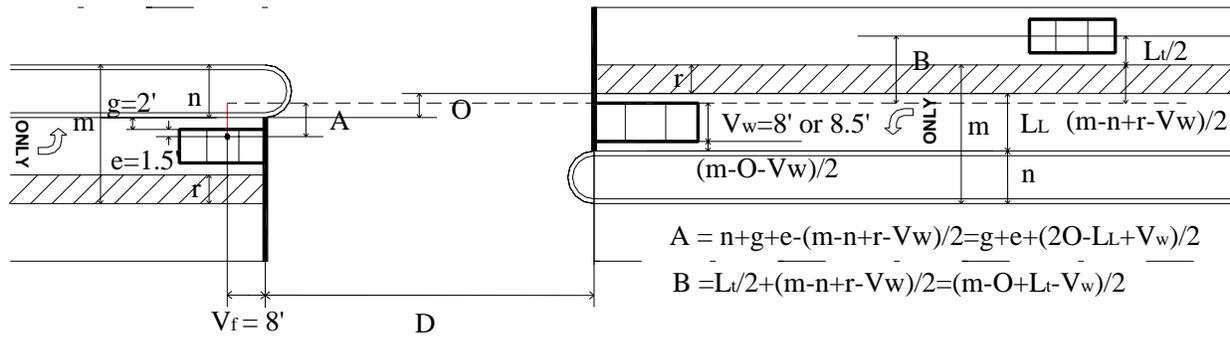
b. For trucks or buses as opposing left-turn vehicles

Figure 3-11: Parameter descriptions of parallel offset left-turn lanes

For parallel offset left-turn lanes, since $n+r=m-L_L$ and $n-r=O$, n is equal to $(m+O-L_L)/2$ and r is equal to $(m-O-L_L)/2$. Using these formulas in place of n and r, Figures 4-a and 4-b show how to calculate terms A and B using O for passenger cars and trucks or buses. Then, substituting those geometric parameters into Equation 3-3, the offset value O can be separately derived as Equation 3-18 for passenger cars and Equation 3-19 for trucks or buses, which can be used to calculate offset values according to sight-distance requirements.

For passenger cars as opposite left-turn vehicles,

$$O = \frac{(V_f + D) * (L_t - L_L + m + 2g + 2e) - 2SD * (2g + e - L_L + V_w)}{2SD - V_f - D} \quad (3\text{-}18)$$

For trucks or buses as opposite left-turn vehicles,

$$O = \frac{(V_f + D) * (L_t - L_L + m + 2g + 2e) - SD * (2g + 2e - L_L + V_w)}{2SD - V_f - D} \quad (3\text{-}19)$$

Since the offset value is negatively related to the sight distance, the smaller the value for O and the more the opposing left-turn lanes move inside each other, the larger the sight distance available. Therefore, the maximum offsets for sight-distance requirements of major road design speeds need to be calculated as intersection layout guidelines. Using Equation 2-1, the required intersection sight distances for passenger cars can be calculated for each highway design speed. Substituting those values (SD) and the related geometric parameters (m and D) into Equations 3-18 and 3-19, the maximum offsets can be calculated for passenger cars, trucks, or buses as sight obstructions.

The maximum offset guideline for the 2-lane minor road intersection is developed as an example, as shown in Figure 3-12. As expected, the higher the major road design speed, the less offset value is needed to provide adequate sight distance. Also, it is clear from Figures 3-12-a, 3-12-b, and 3-12-c that the wider the size of the vehicle in the opposite left lane, the less offset value is needed. However, the median width is positively related to the maximum offset, which is indicated by Equations 3-18 and 3-19. Moreover, medians with widths of 12 to 14 feet that are designed as two-way left-turn lanes could theoretically cause sight-distance problem for buses or trucks. For two-way left-turn lanes, it may be possible to achieve the effect of reducing the offset

of opposing left-turn lanes by simply widening the right lane line between the left-turn lanes and

the adjacent through lanes.

a. Passenger Car

b. Truck

c. Bus

Notes:

1. Left-turn lane width of 12 ft on major road.

2. Different marked lines for major-road design speeds.

25mph   30mph   35mph   40mph
45mph   50pmh   55mph
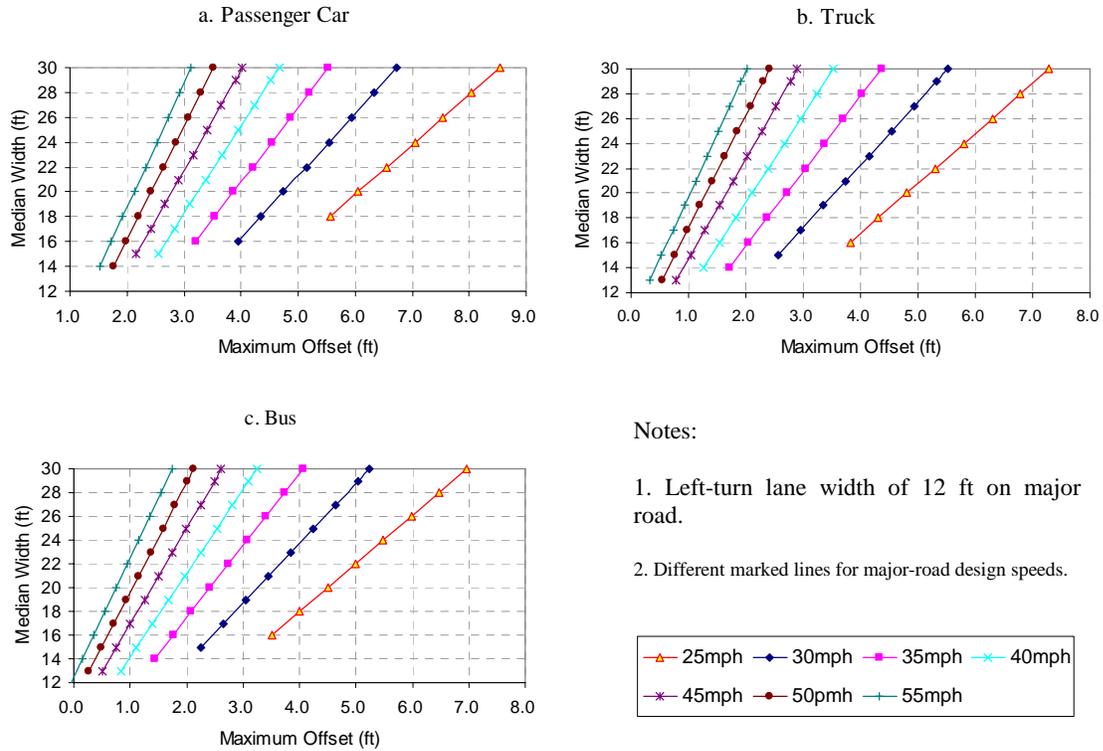
Figure 3-12: Maximum offset guideline for the two-lane minor-road intersection

42

CHAPTER 4. GEOMETRIC MODEL OF SIGHT-DISTANCE

CALCULATION FOR INTERSECTIONS WITH CURVE APPROACHES

For sight obstruction by apposite left-turn vehicles, the basic traffic scenario at an intersection on a horizontal curve is similar to that at an intersection with linear major approaches, as shown in Figures 4-1-a and 4-2-b. The curve scenario may have an increased probability of sight blockage, especially for the driver making a left turn toward the outside of the curve into the minor road approach. The likelihood and severity of this problem will increase with the sharpness of the curve. As shown in the Figure 4-1-a, the sight distance for the left-turners toward the outside of the curve is very short. On the other hand, for left-turners toward the inside of the curve, the sharpness of the curve can mitigate the vision problem and even contribute to unrestricted sight distance, since left-turners benefit from a left-turn lane offset toward the coming traffic.

In Figure 4-1-a, the sight line does not intersect with the route of through vehicles in the nearest coming through lane, which mean the sight distance is unrestricted. However, at a linear-approach intersection, as shown in the Figure 4-1-b, the available sight distances for both opposite left-turners are same and are related to the median width of the major approaches. Therefore, if an intersection is located on a curved major road, the left-turn sight-distance problem may become more complex, requiring developing special geometric models in order to be evaluated.

This chapter presents sight-distance models for left-turning vehicles when opposite vehicles present sight obstructions, evaluates sight-distance problems for left-turning traffic toward the

inside and outside of the curve, and analyzes the relationship between available sight distance and related intersection geometric parameters.
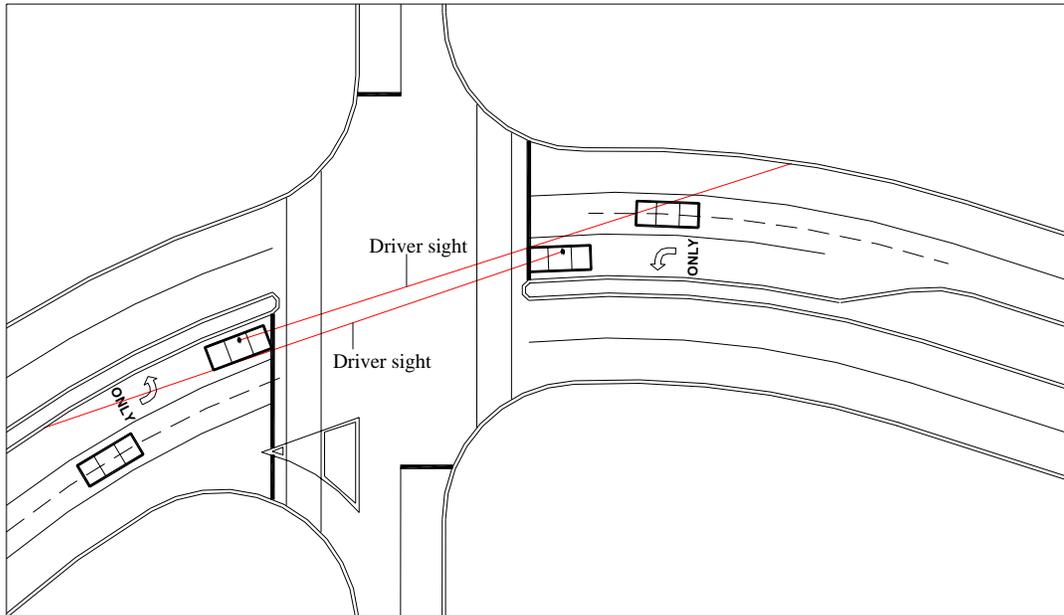
a. Intersection with linear major road approaches
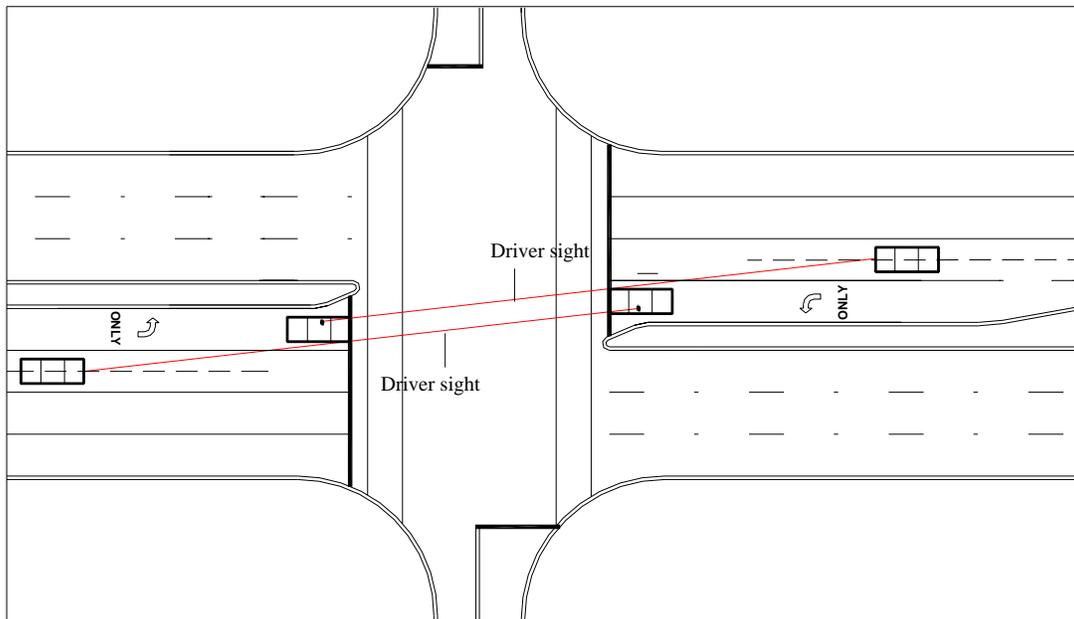
b. Intersection with linear major road approaches

Figure 4-1: Comparison of sight obstructions between a linear-approach intersection and a curve-approach intersection

4.1 Intersection Geometric Features
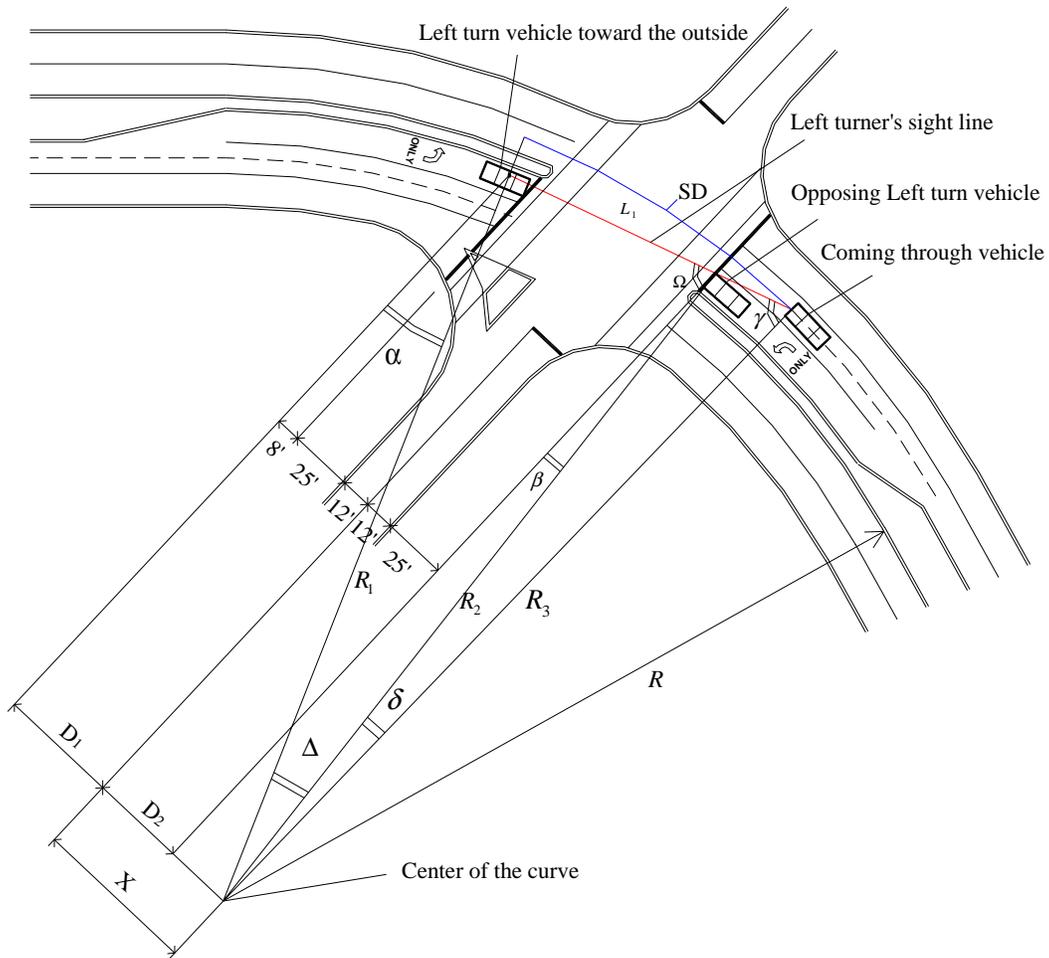
Figure 4-2: Basic descriptions of parameters to calculate sight distance for a left-turn maneuver toward the outside of the curve

A four-approach intersection located on a typical horizontal curve major road is shown in Figure 4-2. Since circular curves are used most often for horizontal curves because of their simplicity and ease of design, the sight-distance models developed in this paper focus on intersections with a single circular curve only. For the curved major road divided by a median, there are one left-turn lane and two directional through lanes on both sides of the median, and

each lane is 12 feet wide. It is assumed that the concrete geometric features for both curved major approaches of the intersection are the same, including median width, median nose width, and left-turn lane width. Also, the intersection design is assumed to be such that the far left edge of the median curb is aligned with the opposing left-turn lane line in the same radius curve. For the undivided linear minor road, two 12-foot lanes are assumed. There are also 10-foot pedestrian crossings to cross the major approaches, and the distance from the stop bar of the major road to the edge of the minor road is assumed to be 25 feet (10' + 10' + 5'). The stop bars of major approaches are designed to be parallel to the minor road direction.

