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16. Abstract

The development of raised medians is an important access management technique commonly used in urban settings. It can be used to control or restrict mid-block left turns, U-turns or crossing maneuvers for implementing of alternative left-turn/U-turn movements. The objective of this research project was to develop guidelines for operationally effective raised medians and the use of alternative movements on urban roadways. To fulfill this goal, the researchers (1) reviewed and synthesized national and peer states' practices, (2) conducted survey of traffic engineers, (3) conducted field studies, (4) analyzed the design issues relating to raised medians and alternative movements through simulation studies, and (5) developed guidelines for future implementation of raised medians and representative alternative movements in Texas.

The results of this study provide recommendations on some critical design issues in the use of raised medians, including median widths, median left-turn lane lengths, placement of median openings, and the use of directional median openings. In addition, a set of implementation-oriented guidelines regarding the applicability, geometric design, and access management of three typical types of alternative movements, including restricted crossing U-turn (RCUT), median U-turn (MUT) and continuous flow intersection (CFI), were developed.

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DEVELOPMENT OF GUIDELINES FOR OPERATIONALLY EFFECTIVE RAISED MEDIANS AND THE USE OF ALTERNATIVE MOVEMENTS ON URBAN ROADWAYS

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The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufactures' names appear herein solely because they are considered essential to the object of this report.

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SUMMARY

The development of raised medians is an important access management technique commonly used in urban settings. A raised median can be used on urban streets where it is desirable to control or restrict mid-block left turns, U-turns, or crossing maneuvers to improve operational and safety performance. Alternative movements, such as right turns followed by U-turns as an alternative to direct left turns, are increasingly used on urban streets to mitigate congestion, reduce conflicts, and improve safety along arterial roads.

In this study, the researchers reviewed peer states' manuals and guidelines for design elements of a raised median, including warrants, median widths, median left-turn lane lengths, placement of median openings, and use of directional median openings. These guidelines provide useful, supplemental guidance to the existing Texas Department of Transportation (TxDOT) guidelines. Collectively, it is widely accepted that raised medians, if properly designed, tend to bring a better safety experience over two-way left-turn lanes (TWLTL) or undivided median treatments. There are fewer existing research endeavors associated with operational impacts than safety impacts of raised medians. The available research showed that it is not conclusive whether raised medians present a better or worse operational performance than TWLTL, since the effectiveness of a raised median depends on a wide range of factors, such as median widths, median left-turn lane lengths, placement of median openings, and use of directional median openings. Regarding alternative movements, prior research reported that, e.g., restricted crossing U-turns (RCUTs), median U-turns (MUTs), and continuous flow intersections (CFIs) can improve intersection operational and safety performance if they are properly implemented.

A survey of transportation professionals at state departments of transportation has been conducted, both within Texas and nationally, about current practices and implementations related to raised medians and alternative movements on arterial roadways. A web-based survey was conducted from April 11, 2011, to June 21, 2011. Totally, 42 responses were received. A wide range of topics associated with raised medians and alternative movements were covered in the survey, providing necessary insights into the current practices related to this project.

The researchers carefully designed and performed two field studies, aimed at collecting field data for the planned simulation-based studies at Jones Rd. in Houston and U.S. 281 Super Street in San Antonio. Field traffic conflicts, historical crash data, and police reports were also collected, analyzed, and compiled. The results showed that:

- Narrow medians, high driveway density, and placing a median opening within the influence area (queue length) of a signalized intersection increased the potential for safety issues related to raised medians. Short left-turn bays did not compromise the safety along studied road segments.
- Super Street/RCUT design significantly improved traffic operation for mainline traffic, but compromised traffic operation for traffic from side streets. Super Street/RCUT design significantly reduced crashes between left turns from the mainline and opposing traffic (shortened cross distance) and reduced rear-end crashes, but it increased right-turn-on-red (RTOR) and sideswipe crash rates for the side street approaches.

Simulation-based studies were conducted to evaluate the operational impacts of various geometric designs and treatments relating to raised medians. The results indicated that:

- The delay caused by using substandard median turn lanes is relatively small; however, the resulting delays can add up, causing significant delays, if such lanes are used consistently along a corridor. Therefore, the desirable lengths recommended by the TXDOT Roadway Design Manual should be used whenever it is practical to do so.
- In terms of traffic operations, directional median openings within the intersection influence area are generally less favorable than full median openings. From traffic safety standpoints, after converting the full median opening into a directional opening, crossing conflicts were reduced significantly and the overall safety performance was generally improved.

On a four-lane curbed roadway, the use of the minimum median width (i.e., 16 or 17 ft) recommended by the TxDOT Roadway Design Manual does not provide adequate space for mid-block U-turn movements by large size vehicles, such as pick-up trucks, SUVs or vans. Researchers investigated the types of vehicles that can be accommodated by restricted right-of-way (ROW; i.e., 80, 90, 100, and 120 ft), and suggested the typical minimum median widths for urban roadways based on swept path analyses.

The researchers conducted simulation studies to analyze the operational and safety impacts of the Super Street intersection. The performance analysis suggested that the crossover distance in a Super Street design should be sufficiently long to provide sufficient storage and deceleration lengths for the U-turn lanes at the crossover and the left-turn lanes at the main intersection. It should also be enough to accommodate the through queue length at the main intersection. Otherwise, the design can result in operational and safety problems.

Based on the reviewed literature and the numerous research findings throughout this project, the researchers developed guidelines for operationally effective raised medians, covering various design elements, and both operational and safety issues. In addition, a set of implementation-oriented guidelines regarding the applicability, geometric design, and access management of three typical alternative movements, i.e., RCUT, MUT, and CFI, were developed.