4.2 Model for a Left-turn Maneuver Toward the Outside of the Curve

According to the definition used by McCoy et al. (1992), the available sight distance (SD) is the distance from the left-turn driver's eye to the point at which his/her line of sight intersects the centerline of the near opposing through lane. For the curved road, it should be the curve length of the centerline in the near opposing through lane along which the opposing through vehicles will traverse (see Figure 4-2). This definition is documented in the 2001 AASHTO manual.

All related parameters to calculate the sight distance for left-turn traffic toward the outside of the curve are defined in Figure 4-2. Based on simple geometric rules, the basic sight-distance model is shown in Equations 4-1, 4-2, and 4-3:

$$SD = R_3(\Delta + \delta) \qquad (4\text{-}1)$$

$$\Delta = \alpha - \beta \qquad (4\text{-}2)$$

Where $\alpha = \arcsin(\dfrac{X + D_1}{R_1})$,

$$\beta = \arcsin(\dfrac{X - D_2}{R_2})$$

$$\delta = \Omega - \gamma \tag{4-3}$$

Where $\Omega = \arcsin(\dfrac{R_1 \sin \Delta}{L_1})$

$$\gamma = \arcsin(\dfrac{R_1 R_2 \sin \Delta}{L_1 R_3})$$

$$L_1 = \sqrt{R_1^2 + R_2^2 - 2R_1 R_2 \cos \Delta}$$

As shown in Figure 4-2, where

SD = available sight distance (ft)

Δ = the angle between the curve radius to the left-turner's eye and the curve radius to the right front corner of the opposing left-turn vehicle (radians)

α = the angle between the curve radius to the left-turner's eye and the parallel line to the minor road (radians)

β = the angle between the curve radius to the right front corner of the opposing left-turn vehicle and the parallel line to the minor road (radians)

δ = the angle between the curve radius to the right front corner of the opposing left-turn vehicle and the curve radius to the point at which left-turner's line of sight intersects the centerline of the near opposing through lane (radians)

Ω = the angle between the curve radius to the right front corner of the opposing left-turn vehicle and left-turner's sight line (radians)

γ = the angle between the curve radius to the point at which left-turner's line of sight intersects the centerline of the near opposing through lane and left-turner's sight line (radians)

D_1 = the distance from the left-turn driver's eye to the centerline of the minor road (ft)

D_2 = the distance from the right front corner of the opposing left-turn vehicle to the centerline of the minor road (ft)

X = the distance from the curve center point to the centerline of the minor road (ft)

L_1 = the distance from the left-turn driver's eye to the right front corner of the opposing left-turn vehicle (ft)

R = the curve radius to the inside edge of the median (ft)

R_1 = the curve radius to the left-turner's eye (ft)

R_2 = the curve radius to the right front corner of the opposing left-turn vehicle (ft)

R_3 = the curve radius to the point at which left-turner's line of sight intersects the centerline of the near opposing through lane (ft)

Based on Equations 4-1, 4-2, and 4-3, the available sight distance can be calculated by D_1, D_2, X, R_1, R_2 and R_3. Of those parameters, D_1, D_2 and X are fixed, since they represent unique features of the intersection; R_1, R_2 and R_3 can be calculated by Equations 4-4, 4-5, and 4-6, respectively.

$$R_1 = R + m - n - g - e \tag{4-4}$$

$$R_2 = R + n + g + V_W \tag{4-5}$$

$$R_3 = R + m + L_t / 2 \qquad\qquad (4\text{-}6)$$

As shown in Figure 4-3, where

m = the width of the median (ft)

n = the width of the median nose (ft)

g = the distance from the left side of the left-turn vehicle to the left lane line (ft) [2 ft can be assumed for design purposes, according to the AASHTO]

e = the distance from the eye of the driver to the left side of the vehicle (ft) [1.5 ft is assumed for a passenger car]

V_w = the width of the opposing left-turn vehicle (ft) [7 ft is assumed]

L_t = the width of the opposing through lane (ft) [12 ft is assumed]
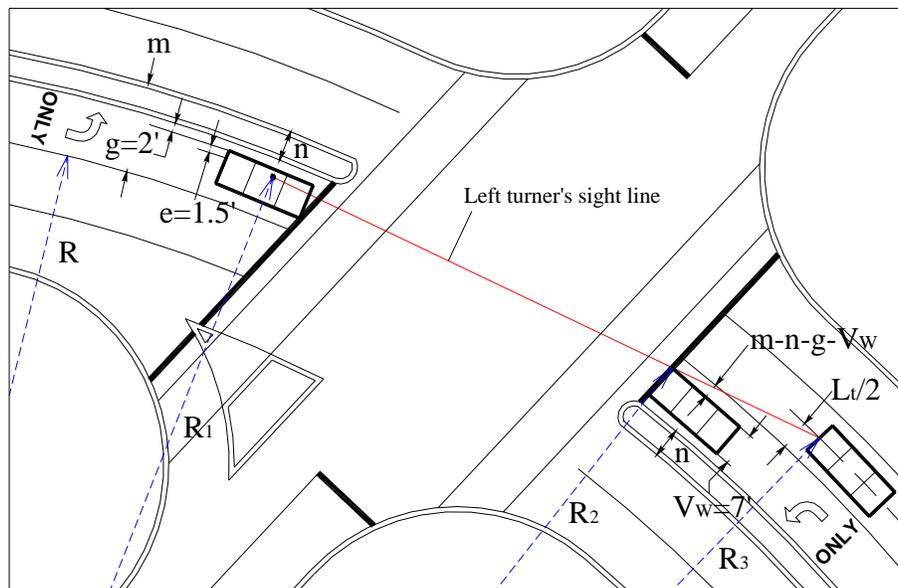
Figure 4-3: Geometric features of intersection with horizontal curve approaches

According to the concrete geometric features of the intersection and appropriate assumed values for left-turning maneuvers, the available sight distance is dependent on median width (m), the width of the median nose (n), the curve radius (R), and terms D_1, D_2 and X, since the other terms are constant values. The stepwise calculation relationships between the sight distance and all parameters are shown in Figure 4-4.
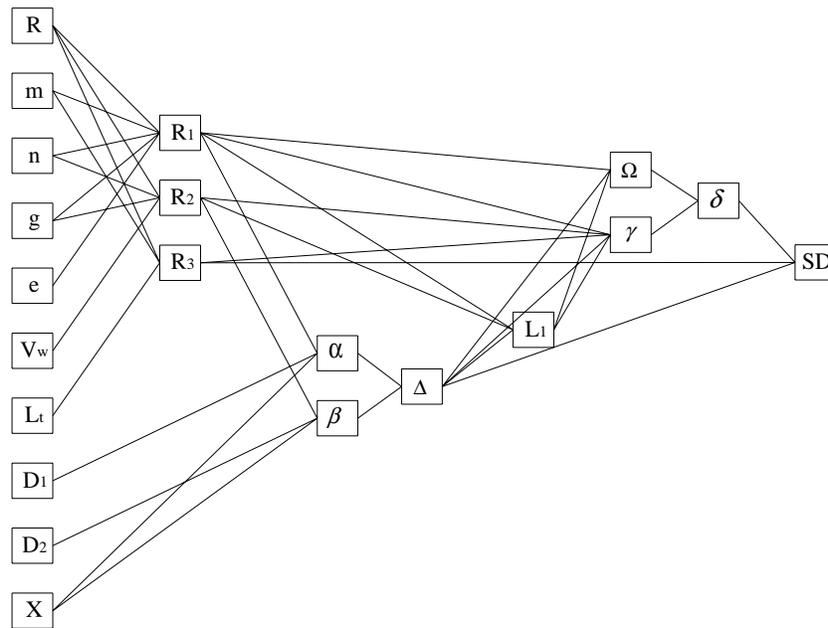
Figure 4-4: Calculation relationships between the sight distance and all parameters

Of those terms, m and n are correlated. For the traditional intersection design, especially with the median width less than 19.5 feet, there is no offset method used for opposing left-turn lanes, so the median width (m) is equal to the width of the median nose (n) plus the left-turn lane width. If the left-turn lane width on the major road is 12 feet, then n is equal to m-12.

According to the Equation 2-1, the available sight distances can be translated into safe major road design speeds. Figure 4-5 shows a sensitivity analysis of median width and curve radius on

sight distance and design speed for a left-turn maneuver toward the outside of the curve, holding

other parameters as X = 0 feet, D_1 = 45 feet, and D_2 = 37 feet, and increasing the radius only

from 500 feet to 12,000 feet. The figure indicates that: 1) the median width m is negatively

related to the sight distance, while the curve radius R is positively related to the sight distance; 2)

the sight distance is more sensitive to curve radius for the narrower medians than for the wider

medians, since the former curves in the figure are steeper than the latter ones; 3) as the curve

radius increases, the increasing rate of the sight distance decreases; and 4) the sensitivity of the

sight distance to the median width increases with the increment of the curve radius, which means

that curve radius is a more important factor to the sight distance for the relatively sharper road

curve, while median width is a more important factor for the relatively flatter road curve.
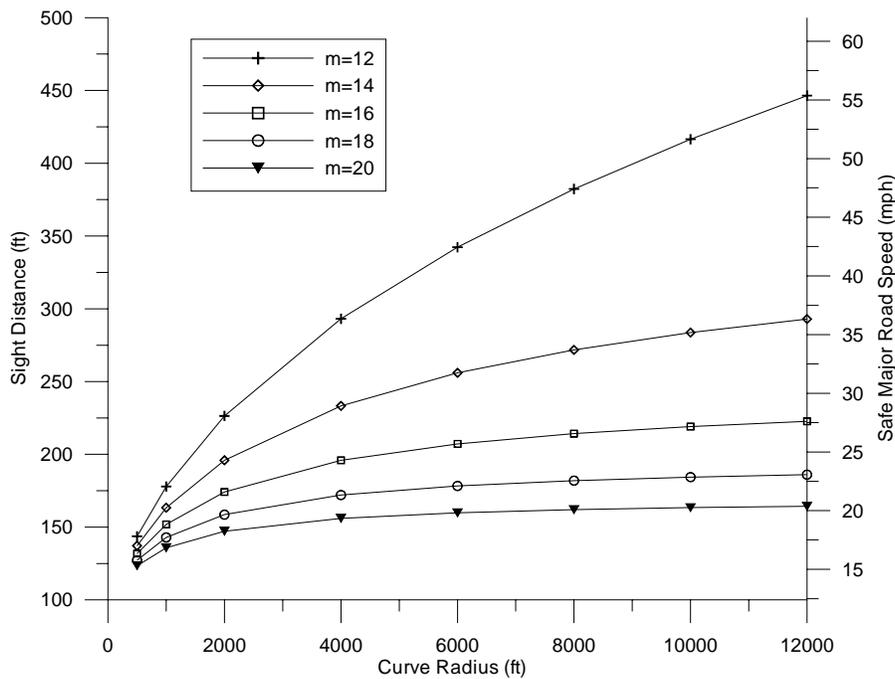
Figure 4-5: Sensitivity analysis of sight distance for left-turn maneuver toward the outside of the

curve

The figure also illustrates that for median widths of less than 20 feet, almost all of the safe major road speeds are less than 55mph. Even for the 12-foot median that is composed of only one left-turn lane, sight-distance requirements of 445 feet for the 55 mph design speed still cannot be satisfied according to the AASHTO criteria unless the curve radius is larger than 12,000 feet. If the major road curve is relatively sharper (R less than 2,000 feet), the available sight distance is less than 230 feet, which cannot support 30 mph major road design speed. Obviously curved intersections present more serious sight-distance problems for unprotected left-turn traffic toward the outside of the curve than the linear type ones that had been studied by prior researchers.

4.3 Model for Left-turn Maneuver Toward the Inside of the Curve

Figure 4-6 shows all basic parameters to calculate the sight distance for left-turning toward the inside of the curve. However, for this situation, it is very possible that there is no sight-distance problem because of the geometry of the site, as shown in the figure. Only if the left-turner's eyesight intersects the centerline of the near opposing through lane could the opposing vehicle be a potential sight obstruction. Therefore, the first step for the model is to check if the opposing left-turn vehicle is a sight obstruction. Comparison between the radius (R_3) of the centerline of the near opposing through lane and the distance (T) from the curve center to the driver's sight line can be used to check that, as shown in the figure.
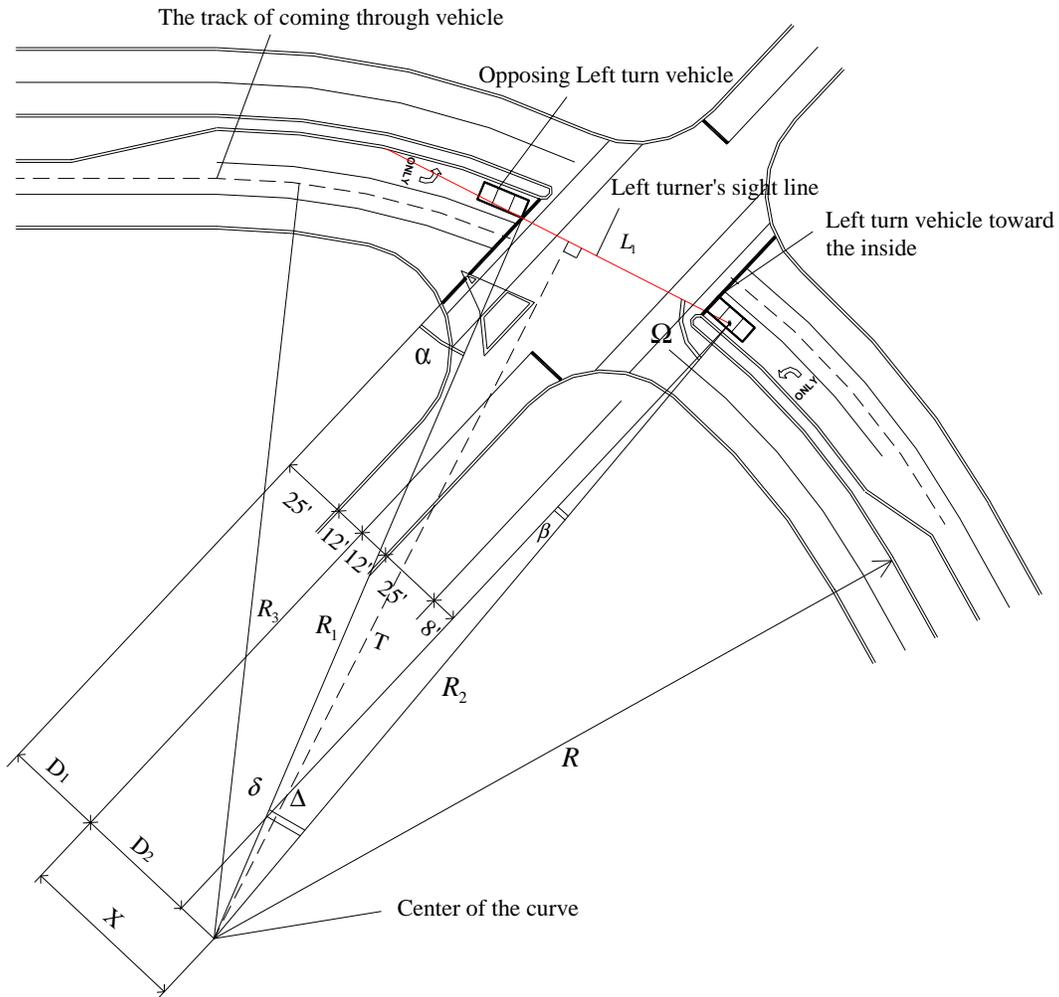
Figure 4-6: Basic descriptions of parameters to calculate sight distance for a left-turn maneuver toward the inside of the curve

Step 1: Check if there is a possible sight-distance problem

If $T = R_2 * \sin \Omega > R_3 \quad \Rightarrow \quad$ There is no intersection between eyesight and the centerline of the nearest opposing through lane and no sight-distance problem.

If $T = R_2 * \sin\Omega \leq R_3$ $\Rightarrow$ There is an intersection between them and possible sight-distance problem; then go to Step 2 to calculate available sight distance, which also shows how to calculate terms R_2, Ω, and R_3.

Step 2: Calculate available sight distance

Figure 6-16 shows the related geometric relationship when there is an intersection between eyesight and the centerline of the nearest opposing through lane. The available sight distance (SD) can be calculated by Equations 4-7, 4-8, and 4-9.

$$SD = R_3(\Delta + \delta) \tag{4-7}$$

$$\Delta = \alpha - \beta \tag{4-8}$$

$$\text{Where,} \, \alpha = \arcsin(\frac{X + D_1}{R_1}),$$

$$\beta = \arcsin(\frac{X - D_2}{R_2})$$

$$\delta = \pi - \gamma - \Delta - \Omega \tag{4-9}$$

$$\text{Where,} \, \Omega = \arcsin(\frac{R_1 \sin\Delta}{L_1})$$

$$\gamma = \pi - \arcsin[\frac{R_1 \sin(\Omega + \Delta)}{R_3}]$$

$$L_1 = \sqrt{R_1^2 + R_2^2 - 2R_1 R_2 \cos\Delta}$$
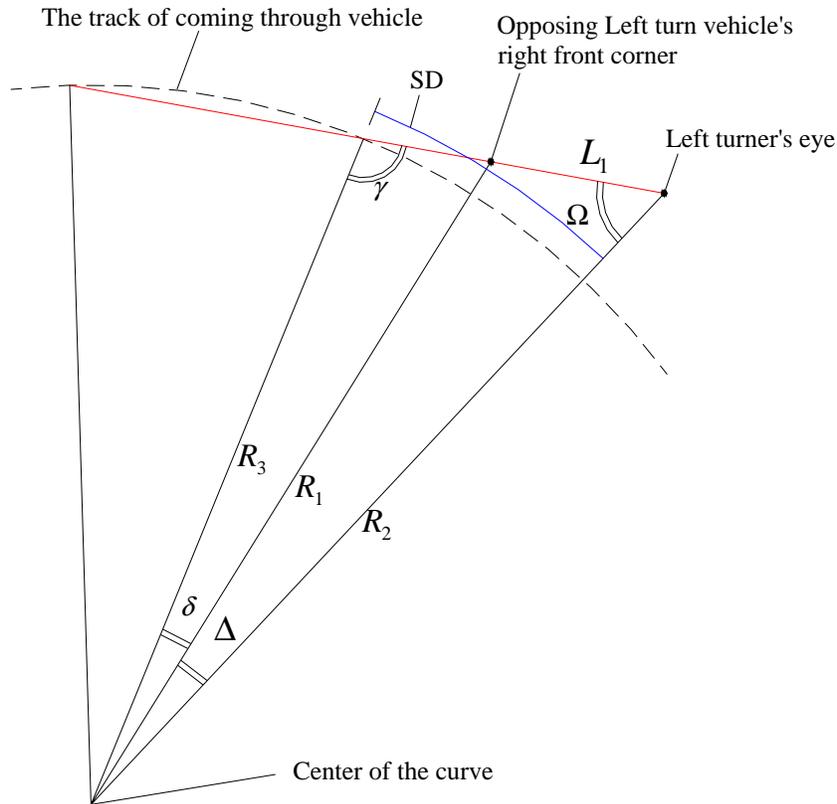
Figure 4-7: Geometric relationship for the model for left-turn maneuver toward the inside of the curve

As shown in Figures 4-6 and 4-7, where

SD = available sight distance (ft)

Δ = the angle between the curve radius to the left-turner's eye and the curve radius to the right front corner of the opposing left-turn vehicle (radians)

α = the angle between the curve radius to the right front corner of the opposing left-turn vehicle and the parallel line to the minor road (radians)

β = the angle between the curve radius to the left-turner's eye and the parallel line to the minor road (radians)

δ = the angle between the curve radius to the right front corner of the opposing left-turn vehicle and the curve radius to the point at which left-turner's line of sight intersects the centerline of the near opposing through lane (see Figure 4-7) (radians)

Ω = the angle between the curve radius to the left-turner's eye and the left turner's sight line (radians)

γ = the angle between the curve radius to the point at which the left-turner's line of sight intersects the centerline of the near opposing through lane and the left-turner's sight line (see Figure 6-16) (radians)

D_1 = the distance from the right front corner of the opposing left-turn vehicle to the centerline of the minor road (ft)

D_2 = the distance from the left-turn driver's eye to the centerline of the minor road (ft)

X = the distance from the curve center point to the centerline of the minor road (ft)

L_1 = the distance from the left-turn driver's eye to the right front corner of the opposing left-turn vehicle (ft)

R = the curve radius to the inside edge of the median (ft)

R_1 = the curve radius to the right front corner of the opposing left-turn vehicle (ft)

R_2 = the curve radius to the left-turner's eye (ft)

R_3 = the curve radius to the point at which left-turner's line of sight intersects the centerline of the near opposing through lane (see Figure 4-7) (ft)

R_1, R_2 and R_3 can be calculated by Equations 4-10, 4-11, and 4-12, respectively, based on the same definitions of R, m, n, g, e, V_w, and L_t as in the previous model.

$$R_1 = R + m - n - g - V_w \qquad (4\text{-}10)$$

$$R_2 = R + n + g + e \qquad (4\text{-}11)$$

$$R_3 = R - L_t / 2 \qquad (4\text{-}12)$$

For the model for the left-turn maneuver toward the inside of the curve, both the median width m and curve radius R are negatively related to the sight distance. Figure 4-8 shows a sensitivity analysis of median width and curve radius on sight distance and the major road design speed, if holding other parameters, X=0 feet, D_1=45 feet, and D_2=37 feet, and gradually increasing the radius from 1,000 feet to 14,000 feet in 1,000-foot increments. The figure indicates that: 1) both curve radius and median width are negatively related to the sight distance; 2) if the curve radius is less than 1,000 ft, there will be no sight-distance problem for most median types, unless medians widths are greater than 24 feet; 3) once the opposing vehicle becomes the sight obstruction, the available sight distance can be small, which may not support higher major road speed; and 4) as the curve radius increases, its sensitivity to the sight distance decreases, and median width is a more important factor to the sight distance for the relatively flatter road curve.
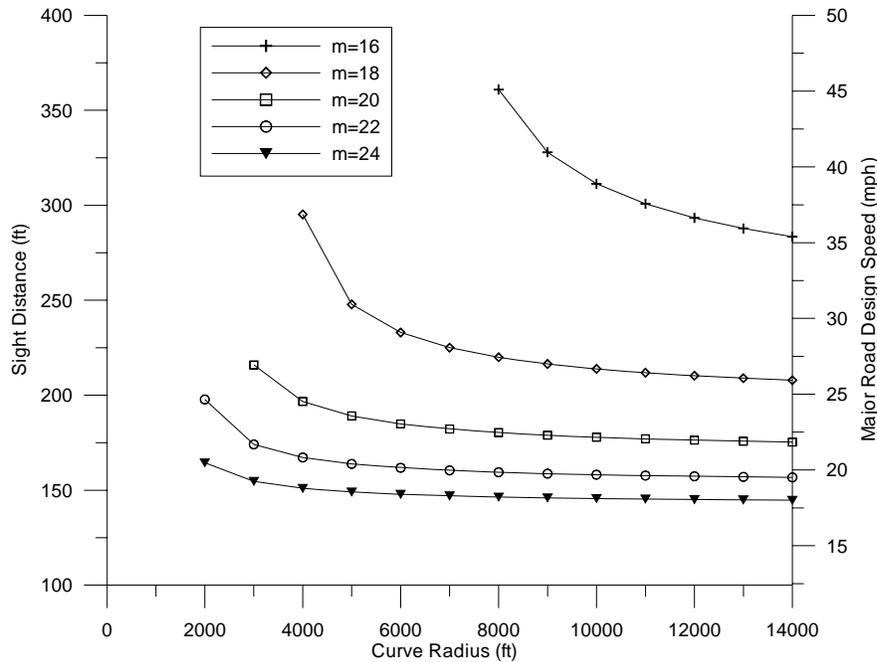
Figure 4-8: Sensitivity analysis of sight distance for a left-turn maneuver toward the inside of the curve

Another interesting phenomenon is that there is a threshold for the sight distance if other parameters are held constant and only the curve radius increases. It happens when the left-turner's sight line is the tangent of the nearest coming through lane's centerline ($T = R_3$). The threshold is the maximum available sight distance once the opposing vehicle can be a sight obstruction, and then the sight distance becomes less and less as the curve radius increases. Table 4-1 lists a series of the threshold values of sight distance and the corresponding curve radii, which decrease with the increment of the median width. However, for medians narrower than 16 feet, although there are sight-distance thresholds, the corresponding curve radii are larger than 10,000 feet. For that situation, the curves are so flat that the related available sight distances are very close to the results from the models for linear-approach intersections.

Table 4-1: Threshold Values of Sight Distance and the Corresponding Curve Radii

X (ft)	D$_1$ (ft)	D$_2$ (ft)	M (ft)	R (ft)	SD (ft)	SPEED (mph)
0	45	37	12	497,509.9	3,030.1	375.6
0	45	37	13	58,199.1	1,104.3	136.9
0	45	37	14	21,983.3	709.9	88.0
0	45	37	15	11,733.6	540.3	67.0
0	45	37	16	7,406.8	445.3	55.2
0	45	37	17	5,162.3	385.1	47.7
0	45	37	18	3,840.6	342.9	42.5
0	45	37	19	2,992.2	312.3	38.7
0	45	37	20	2,412.6	288.1	35.7
0	45	37	21	1,997.4	269.0	33.4
0	45	37	22	1,688.7	253.8	31.5
0	45	37	23	1,452.3	240.7	29.8
0	45	37	24	1,266.7	229.9	28.5

CHAPTER 5. GEOMETRIC MODELS OF SIGHT-DISTANCE CALCULATION FOR INTERSECTIONS WITH CURVE-LINEAR COMBINED APPROACHES

For sight obstruction by opposite left-turn vehicles, the basic models in Chapter 3 and Chapter 4 can be used to calculate sight distances for traffic scenarios at an intersection with linear major approaches or on a horizontal curve, as shown in Figures 5-1-a and 5-2-b. However, when intersections are located at a major highway that is close to the tangent points of the linear and curved segments, the sight-distance calculation models could be more complicated than the linear or the curve models. The combination of the curve and linear segments may result in four different intersection configurations: linear approach leading a curve segment for left turn toward outside of the curve (see Figure 1-2-c), linear approach leading a curve segment for a left turn toward the inside of the curve (see Figure 1-2-d), curve approach leading a linear segment for a left turn toward the outside of the curve (see Figure 1-2-e), and curve approach leading a linear segment for a left turn toward the inside of the curve (see Figure 1-2-f). In this chapter, for more comprehensive and practical application to intersection design, theoretical geometric models need to be developed to calculate sight distance for unprotected left-turning vehicles for complex geometric configurations of signalized intersections.

5.1 Linear Approach Leading a Curve Segment for a Left-turn Toward the Outside of the Curve

As shown in Figure 5-1, first the validity of the linear model should be checked. If the linear segment length of the intersection approach (Y_1) is less than the part of sight distance (Y) calculated by the linear model, the left turner's line of sight will intersect the track of the coming through vehicle on the curved segment.
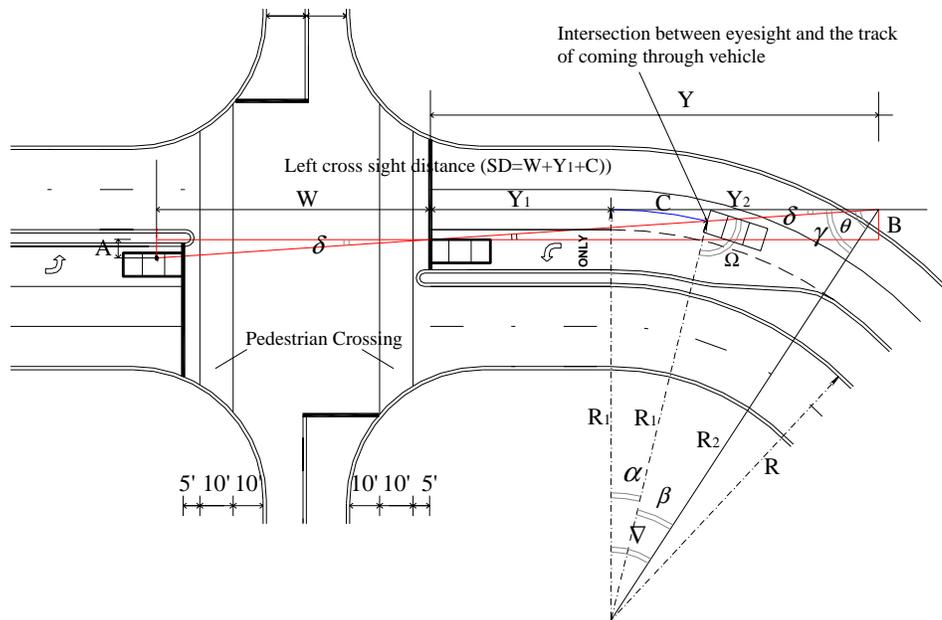
Figure 5-1: Geometric model for linear approach leading a curve for a left turn toward the outside of the curve

Based on the simple geometric rules, the procedure to derive SD is shown as follows:

$$\delta = \arctan(\frac{A}{W})$$

$$\gamma = \arctan(\frac{R_1}{Y_2})$$

$$\theta = \gamma - \delta = \arctan(\frac{R_1}{Y_2}) - \arctan(\frac{A}{W})$$

Since, $\dfrac{\sin \Omega}{R_2} = \dfrac{\sin \theta}{R_1}$ → $\Omega = \pi - \arcsin(\frac{R_2}{R_1} \sin(\arctan(\frac{R_1}{Y_2}) - \arctan(\frac{A}{W})))$

$$\beta = \pi - \Omega - \theta$$

$$\nabla = \frac{\pi}{2} - \gamma$$

$$\alpha = \nabla - \beta = \Omega - \delta - \frac{\pi}{2}$$

$$C = R_1 * \alpha$$

$$SD = W + Y_1 + R_1 * (\frac{\pi}{2} - \arcsin(\frac{R_2}{R_1} \sin(\arctan(\frac{R_1}{Y_2}) - \arctan(\frac{A}{W}))) - \arctan(\frac{A}{W}))$$

$$R_2 = \sqrt{(Y - Y_1)^2 + R_1^2}$$

$$SD = W + Y_1 + R_1 * (\arcsin(\frac{\pi}{2} - \frac{\sqrt{(Y - Y_1)^2 + R_1^2}}{R_1} \sin(\arctan(\frac{R_1}{Y - Y_1}) - \arctan(\frac{A}{W}))) - \arctan(\frac{A}{W}))$$

<div align="right">(5-1)</div>

Equation 5-1 is used to calculate the sight distance at the linear-curve approach for a left turn toward the outside of the curve. The definitions of W and A are the same as those in the model for the intersection with only linear approaches. Y_1 is defined as the linear segment length of the intersection approach. R_1 is the curve radius to the point at which the left-turner's line of sight intersects the centerline of the near opposing through lane, which is equal to the curve radius (R) plus the median width plus half of the through lane width.

5.2 Linear Approach Leading a Curve Segment for a Left-turn Toward the Inside of the Curve

Figure 5-2-a and Figure 5-2-b show all basic parameters needed to calculate sight distance for a left-turn toward the inside of the curve. However, for this situation it is very possible that there is no sight-distance problem if there is no intersection between the left turner's line of sight and the curve track of the apposing through vehicle. Therefore, when Y_1 is less than Y, the first step for the model is to check if the opposing left-turn vehicle presents a sight obstruction.

a. Geometric features

Left-turn sight distance (SD=W+Y$_1$+C)
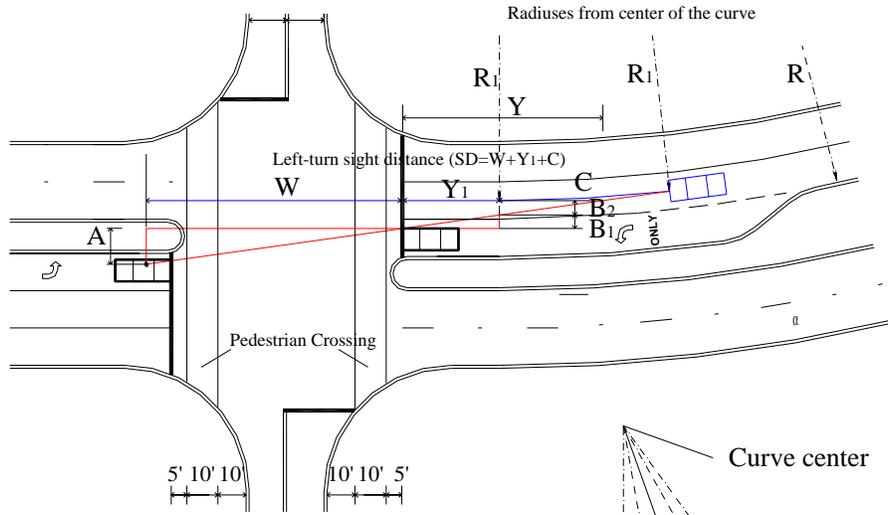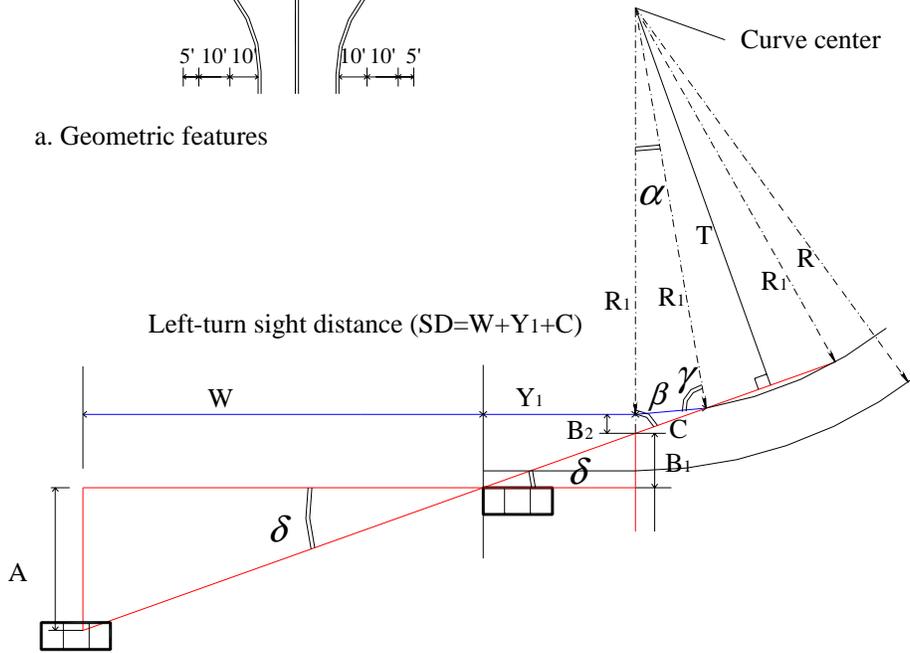
b. Geometric relationshio and parameter descriptions

Figure 5-2: Geometric model for linear approach leading a curve for a left turn toward the inside

of the curve

As shown in Figure 5-2-b, if $T = (R_1 + B_2) * \sin\beta$ >R1, there is no sight-distance problem;

otherwise, special calculations are needed for sight distance. R_1 is the curve radius to the point at

which the left-turner's line of sight intersects the centerline of the near opposing through lane,

which is equal to the curve radius (R) minus half of the through lane width. Terms β and B_2 can be calculated as follows:

$$\delta = \arctan(\frac{A}{W})$$

$$\beta = \frac{\pi}{2} - \delta = \frac{\pi}{2} - \arctan(\frac{A}{W})$$

$$B_1 = \frac{A * Y_1}{W}$$

$$B_2 = 0.5L_t + m - n - g - V_w - B_1 = 0.5L_t + m - n - g - V_w - \frac{A * Y_1}{W},$$

where all the related parameters had been defined in previous models. Then, based on simple geometric rules, the procedure to calculate C and SD is shown as follows:

$$\frac{B_2 + R_1}{\sin \gamma} = \frac{R_1}{\sin \beta} = \frac{R_1}{\cos \delta} \quad \rightarrow \quad \gamma = \arcsin(\frac{(B_2 + R_1) * \cos \delta}{R_1})$$

$$\alpha = \pi - \beta - \gamma = \frac{\pi}{2} + \arctan(\frac{A}{W}) - \arcsin(\frac{(B_2 + R_1) * \cos(\arctan(\frac{A}{W}))}{R_1})$$

$$C = R_1 * \alpha$$

$$SD = W + Y_1 + C = W + Y_1 + R1 * (\frac{\pi}{2} + \arctan(\frac{A}{W}) - \arcsin(\frac{(B_2 + R_1) * \cos(\arctan(\frac{A}{W}))}{R_1})) \quad (5\text{-}2)$$

Equation 5-2 is the model to use for calculating the sight distance at the linear-curve approach for a left turn toward the inside of the curve.

5.3 Curve Approach Leading a Linear Segment for a Left-turn Toward the Outside of the Curve

Figure 5-3 shows the basic geometric relationship and corresponding parameters needed to calculate sight distance at an intersection with curve approach leading a linear segment curve-linear approach for a left turn toward the outside of the curve. If the central angle η, corresponding to the curve segment length of the intersection approach (C_1), is less than δ, the left turner's line of sight will intersect the track of the coming through vehicle on the linear segment. For this case, based on simple geometric rules, the procedure to derive SD is shown as follows:

$$\eta = \frac{C_1}{R}$$

$$\lambda = \Omega - \eta$$

$$\frac{R_1}{Sin(\lambda)} = \frac{D_1}{Sin(\pi - \Omega - \Delta)} \quad \rightarrow \quad D_1 = \frac{\sin(\Omega + \Delta) * R_1}{\sin \lambda}$$

$$D_2 = R_3 - D_1$$

$$Y = D_2 * \tan \lambda \quad \rightarrow \quad Y = (R_3 - D_1) * \tan \lambda$$

$$Y = (R_3 - \frac{\sin(\Omega + \Delta) * R_1}{\sin(\Omega - \frac{C_1}{R})}) * \tan(\Omega - \frac{C_1}{R})$$

$$SD = C + Y = R_3 * (\Delta + \frac{C_1}{R}) + (R_3 - \frac{\sin(\Omega + \Delta) * R_1}{\sin(\Omega - \frac{C_1}{R})}) * \tan(\Omega - \frac{C_1}{R}) \qquad (5\text{-}3)$$

a. Geometric features   b. Basic geometric relationship

Figure 5-3: Geometric model for curve approach leading a linear segment for a left turn toward the outside of the curve

Equation 5-3 is the eventual model to calculate the sight distance at the linear-curve approach for a left turn toward the outside of the curve. Except for C_1, all the terms have the same definitions as those in the previous curve model for a left-turn toward the outside of the curve. C_1 is the curve segment length of the intersection approach along the inside of the median.

5.4 Curve Approach Leading a Linear Segment for a Left-turn Toward the Inside of the Curve

When the curve approach of the intersection leads to a linear segment, first it is necessary to check if the left turning driver's line of sight intersects the track of the opposing through vehicle on the linear segment. As shown in Figure 5-4, if $\lambda = \Omega + \Delta + \eta \geq \pi / 2$, there is no sight-distance

67

problem; otherwise, special calculations are needed for sight distance. For this case, based on simple geometric rules, the procedure to derive SD is shown as follows:

$$\eta = \frac{C_1}{R}$$

$$\lambda = \Omega + \Delta + \eta$$

$$\frac{R_2}{\sin(\pi - \eta - \Delta - \Omega)} = \frac{D_1}{\sin(\Omega)} \quad \rightarrow \quad D_1 = \frac{R_2 \sin(\Omega)}{\sin(\lambda)}$$

$$D_2 = D_1 - R_3 \quad \text{and} \quad Y = D_2 * \tan\lambda$$

$$Y = (\frac{R_2 \sin(\Omega)}{\sin(\lambda)} - R_3) * \tan(\lambda)$$

$$SD = C + Y = R_3 * (\Delta + \frac{C_1}{R}) + (\frac{R_2 \sin(\Omega)}{\sin(\Omega + \Delta + \frac{C_1}{R})} - R_3) * \tan(\Omega + \Delta + \frac{C_1}{R}) \qquad (5\text{-}4)$$
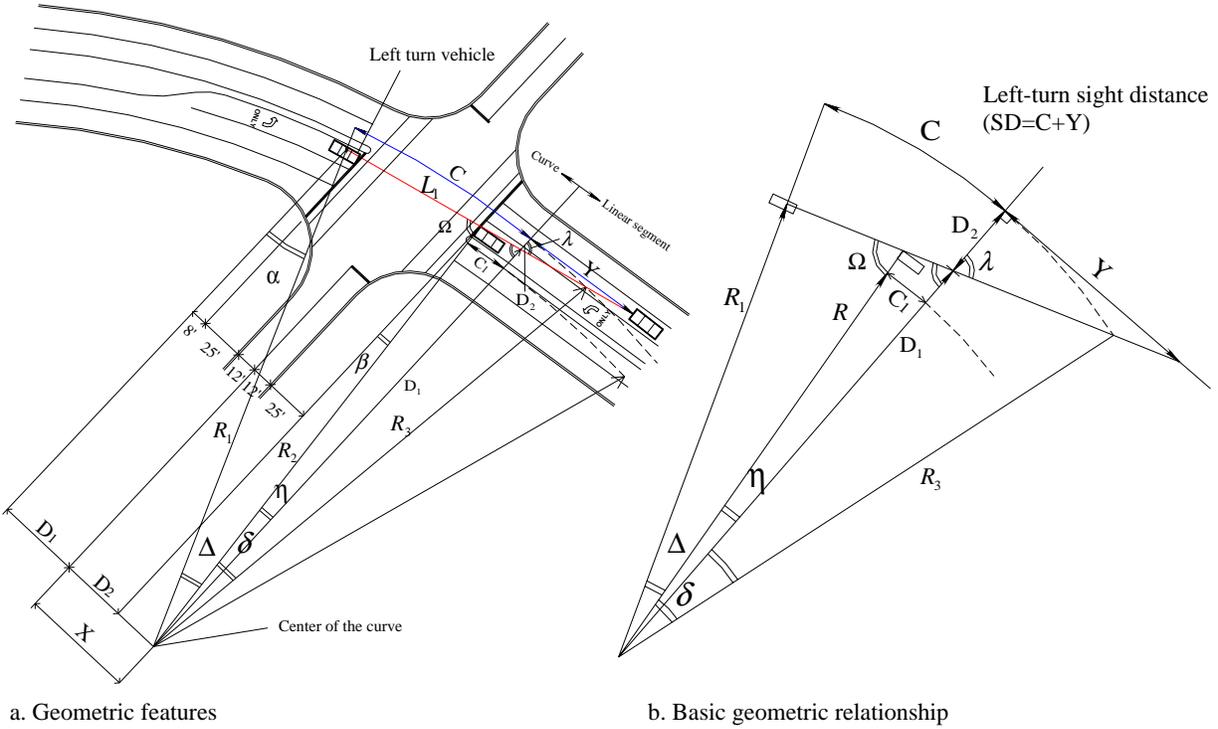

a. Geometric features

b. Basic geometric relationship
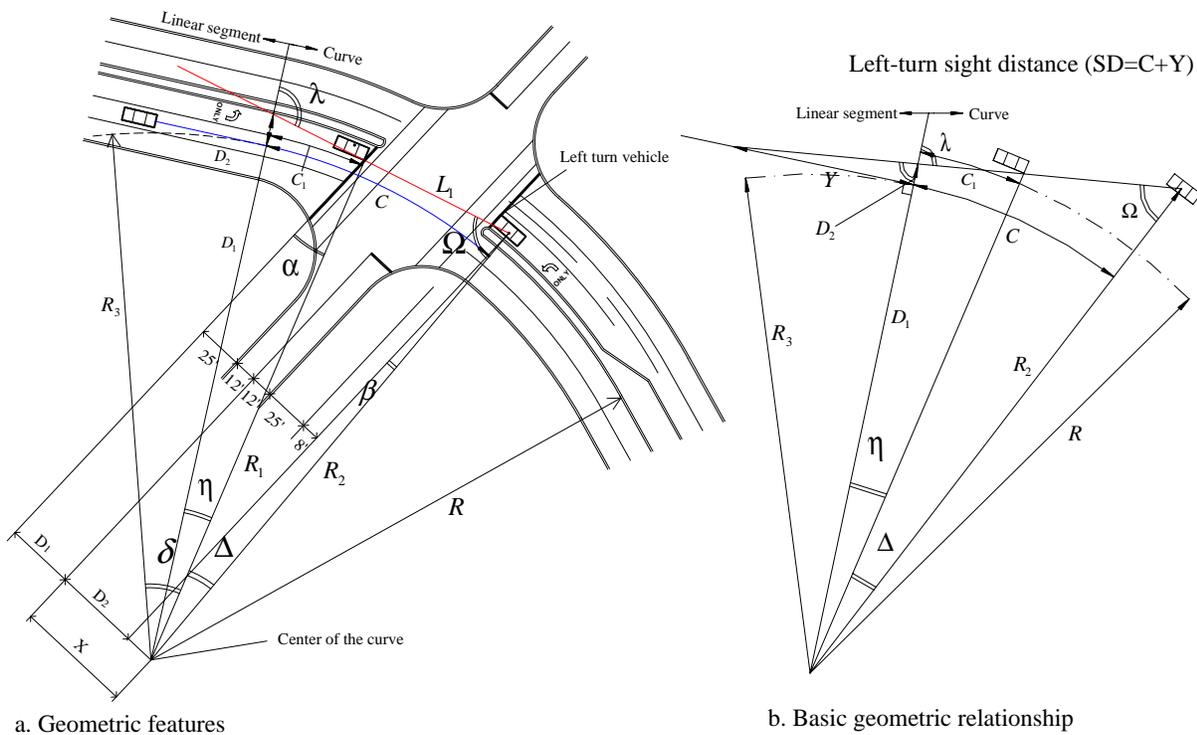
Figure 5-4: Geometric model for curve approach leading a linear segment for a left turn toward the inside of the curve

Equation 5-4 is the eventual model to calculate the sight distance at the linear-curve approach for a left turn toward the inside of the curve. Except for C_1, all the terms have the same definitions as those in the previous curve model for a left-turn toward the inside of the curve. C_1 is the curve segment length of the intersection approach along the inside of the median.

5.5 Evaluation of Sight-distance Problem and Parameter Analyses

For linear type intersections, the study indicated that the available left-turn sight distance is inversely related to the median width (m). The sight-distance problem could even occur on the traditional left-turn lane design with 14- to 18-foot medians at high major-road design speed. If the intersection is located on or near a horizontal curve, besides the effect of the median width (m), the curve presence may contribute to or mitigate the sight-distance problem, depending on whether the left-turn maneuvers are toward the outside or inside of the curve. To compare the sight-distance calculation by different type of models, the same basic geometric features are assumed:

- the median width (m) is 16 feet
- the median nose width (n) is 4 feet
- the width of left-turn lane is 12 feet
- the width of the opposing through lane (L_t) is 12 feet
- the distance between stop bars of the opposing left lanes (term D in linear model) is 74 feet (2-lane minor road assumed)

Figures 5-5-a and 5-5-b illustrate a sensitivity analysis of the curve radius (R) and the linear segment length (Y_1), and a sight-distance calculation comparison between the linear model and those related to curves. Figures 5-5-c and 5-5-d illustrate the analysis of curve radius (R) and the curve segment length (C_1), and a sight-distance calculation comparison between the curve model and those related to linear segments.
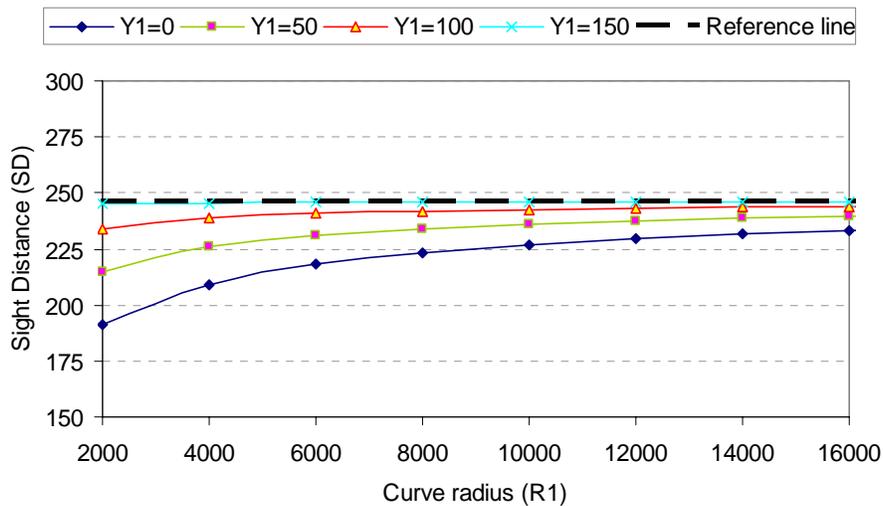
a. Linear approach leading a curve segment for left turn toward outside of the curve
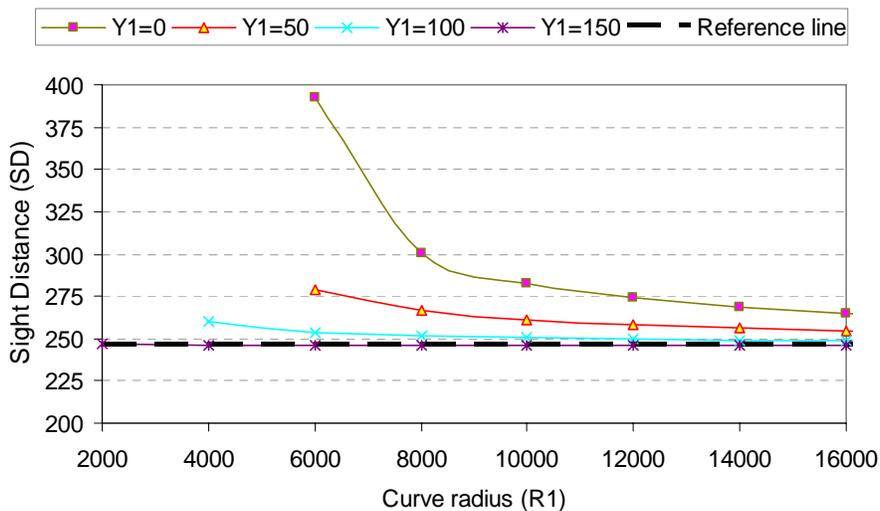
b. Linear approach leading a curve segment for left turn toward inside of the curve
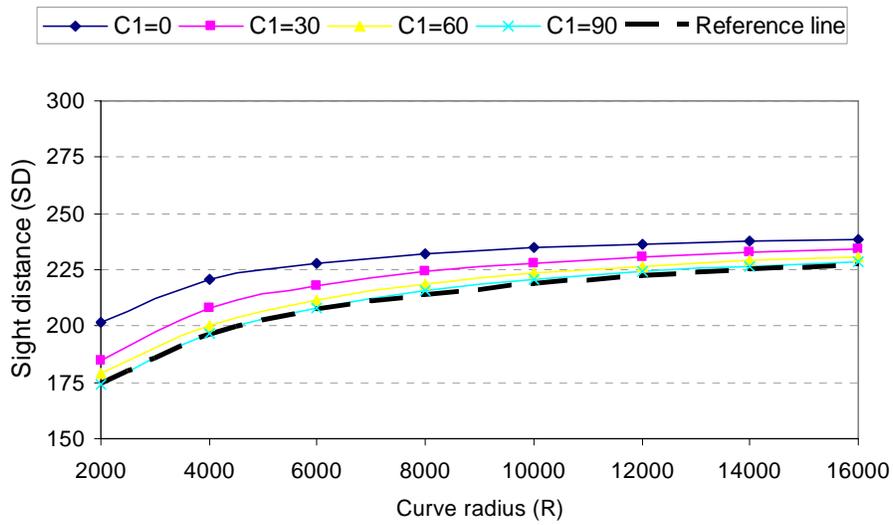
c. Curve approach leading a linear segment for left turn toward outside of the curve
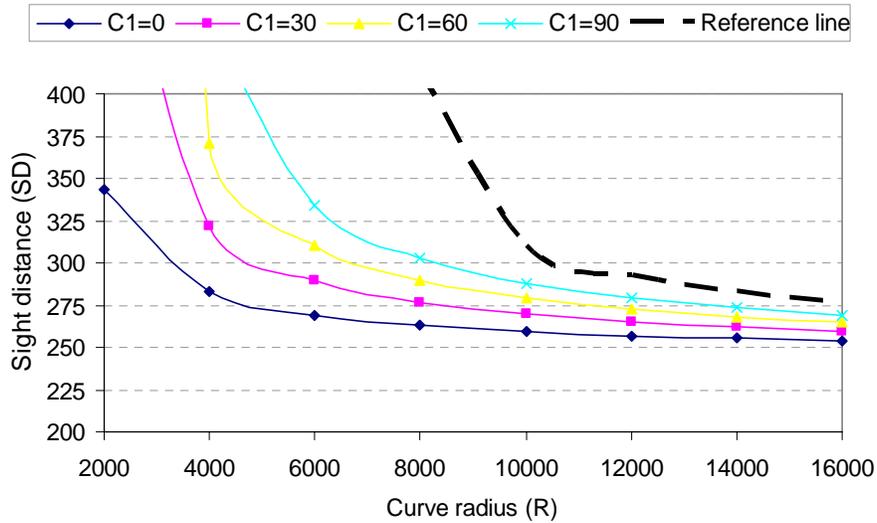
d. Curve approach leading a linear segment for left turn toward inside of the curve

Figure 5-5: Evaluation of the sight-distance problem and parameter analysis for different models

As shown in Figure 6-22-a, if there is an opposite linear approach leading a curve segment and drivers are making a left turn toward the outside of the curve (scenario illustrated in Figure 6-2-c), the presence of a curve always deteriorates the sight-distance problem. Both R and

Y1 are positively related to the SD. The sight distance is more sensitive to curve radius for the shorter length of Y1, and as the Y1 and R increase, the sight distance is closer to the value (246 feet) attained from the linear model calculation and shown as a dash line. However, even a 246-foot sight distance can provide only 30.5 mph safe design speed, according to Equation 1. Therefore, for this case, the sight distance may not be sufficient for a major road with relatively higher speed limit.

Figure 6-22-b shows the sight-distance calculation for an opposite linear approach leading a curve segment when drivers are making a left turn toward the inside of the curve (scenario illustrated in Figure 6-2-d), where the presence of a curve can always mitigate the sight-distance problem. Both R and Y1 are inversely related to the SD. The sight distance is more sensitive to curve radius for the shorter length of Y1, and as the Y1 and R increase, the sight distance gets closer to the result from the linear model calculation. When Y1 is beyond 150 feet, the curve is not under consideration. If the curve radius is smaller, especially less than 4,000 feet, the curve will even result in unrestricted sight distance. However, if the curve radius is larger than 8,000 feet, the available sight distances are less than 300 feet, which can provide 37.2 mph design speed and may still not be sufficient for a higher speed limit.

Figure 6-22-c shows the sight-distance calculation for an opposite curve approach leading a linear segment when drivers are making a left turn toward the outside of the curve (scenario illustrated in Figure 6-2-e). The reference dash line in the figure is the sight distance for a pure curve approach. For this situation, the major road curve can result in a serious sight-distance problem. The R is a positive related sight distance, and for the 16-foot median, the available

sight distance might be very short (less than 225 feet) even if the curve radius is very large, which cannot provide a 30 mph design speed. Compared to the results from the curve model, the presence of a linear segment can slightly mitigate the sight-distance problem, and the curve segment length to the tangent point (C_1) is inversely related to the sight distance.

Figure 6-22-d shows the available sight distance for an opposite curve approach leading a linear segment when drivers are making a left turn toward the inside of the curve (scenario illustrated in Figure 6-2-f). The presence of the curve can greatly mitigate the sight-distance problem, and the radius R is inversely related to the SD. An interesting phenomenon for the left turn toward the inside is that there is a threshold for the sight distance if other parameters are held constant and if only the curve radius increases. It happens when the left-turner's sight line is the tangent of the nearest coming through lane's centerline. The threshold is the maximum available sight distance once the opposing vehicle can be a sight obstruction, and then the sight distance decreases as the curve radius increases. For 16-foot medians, the sight-distance threshold is 445.3 feet, and the corresponding curve radius is 7,406.8 feet for the pure curve approach. However, the presence of a linear segment can decrease the sight-distance benefit from the curve. The curve segment length to the tangent point (C_1) is positively related to SD; when C_1 is zero, the SD calculation results are closer to that of the linear model as the R increases.

CHAPTER 6. INFLUENCE OF RESTRICTED SIGHT DISTANCES ON UNPROTECTED LEFT-TURN OPERATION AT SIGNALIZED INTERSECTIONS

In this chapter, a field data collection effort was first conducted to analyze the gap-acceptance difference between two situations for left-turn drivers: restricted sight distance and sufficient sight distance. Furthermore, theoretical models were developed and used to evaluate the effect of restricted sight distances on the left-turn capacity. The analyses in this chapter provided a better understanding of the relationship between highway visibility and traffic operation.

6.1 Data Collection Methods

6.1.1 Observation site description

In this study, the main factors considered for the observation site selection were (1) the adequacy of the median width to yield drivers' sight-distance problems from the opposing left-turn vehicles; and (2) appropriate opposing left-turn volume to efficiently observe gap acceptance behaviors with and without sight obstruction. Based on the two factors, a four-leg level intersection with a protected/permitted left-turn signal phase was selected, as shown in Figure 6-1. At the intersection, there are a four-lane major road, a two-lane minor road, and one exclusive left-turn lane at each approach. The width of the major road is 20 feet. According to the AASHTO (2001), a median wider than 18 feet should cause a sight-distance problem for left-turn drivers due to the opposing left-turn vehicles. The speed limit of the major road was 45 mph.

6.1.2 Data collection using video-based systems

Two digital video cameras were positioned upstream of both major road approaches to obtain visual data during the permitted left-turn phase (see Figure 6-1). Adobe Premiere Pro software was used to upload and compress the video for computer storage in Window's avi format. Video data collection methodology may produce higher quality traffic data than manual methods. With a rate of 30 frames per second for the videos, the error caused by the video program is 0.03 sec for the event-time data. Due to the analyst's visual judgment error for vehicle positions, the total possible error for the event-time data could be up to 0.1 sec (Bonneson and Fitts 1995). By using the frame-by-frame replaying feature, a researcher could carefully analyze unusual, complicated, or rapid events.
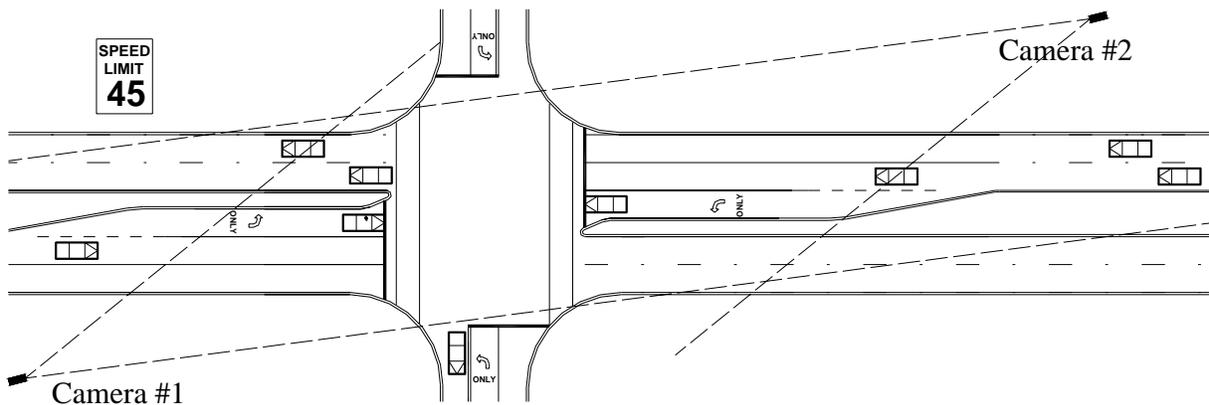
Figure 6-1: Restricted left-turn sight distance due to the opposing left-turning vehicle

6.1.3 Data measurements

The field observations were taken from six separate weekdays between 10 a.m. and 4 p.m. A total of 11 hours of video was used to extract data measurements based on the Premiere software, and data were classified into two groups as shown in Table 6-1. The variables in the first group were used for driver gap-acceptance analysis, including Sight, Gap, Gap Decision, Follow-up

time, Response Time, and Turn type. Sight was coded in two levels: 0 means that there was no opposing left-turn vehicle (no sight-distance problem); 1 means that there was an opposing vehicle blocking the driver's view. Gap means the time duration of the available gap or lag. A gap was measured as the inter-arrival time between two opposing through vehicles passing by the driver who was waiting for a turn movement. A lag is the portion of a gap that remains when the turning vehicle first arrives at the stop line. Note that in the latter analysis, this study did not distinguish between driver's gap and lag acceptance behaviors since very few lag observations were recorded. The variable Gap Decision was used to record whether a driver accepted or rejected a gap or lag (0 = rejection and 1 = acceptance). The follow-up time was measured as the inter-arrival time between two continuous left-turning vehicles crossing the nearest opposing-through lane. Only if a driver accepted a gap was the Response Time measured. Response Time is defined as the time difference from the moment at which the first vehicle in the gap reached the left-turn vehicle to the moment at which left-turning vehicles crossed the nearest opposing through lane. The hypothesis to be tested for the Response Time is that with restricted view, the left turning drivers need more reaction time to accept a gap, resulting in needless traffic delays. Moreover, Turn Type was used to record if the turn movement was a left turn or U-turn.

Table 6-1: Data Measurement Descriptions

	VARIABLE	VARIABLE DESCRIPTION	
Group #1: Driver gap acceptance behaviors	Sight	Whether the driver sight was blocked by an opposing left-turn vehicle.	0 = without opposing vehicle 1 = with opposing vehicle
	Gap	Gap or lag size	Continuous (sec)
	Gap Decision	Gap acceptance Decision	0 = Rejection 1 = Acceptance
	Follow-up Time	Headway between queued left-turning vehicles	Continuous (sec)
	Response Time	Driver's response time spent in accepting a gap	Continuous (sec)
	Turn type	If the turn movement is a left turn or U-turn.	0 = Left turn 1 = U-turn
Group #2: Abnormal Driving Behaviors	RLAS	Rejected a large gap but accepted a small gap	
	CONFLICT	Traffic Conflict between vehicles	
	NOTURN	Diver did not turn during the permitted left-turn phase and the largest rejected gap is larger than 12 sec	

In Table 6-1, the variables classified in the second group were used mainly to analyze if the sight obstruction can lead to abnormal driving behaviors for the turning drivers. The variable RLAS recorded drivers' inconsistent gap acceptance behavior: a driver rejected a larger gap but accepted a smaller gap later. The variable CONFLICT recorded traffic conflict between vehicles. Conflicts were tracked according to the following definition: Traffic conflicts are interactions between two or more vehicles or road users when one or more vehicles or road users take evasive action, such as braking or weaving, to avoid a collision (Parker and Zegger 1988). Another variable, NOTURN, was used to record the behavior of not taking advantage of very large gaps (larger than 12 seconds) to make a turn movement until the protected phase appeared. Usually, it is logical to assume that drivers will accept gaps greater than 11 seconds. A previous gap acceptance study suggested that there is no meaningful information regarding driver gap acceptance behavior when the accepted gap size is above 12 seconds (Gattis and Sonny 1999).

Too many drivers refusing the permitted phase can cause left-turn capacity to be greatly decreased.

6.2 Left-turn Gap Acceptance Behaviors

6.2.1 Linear regression analysis based on the Siegloch method

Linear regression analysis based on the Siegloch method was first performed to obtain the follow-up time and critical gap. The implementation of this method reflected the relationship between gap size and the total number of left-turning vehicles that had accepted this gap. Based on the video analysis, 50 gaps were accepted by one or more vehicles in the left-turn queues without sight obstruction and 119 gaps were accepted by queued vehicles with sight obstruction. Figure 6-2 illustrates the linear relationship between gap size and the number of left-turn vehicles. It appears that for the same number of left-turn vehicles, the required gap sizes with sight obstruction tend to be larger and more variable than those without sight obstruction. For some quite large gaps (10–20 sec), only one or two vehicles could make use of the gaps to cross the intersection when there was an opposing vehicle blocking the driver's sight.

The follow-up time and critical time are summarized in Table 6-2, based on the regression results. Without sight obstruction, the follow-up time and critical time were 2.4 sec and 4.4 sec. With sight obstruction, the mean follow-up time and critical time increased to 3.6 sec and 5.4 sec. However, since the variances of the gap sizes accepted by the same numbers of left-turning vehicles were very large, the R square (0.6387) of the linear regression for left turn with

sight obstruction is very small (see Figure 6-2). Therefore, the estimates of follow-up time and critical time for left turn with sight obstruction may be less accurate.
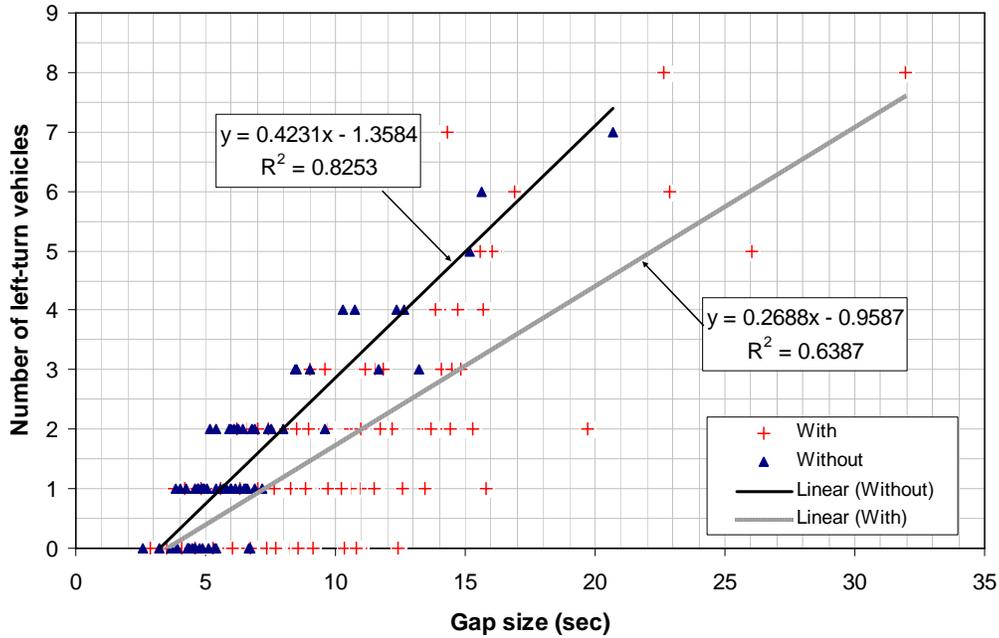
Figure 6-2: Linear relationship between gap size and the number of left-turn vehicles

Table 6-2: Siegloch Method Values

Sight obstruction	Intercept (t_0)	Follow-up time (t_f)	Critical gap $(t_0+0.5t_f)$
Without	3.21	2.36	4.39
With	3.57	3.72	5.43

Using the number of vehicles as a dependent variable, a multiple linear regression analysis showed that there is an interaction between Gap and Sight (see Table 6-3). The slope of the linear regression line without sight obstruction is statistically larger than that with sight obstruction. In other words, the driver's follow-up time (the reciprocal of the slope) without sight obstruction is statistically smaller than that with sight obstruction.

Table 6-3: Independent variable Coefficient Estimates in a multiple linear regression model

Label	Estimate	Std.Error	t-value	p-value
Constant	-1.3584	0.2405	-5.649	0.0000
Gap	0.4231	0.0322	13.137	0.0000
Sight	0.3997	0.2769	1.443	0.1502
Sight*Gap	-0.1543	0.0352	-4.377	0.0000

6.2.2 Independently estimating follow-up time

As an independent measurement, the follow-up time is the mean headway between queued left-turning vehicles that move through the intersection during the larger gaps in the major stream. This quantity is similar to the saturation headway at signalized intersections. As shown in Table 6-4, there are a total of 289 observations for the left-turn follow-up time analysis, including 110 observations without sight obstruction and 179 observations with sight obstruction. The table shows that without sight obstruction the mean follow-up time is 2.2 sec, which is exactly same as the recommended value for two-way stop-controlled intersections in the HCM manual but smaller than the 2.5 sec for signalized intersections. With sight obstruction, the mean follow-up time is 2.9 sec.

The results indicate that with the sight-distance problem, the drivers' left-turn follow-up time is significantly increased compared to those without the problem ($t = 5.974$, $df = 287$, $p < 0.001$). Furthermore, the follow-up time histogram without sight obstruction appears to be very close to a normal distribution, as shown in Figure 6-3-a, but the distribution with sight obstruction illustrates a large variability in Figure 6-3-b. Without sight obstruction the maximum follow-up time is 4.7 sec. However, with the sight-distance problem 8.4 percent of the left-turn drivers need

more time than 4.7 sec. The larger follow-up time can contribute to a reduction of the left-turn capacity.

Table 6-4: Follow-up Time Comparison With Sight Obstruction and Without Sight Obstruction

Sight obstruction	Mean	N	Std. Deviation	Minimum	Maximum
Without	2.2	110	0.57	0.7	4.7
With	2.9	179	1.19	1.1	9.9
Total	2.6	289	1.06	0.7	9.93
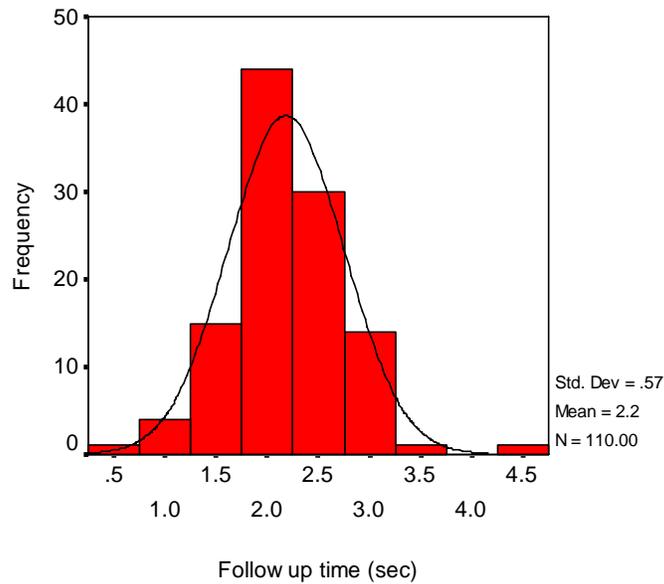
a) Without sight obstruction
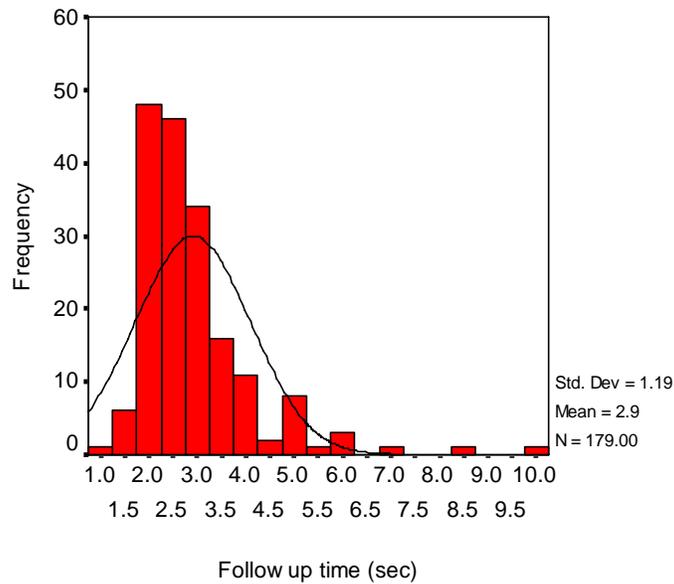
b) With sight obstruction

Figure 6-3: Follow-up time distributions with and without sight-distance problem

6.2.3 Critical gap based on logistic regression

In the dataset, 1,485 gap decisions from a total of 323 left-turning movements were recorded, including 105 observations without sight obstruction and 218 observations with sight

obstruction. The logistic regression method used in this study is a statistical technique for developing predictive models for the probability that an event (such as the acceptance of a gap) will or will not occur, as shown in Equation 6-1.

$$P = \frac{e^{g(x)}}{1 + e^{g(x)}} \qquad (6\text{-}1)$$

The logit of the multiple logistic regression model (Link Function) is given by Equation 2:

$$g(x) = \ln\left[\frac{P}{1+P}\right] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2, \qquad (6\text{-}2)$$

where P is the probability the left-turn driver accepts a gap or not; x_1 is a continuous independent variable for gap time available by left-turn drivers; and x_2 is a categorical independent variable for sight obstruction (0 for no sight obstruction; 1 for sight obstruction). The interaction between gap size and sight obstruction can also be accommodated as the term $x_1 x_2$. β_1, β_2, and β_3 are model coefficients. Using the logistic regression model to fit left-turn gap acceptance data, it was found that independent variables Gap, Sight, and interaction between them are significant at the 0.05 significance level. The modeling results are shown in Table 6-5 and Equation 6-3.

$$g(x) = -5.307 + 0.944 Gap + 1.651 Sight - 0.467 Gap \times Sight \qquad (6\text{-}3)$$

Table 6-5: Logistic Regression Model for Left-turn Gap Acceptance

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-5.3068	0.4429	143.5695	<.0001
Gap	1	0.9443	0.0923	104.674	<.0001
Sight	1	1.6508	0.489	11.3951	0.0007
Gap*Sight	1	-0.4673	0.0986	22.4388	<.0001

Figure 6-4 illustrates the predicted probability that drivers accept gaps to make left turns based on the regression results. Generally, the larger the available gaps, the higher the probability that drivers will accept the gaps. The critical gap is defined as the median of accepted gaps that are accepted by 50 percent of the drivers. Based on Equation 6-3, the critical gap is 5.6 sec when there is no opposing left-turn vehicle and it is 7.7 sec when there is an opposing left-turn vehicle. this difference in critical gap proves that the sight-distance problem contributes to a significant increment of the critical gap. It was also found that at this intersection, the critical gaps for both situations are larger than the recommended value of 4.5 sec from the HCM manual.
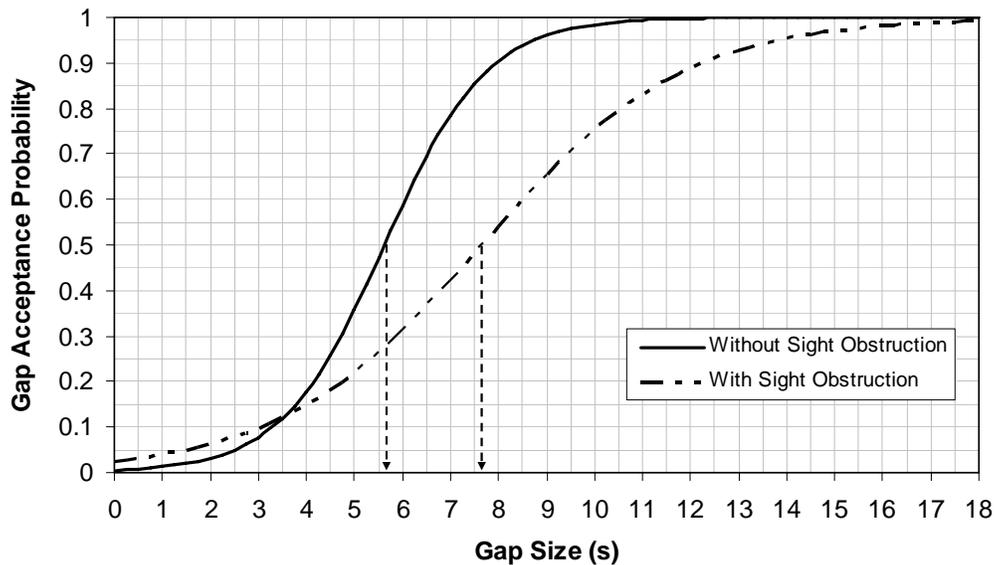
Figure 6-4: Predicted probability that drivers accept gaps to make left turns

Figure 6-4 also shows that the effect of the sight-distance problem on the gap-acceptance decision is correlated with the gap size. When the available gaps are larger than 3.5 sec, left turners without sight obstruction are more likely to accept the relatively smaller gaps compared to those with sight obstruction. However when the available gaps are smaller than 3.5 sec, left turners with the sight-distance problem are more likely to accept a very small gap compared to those without the sight-distance problem. One explanation is that some drivers could not see the coming though vehicle beyond the opposing left-turn vehicle and assumed there was a big gap available, causing them to unintentionally accept a small gap. Another possible explanation is that aggressive drivers were more willing to accept the current small gap if they could not see the coming large gaps among opposing-through traffic. Accepting very small gaps may contribute to traffic conflicts and even angle collisions between left-turning vehicles and coming through vehicles.

6.2.4 Gap acceptance response time

Gap acceptance response time is the time that drivers need to decide to accept the current available gap. Generally, after the leading vehicle passes by left-turn drivers, they should immediately start to cross the intersection if the sight distance is sufficient. As shown in Table 6-6, 227 observations of response time were recorded, including 56 cases without sight obstruction and 171 cases with sight obstruction. Without sight obstruction the mean response time is 1.7 sec; with sight obstruction the mean is 3.1 sec. The t test shows that when the driver's view is blocked, significantly more time is needed to decide to accept the available gap ($t = 4.731$, $df = 225$, $p < 0.001$). The response-time histogram without sight obstruction appears to be very close to a normal distribution in Figure 6-5-a, but the distribution with sight

obstruction illustrates a large variability in Figure 6-5-b. Without the sight-distance problem, the

maximum follow-up time is 3.3 sec. However, with the sight-distance problem there are 28.1

percent left-turn drivers who need longer than 3.3 sec to make sure the coming through vehicle is

still far away. The response-time analysis explains why the left-turn critical gap and follow-up

time are significantly increased when the driver's view is blocked.

Table 6-6: Response Time Comparison With Sight Obstruction and Without Sight Obstruction

Sight obstruction	Mean	N	Std. Deviation	Minimum	Maximum
Without	1.7	56	0.51	0.5	3.3
With	3.1	171	2.20	0.7	12.1
Total	2.7	227	2.01	0.5	12.1

Std. Dev = .51
Mean = 1.67
N = 56.00

Rsponse time (sec)

a) Without sight obstruction

Std. Dev = 2.20
Mean = 3.07
N = 171.00
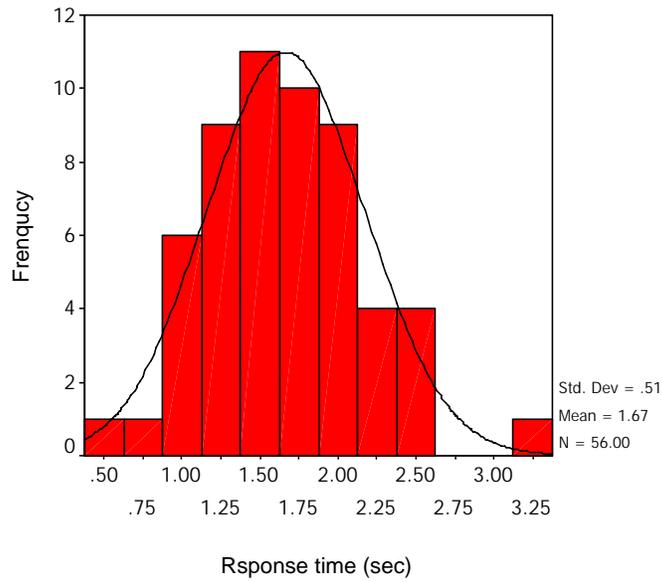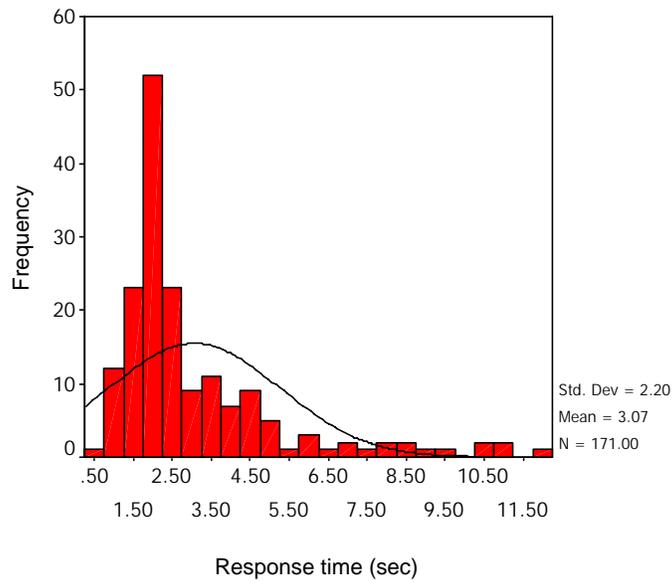
Response time (sec)

b) With sight obstruction

Figure 6-5: Response time distributions

6.3 U-turn Gap Acceptance Behaviors

During the observation period, 768 gap decisions from a total of 161 left-turning movements were recorded, including 32 observations without sight obstruction and 129 observations with sight obstruction. Since characteristics of U-turn gap acceptance are similar to the left-turn movements, the logistic regression model was also used to obtain the critical gaps for the unprotected U-turn. The regression result shows that independent variables Gap, Sight, and interaction between them are significant at a 0.05 significance level (see Table 6-7 and Equation 6-4).

$$g(x) = -13.439 + 2.485Gap + 9.058Sight - 1.871Gap \times Sight \tag{6-4}$$

Table 6-7: Logistic Regression Model for U-turn Gap Acceptance

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-13.4394	3.6828	13.3172	0.0003
Gap	1	2.4849	0.6803	13.343	0.0003
Sight	1	9.0581	3.6991	5.9962	0.0143
Gap*Sight	1	-1.8706	0.6826	7.5098	0.0061

Based on Equation 4, the critical gap is 5.4 sec for U-turn drivers without sight obstruction and 7.1 sec for drivers with sight obstruction (see Figure 6-6). The results showed that the sight-distance problem contributes to a 1.7 sec increment of the critical gap. Without or with sight obstruction, the U-turn critical gaps appear close to and even slightly smaller than those for left-turn gap acceptance. Figure 6-6 illustrates the predicted probability that drivers accept gaps to make U-turns. It was found that the effect of the sight-distance problem on the gap acceptance decision is correlated with the gap size. When the available gaps are larger than 4.8 sec, the U-

turn drivers with sight obstruction are more likely to accept a larger gap compared to those without sight obstruction. When the available gaps are smaller than 4.8 sec, the drivers with sight obstruction are more likely to accept a small gap compared to those without sight obstruction. The logistic regression results for U-turns showed the same trend as the left-turn analysis.
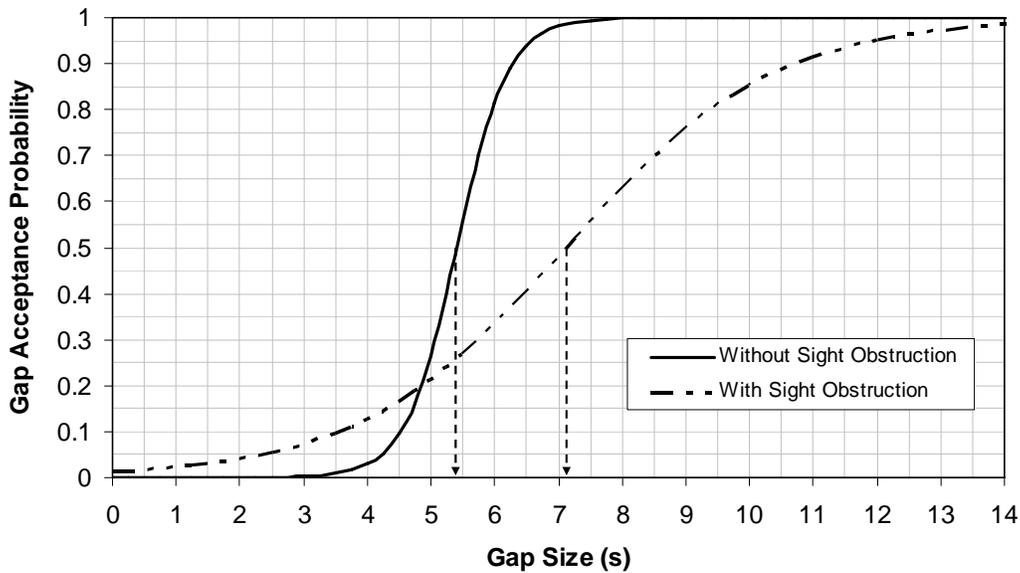
Figure 6-6: Predicted probability that drivers accept gaps to make U-turns

Since the U-turn maneuver is restricted by the limitation of the vehicle turn radius, most drivers had to turn onto the second (outside) through lane. An interesting phenomenon for U-turn gap acceptance is that if the current small gap was in the inside through lane and the outside through lane was clear, those aggressive drivers were more willing to accept the small gap and rapidly accelerate their vehicles to outside lanes. This phenomenon particularly happened when the driver's sight was blocked by the opposing left-turn vehicle because the driver's visibility for the outside lane is better that that for the inside lane as illustrated in Figure 6-7. For this case, the minimum accepted gap that was observed was only 2.2 sec.
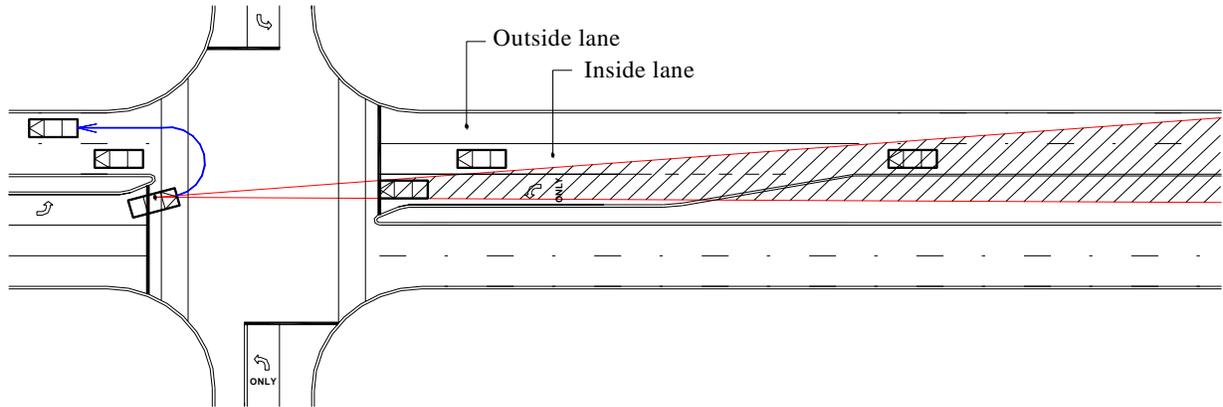
Figure 6-7: Illustration for U-turning drivers who accepted a small gap in the inside lane

6.4 Abnormal Driving Behaviors

As mentioned before, the three variables RLAS, CONFLICT, and NOTURN were used to analyze drivers' abnormal behaviors. As shown in Table 6-8, drivers with sight obstruction showed more abnormal behaviors than those without sight obstruction (34 vs. 4). The Chi-square test showed that the p-value is 0.0113 ($\chi_{1,484}^{2} = 6.424$), and the increment of drivers' abnormal behaviors due to sight obstruction is statistically significant at the 0.05 level.

Table 6-8: Observations for Drivers' Abnormal Behaviors

Opposing obstruction	RLAS		CONFLICT		NOTURN		Total		Number of turns
	Freq.	Rel. Freq.	Freq.	Rel. Freq.	Freq.	Rel. Freq.	Freq.	Rel. Freq.	
Without	1	0.007	1	0.007	2	0.015	4	0.029	137
With	9	0.026	9	0.026	16	0.046	34	0.098	347
Total	10	0.021	10	0.021	18	0.037	38	0.079	484

For the RLAS, there were not a lot of inconsistent gap acceptance behaviors found during the observation period. Only one driver without sight obstruction and nine drivers with sight

obstruction rejected a larger gap but accepted a smaller gap. They represent 0.7 percent and 2.6 percent of total turn drivers without sight obstruction and those with sight obstruction, respectively. Based on the observation result from this study, since the inconsistent gap acceptance is not a frequent driving behavior, the consistent gap acceptance assumption in HCM (2000) should be valid.

For the CONFLICT, there were a total of ten traffic conflicts recorded. Without sight obstruction, there was only one traffic conflict between left-turning and coming through vehicles, which represents 0.7 percent of total turn movements. In this conflict, the accepted gap was only 2.8 sec, and the left-turning vehicle did not rapidly accelerate to cross the intersection. With sight obstruction, there were 9 traffic conflicts, which represent 2.6 percent of total turn movements. Of those, 3 cases occurred between left-turning vehicles and coming through vehicles because drivers accepted very small gaps (2.1 sec, 2.2 sec, and 2.9 sec); 5 cases occurred between U-turning vehicles and coming through vehicles because of drivers' accepting small gaps (2.2 sec, 2.5 sec, 2.5 sec, 2.9 sec, and 2.9 sec). Another conflict happened between two continuous turning vehicles, in which the leading vehicle's stop caused the following driver to make an abrupt stop to avoid a rear-end collision.

For the NOTURN, it was found that without sight obstruction, there were only two drivers who did not make use of the very large gaps (larger than 12 sec) to turn during the permitted left-turn phase. However, when the opposing turning vehicle blocked the driver's sight, there were 16 drivers who didn't accepted large gaps. With sufficient visibility, the no-turn drivers during the permitted phase might not fully understand the meaning conveyed by the traffic signal. This is

particularly true for a foreign driver or an inexperienced driver. Another possible reason is that drivers might be distracted because of cell-phone use or conversation with other passengers. With sight obstruction, some of the drivers missed the large gaps because they needed a very long time to ensure that the current gap was really large enough. The typical behavior for those drivers was that they slowly moved forward inside the intersection and tried to position the vehicle to maximize the available sight distance. After they failed to make the turn movement during the whole permitted left-turn phase, they withdraw back to the left-turn lane. Moreover drivers who keep within the left-turn lane when their view is blocked by an opposing turn vehicle may become too conservative to make unprotected turn movements. Too many drivers refusing the permitted phase can cause left-turn capacity to be reduced.

6.5 Analysis of a Left-turn Crash

Although the purpose of the field study was not to record accidents, one left-turn crash that occurred during the observation period is worth discussing. Before the traffic accident occurred, a passenger car was trying to find a proper gap to make a left turn, but the driver's view was obstructed by an opposing left-turn passenger car. After the driver missed a relatively large gap (5.1 sec), the driver behind her sounded the car's horn to rush her through the intersection. She then positioned the car inside the intersection to obtain a better view. However, due to the heavy opposing-through traffic volume in this cycle, there was no gap larger than 2.5 sec available until the permitted green phase ended. Unfortunately, she accepted a very small gap (1.8 sec) during the amber phase and was hit by the coming-through passenger car. Obviously, the sight-distance problem played an important role in this accident. With sufficient visibility, the driver would

easily have seen the vehicle coming at a high speed. In approximately 400 reviewed Florida police accident reports related to gap-acceptance accidents, a very common explanation was recorded on the crash forms as "the left-turn driver looked but failed to see the coming vehicle." None of these reports clearly explained why drivers couldn't see the vehicle. It seems hard to collect statistical data about how many accidents were caused by or related to the opposing-vehicle sight obstruction. However, this in-depth accident analysis provided evidence that opposing vehicle sight obstruction can contribute to the occurrence of gap-acceptance crashes.

6.6 Capacity Analysis of Unprotected Left-turn Traffic

6.6.1 Capacity model formulation

In the HCM chapter for signalized intersections, capacity estimation is based on the concept of saturation flow rate. The saturation flow rate is the flow (in vehicles per hour) that can be accommodated by the lane group, assuming that the green phase was displayed 100 percent of the time (i.e., g/C= 1.0). Without considering other factors (adjustments for heavy vehicles, parking, bus blockage, area type, lane utilization, right turns, and pedestrians and bicyclists), a saturation flow rate for the unprotected left-turn group is computed according to Equation 6-5.

$$s_{LT} = V_o \frac{\exp(-V_o t_c / 3600)}{1 - \exp(-V_o t_f / 3600)} \, , \qquad (6\text{-}5)$$

where s_{LT} = filter saturation flow of permitted left turns (veh/h/ln)

V_o = opposing-through traffic flow rate (veh/h)

t_c = critical gap (s)

t_f = follow-up headway (s)

Based on the saturation flow rate, the capacity of an exclusive permitted left-turn group may be stated as shown in Equation 6-6.

$$C_{LT} = s_{LT} \frac{g - g_q}{c},$$ (6-6)

where C_{LT} = left-turn capacity of an exclusive permitted left-turn group (veh/h)

s_{LT} = filter saturation flow of permitted left turns (veh/h/ln)

g = effective green time for subject permitted left turn (s)

g_q = the portion of effective green blocked by the clearance of an opposing queue of

vehicles(s)

c = the length of the cycle(s)

In general, after the beginning of the green phase of the permitted portion of the cycle, a left-turning vehicle should wait for an opportunity to proceed by searching for a gap in its opposing through traffic. Such a gap is not possible until the queue of the opposing through movement is cleared. The portion of effective green blocked by the clearance of an opposing queue of vehicles (designated as g_q) significantly influences the left-turn capacity. Assuming that there are no effects of lane utilization factor and platoon ratio for opposing traffic, g_q can be calculated by Equation 6-7.

$$g_q = \frac{v_{o/c}(1 - g/c)}{0.5 - \dfrac{v_{o/c}(1 - g/c)}{g}} - t_L \quad,$$ (6-7)

where $v_{o/c}$ = adjusted opposing flow rate per lane per cycle

       g = effective green time for subject permitted left turn(s)

       c = the length of the cycle(s)

       t_L = lost time for opposing lane group(s)

At signalized intersections with the restricted sight-distance problem, the severity of the left-turn capacity reduction is dependent on the probabilities (P) that the opposing left-turning traffic will operate in a queue state to be considered (there is at least one vehicle in the opposing left-turn lane). Thus, the potential left-turn capacity can be calculated by Equation 6-8.

$$C_{LT} = C_{LT,\min} P + C_{LT,\max}(1 - P) \,,$$ (6-8)

where C_{LT} = left-turn capacity of an exclusive permitted left-turn group

       $C_{LT,\min}$ = minimum left-turn capacity with sight-distance problem

       $C_{LT,\max}$ = maximum left-turn capacity without sight-distance problem

       P = probability that the opposing left-turning traffic will operate in a queue state

According to the results of this field study, without the sight-distance problem the critical gap and follow-up time are 5.6 sec and 2.2 sec based on the independent gap-acceptance parameter estimates, which can be used to calculate the maximum left-turn capacity ($C_{LT,\max}$); with the sight-distance problem, the critical gap and follow-up time are 7.7 sec and 2.9 sec, which can be used to calculate the minimum left-turn capacity ($C_{LT,\min}$). The term P (probability that there is at least one vehicle in the opposing left-turn lane) can be calculated by Equation 6-9. Actually, the probability is equal to the v/c ratio, the volume-to-capacity ratio.

$$P = \frac{V_{OLT}}{C_{OLT,\min}}, \tag{6-9}$$

where P = probability that the opposing left-turning traffic will operate in a queue state

V_{OLT} = opposing left-turn flow rate during the permitted left-turn phase

$C_{OLT,\min}$ = minimum opposing left-turn capacity with sight-distance problem

6.6.2 Effect of restricted sight distance on left-turn capacity

An isolated signalized intersection with a fixed signal phase was used as an example to analyze the left-turn capacity reduction due to restricted sight distances. In this case, it is assumed that:

- the length of the cycle is 90 sec
- the length of the permitted green (green for major road-through traffic) is 60 sec
- the lost time for opposing through vehicles is 2 sec

If left-turn traffic in both opposing left-turn lanes is operating at saturation conditions (v/c=1), the calculations of left-turn capacity based on the critical gaps and follow-up times from the observed data are listed in Table 6-9. Compared to a similar intersection without the sight-distance problem, the left-turn capacities with the sight-distance problem are much lower, and the capacity reduction rate increases as the opposing-through traffic volume increases. When the opposing-through traffic volume increases up to 1,800 veh/hour, the reduction rate could be as high as 70 percent. When the opposing through traffic volume is larger than 1,200 veh/hour, the left-turn capacity is less than 100 vehicles per hour, and on average no more than 2 vehicles per cycle can take advantage of the permitted phase to make left turns.

Table 6-9: Calculation Results of Left-turn Capacity Estimation

| Opposing through volume (veh/h) | Capacity estimation | | | | Capacity reduction rate |
| | Without sight problem | | With sight problem | | |
	(veh/h)	(veh/cycle)	(veh/h)	(veh/cycle)	
1800	58	1.5	18	0.4	70%
1600	90	2.2	30	0.8	66%
1400	132	3.3	49	1.2	62%
1200	186	4.7	78	1.9	58%
1000	259	6.5	119	3.0	54%
800	354	8.8	181	4.5	49%

It is possible that the left-turn traffic in one approach lane is saturated but that the traffic in the opposing left-turn lane is not. For such a case, the left-turn capacity reduction rates due to the restricted sight-distance problem are related to the v/c ratios (*P*) for opposing left-turn traffic. Figure 6-8 depicts the effect of restricted sight distance on the unprotected left-turn capacity with different v/c ratios of opposing left-turn traffic. The lower opposing left-turn traffic may mitigate the extent of capacity reduction. However, even for the 0.5 v/c ratio, the capacity reduction rates could range from 15 percent to 35 percent for different opposing through traffic volumes.
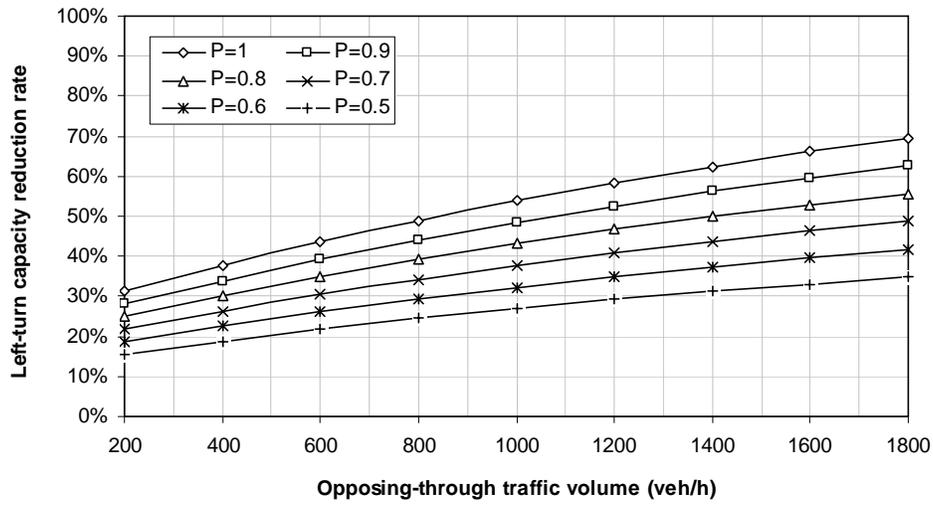
Figure 6-8: The effect of restricted sight distance on the unprotected left-turn capacity

CHAPTER 7. CONCLUSIONS AND DISCUSSION

Left-turn sight distance is an important geometric design factor for traffic turning left during the unprotected green phase at signalized intersections. The challenge that left-turners confront is the blockage of view introduced by vehicles located in the opposing left-turn lane. Inadequate sight distance can cause drivers to aggressively accept small gaps to cross the opposing through traffic and even contribute to illegal traffic performance. To maximize available sight distance, left-turning drivers might move the vehicle out beyond the stop bar of the left-turn lane and encroach into the pedestrian crossing or drive the vehicle as near as possible to the median. These behaviors can both reduce the driving comfort level and increase the probability of traffic crashes.

This study introduced six geometric models to calculate left-turn sight distance for intersections with different configurations. They include intersections located on a linear road, a curved road, a linear segment leading a curved segment, and a curved segment leading a linear segment. The geometric models presented in this study can be used to identify a better intersection location along the major road when a curve exists, to lay out the geometric design of intersections, or to evaluate the sight-distance problem of an existing intersection configuration to ensure safe left-turn maneuvers by drivers.

For linear-type intersections, the study focused on the design aspect of left-turning drivers, and geometric models were developed to evaluate the improvement effects of the two offset methods for opposing left-turn lanes. Using reasonable values assumed for geometric parameters of the intersection, the models verified that the sight-distance problem for left-turners could occur even

on the traditional left-turn lane design with 14- to 18-foot medians at high major-road design speed. AASHTO has indicated that medians narrower than 18 feet should not have sight-distance problems. Through the use of the developed models, sensitivity analyses illustrated the relationship between the sight distance and the offset value for parallel left lanes, as well as the effect of the left-turn lane length and taper angle on sight-distance improvement. The models can be adjusted to accommodate special features. For example, in Equation 3-4, the A assumes that the far left edge of the median curb is aligned with the opposing left-turn lane line. In fact, sometimes there is a small offset by one or two feet between two major approaches. This value can be added into term A in both equations so that the model is still valid. In addition to 90-degree intersections, the models can also be applied to skewed intersections, since there is no essential change in the relationship among all parameters used for the major approaches, but it should be cautioned that the required sight distances may differ from the normal ones due to the change of drivers' gap-acceptance behavior.

For intersections located on a horizontal curve, sight-distance calculation models for left-turn maneuvers toward the outside of the curve and toward the inside of the curve are presented in this study. The former model concluded that the major road curve can result in a sight-distance problem and concluded that the curve's radius is positively related to the sight distance. For the 12-foot median, the available sight distance might be insufficient for the higher design speed on the major road even if the curve is not sharp. The latter model indicated that the curve radius is negatively related to the sight distance and there is a threshold of the radius for different median widths. Only if the radius is larger than the threshold value could the opposing left-turn vehicle be a potential sight obstruction. For 12- to 16-foot medians, there is normally no sight-distance

problem for a curved major road; for median widths beyond 16 feet, if the curve radius is large, the sight distance is possibly insufficient for the higher design speed on the major road. In addition, for both models, the curve radius lacks sensitivity to the available sight distance if it is larger than 10,000 feet. Instead, median width plays a more important role.

The models and related analyses can be used to lay out intersection design or evaluate the sight-distance problem of an existing intersection configuration to ensure safe left-turn maneuvers by drivers. In particular, if the left-turn traffic volumes in both left-turn lanes are relatively heavy, a protected phase is suggested for left-turn traffic toward the outside of the curve. In the models, the term X is the distance from the curve center point to the centerline of the minor road, which is related to the intersection type. If X is equal to zero, it means that the minor road intersects the major road curve at a right angle; if X is unequal to zero, the intersection is skewed. According to the calculation analysis, X is not sensitive to the sight distance. Compared to zero X, a value of 200 feet for X can cause only a 1.3-foot sight-distance difference for a 1,000-foot curve radius. In addition, the models and related analyses assume that the far left edge of the median curb is aligned with the opposing left-turn lane line in the same radius curve. If not, the terms R_1, R_2 and R_3 need to be adjusted. Additionally, the model development focused on the situation in which the major road of the intersection is a single circular curve. For an intersection with special geometric features, such as two-circular curve combination or a spiral curve, the models will be invalid.

Based on the sight-distance calculation for opposite linear approach leading a curve segment, the presence of a curve can always mitigate the sight-distance problem when drivers are making a

left turn toward the inside of the curve. Conversely, if drivers are making a left turn toward the outside of the curve, the major road curve can result in a serious sight-distance problem. Compared to the results from the curve model, the presence of a linear segment can slightly mitigate the sight-distance problem. The curve segment length to the tangent point is inversely related to the sight distance.

When an opposite curve approach leads a linear segment and drivers make a left turn toward the outside of the curve, the major road curve can result in a serious sight-distance problem, but the presence of a linear segment can slightly mitigate the sight-distance problem. The curve segment length to the tangent point is inversely related to the sight distance. On the other hand, if drivers make a left turn toward the inside of the curve, the presence of the curve can greatly mitigate the sight-distance problem. In this case, the curve radius is inversely related to the sight distance. However, the presence of a linear segment can reduce the sight-distance benefit from the curve. The curve segment length to the tangent point is positively related to the sight distance. When the curve length is zero, the SD calculation results are closer to that of the linear model.

It is notable that two studies (Alexander, et al. 2002; Darzentas, et al. 1980) indicated that major road traffic speed has an important effect on drivers' gap acceptance. Those studies are challenging the constant gap time applied to Equation 2-1, so that the required sight distance may be different from the AASHTO guideline. In addition, AASHTO did not consider driver age difference as a variable for study on gap acceptances and intersection sight distances. However many related studies (Alexander, et al. 2002; Lerner, et al. 1995; Tarawneh and McCoy 1996) showed that older drivers usually accept gaps apparently longer than younger drivers. Therefore,

in areas with high-density older-driver population, the threshold of the intersection sight-distance design needs to be investigated.

The field study in this project confirmed the negative effect of the sight-distance problem on the traffic operation efficiency and safety. The results showed that sight obstruction due to the opposite turning vehicles may contribute to significant increments of the critical gap for both left-turn and U-turn drivers. With the sight-distance problem, the drivers' left-turn follow-up time is also significantly increased compared to those without the problem. These findings can be explained by the fact that when the driver's view is blocked, more response time is needed to accept the available gap or lag. The larger critical gap and follow-up time could result in an extra traffic delay and a capacity reduction. Furthermore, the capacity model calculation results showed that the capacity reduction rate increases with the increase of the opposing-through volume and the volume-to-capacity ratio for the opposing left-turn traffic.

On the other hand, when the available gaps are relatively small, the left-turn or U-turn drivers with sight-distance problems are more likely to accept a very small gap compared to those drivers with unrestricted sight distance. The video analysis did show that more traffic conflicts happened because the left-turn or U-turn drivers with the sight-distance problem accepted smaller gaps. Moreover, the in-depth analysis of a left-turn accident provided evidence that opposing vehicle sight obstruction can contribute to the occurrence of gap-acceptance crashes. Additionally, the sight-distance problem may cause drivers' abnormal behaviors to increase. When the opposing vehicle restricts the driver's view, more drivers are likely to reject a larger

gap but accept a smaller gap, and the conservative drivers could miss very large gaps and even refuse the permitted phase.

In this study, both the linear regression model (Siegloch method) and the logistic regression model were used to obtain the critical gaps for the left-turn gap acceptance. It was found that the critical gaps from linear regression were less than those from logistic regression. One possible reason is that if the left-turn vehicles were in the queue, the leading drivers might be pressured by the vehicles behind them to accept smaller gaps or lags. It was noted that the Siegloch method was used only as a left-turn queue-acceptance model. When multiple vehicles accepted a large gap, except for the leading vehicle, most vehicles were accepting the lag instead of the gap. However, very few lag data (less than 5 percent) were observed and used to fit the logistic regression model. Gattis and Sonny (1999) indicated that the critical gap values were greater than the critical lag values, and they explained that drivers were more willing to accept a lag than a gap of the same size. Another study (Kyte, et al. 1994) found that the Siegloch method produced less stable critical gap estimates than the maximum likelihood method.

Based on the findings of this study, checking the potential sight-distance problem for intersections with a wide median is strongly recommended, particularly for intersections at which gap-acceptance crashes frequently occur or where the efficiency of the permitted left-turn phase is abnormally low during peak hours. Once the sight-distance problem is identified for an existing intersection, offsetting left-turn lanes may be an effective method to improve the drivers' sight distance. If opposing through traffic volumes are relatively high, it is recommended that an exclusive-only phase be used instead of the permitted one.

The analyses in this study focused only on signalized intersections with a permitted left-turn phasing scheme. Similar issues related to sight visibility for left-turning vehicles could potentially occur for non-signalized intersections such as a two-way stop–controlled intersection. Both field observation and crash data analysis are suggested to extend this topic to the non-signalized intersections.

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