Finally, the applications of representative developed guidelines were demonstrated through a case study. The results of traffic simulations proved that implementing the recommended guidelines in the studied roadway segment can help improve its safety and operational performances, which verified the applicability and effectiveness of the developed guidelines.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The development of raised medians is an important access management technique that is commonly used in urban settings. A raised median can be used on urban streets where it is desirable to control or restrict mid-block left turns, U-turns, or crossing maneuvers. Compared to flush medians, installing such non-traversable medians can result in a series of benefits including improved traffic safety, possibly increased throughput capacity and reduced delays, provision of pedestrian refuge areas, and focused left-turn and crossing maneuvers at appropriate locations.

Statistics compiled by the Federal Highway Administration (FHWA) reveal that TxDOT owns and operates 9,156 miles of urban arterials and collector roadways throughout Texas. In light to the TxDOT Roadway Design Manual, the placement of raised medians is recommended for roadways (a) where the average daily traffic (ADT) volumes exceed or are expected to exceed 20,000, or (b) where the demand for mid-block turns is high. Thus, a large number of existing and planned roadways or road segments are eligible for the use of raised medians in Texas.

However, currently, there are limited guidelines provided in the TxDOT Roadway Design Manual and Access Management Manual regarding the design and implementation of raised medians, leaving traffic engineers to make design decisions relying on their engineering judgments. In addition, problems may also be presented when raised medians are developed in strict compliance with the criteria established in the Roadway Design Manual. For example, in the determination of the placement and frequency of the median opening, the deceleration and storage length for turning vehicles required by the Roadway Design Manual often exceed the available length along the roadway centerline due to the high turning demand at the median openings. Furthermore, the available official guidelines did not list all the available tools for practitioners in determining appropriate solutions to access issues, which makes the engineers hesitant to use alternate geometric treatments. Note that some alternative geometric treatments may enable the engineers to optimize access and mobility, for example, operational benefits may be achieved through the use of alternative left-turn/U-turn treatments, which remove left turns/U-turns from intersections and relocate them to appropriate median openings. Therefore, guidelines are needed for effectively implementing raised medians and for appropriately using alternative movements on urban roadways.

1.2 RESEARCH GOALS AND OBJECTIVE

The goal of the proposed project was to develop guidelines for operationally effective raised medians and the use of alternative movements on urban roadways. To this end, the research entailed the following specific objectives:

1. Examine the important issues related to the design of raised medians, including:

(a) Placement of median openings.
(b) Appropriate length for the turning lanes at median openings.
(c) Use of directional median openings.
(d) Appropriate width of raised medians, e.g., for four-lane highways in accommodating U-turn maneuvers.

2. Synthesize the best practices on the use of alternative movements.
3. Examine the important issues related to the design of representative alternative movements design.
4. Develop implementation-oriented guidelines for the use of raised medians and alternative movements.

1.3 OUTLINE OF THIS REPORT

This report covers all the tasks conducted during the span of the research project. In Chapter 2, national and peer states' practices are reviewed and synthesized. In Chapter 3, a survey of traffic engineers is introduced, and the survey responses are analyzed. The field data collection is described in Chapter 4. In Chapter 5, traffic simulation based studies that investigated two critical issues relating to raised median design, i.e., the use of short left-turn lanes at unsignalized median opening and the use of directional median openings, are presented. After that, a set of developed guidelines for operationally effective raised medians is described in Chapter 6. In Chapter 7, two representative applications of alternative movements in Texas, i.e., U.S. 281 Super Street in San Antonio and the "Michigan U" intersection in Plano, are described, and some key design issues are discussed. Chapter 8 presents guidelines developed for the use of three representative alternative movements, i.e., RCUT, MUT, and CFI. In Chapter 9, through a case study, the applications of some developed guidelines are demonstrated. Finally, conclusions and recommendations are provided in Chapter 10.

CHAPTER 2: LITERATURE REVIEW

Numerous studies have been conducted regarding raised median and other alternatives. To develop a full context for the project, the state-of-the-art/practice associated with the use of raised medians and alternative movements has been thoroughly reviewed.

The chapter is organized as follows. Section 2.1 clarifies concepts, definitions, and backgrounds related to the project. Section 2.2 focuses on existing department of transportation (DOT) design standards on raised medians, while Sections 2.3 to 2.5 present the existing research and their major findings on safety, operational, and economic impacts of raised medians. Section 2.6 focuses on the major existing findings on the operational and safety impacts of alternative movements. Finally, a brief summary is provided as concluding remarks.

2.1 CONCEPTS, DEFINITIONS, AND BACKGROUNDS

2.1.1 Access Management

Access management represents a very general principle to improve safety and mobility by managing the access to and from abutting properties along streets and highways. So far, there are more than 100 individual access management techniques that have been identified (NCHRP Report 420, 1999). Among them, raised medians and alternative movements are recognized as representative techniques that may help preserve capacity, maintain mobility, and improve safety.

2.1.2 Access Point

An access point defines all unsignalized access locations, which can be either a driveway or a public street approach. Access point density typically means the total number of access points on both sides of the major-street segment (i.e., a two-way total) divided by the length of the segment (in miles). Driveway density and public street approach density are defined in a similar manner.

2.1.3 Raised Median

Raised median defines raised, non-traversable dividers in the center of a roadway, as shown in Figure 2-1. It is generally concluded that a properly designed raised median can bring a series of benefits, including:

- Better safety performance over other median treatments, e.g., TWLTL, or undivided cross-section. Raised medians concentrate turning movements at appropriate locations, and separate left turns and U-turns from through traffic movements, which contributes to a reduction in conflict points.

- Providing crossing pedestrians with refuge areas at mid-blocks and intersections.
- Providing space for control devices at mid-blocks and intersections.
- Opening up landscaping opportunities for urban aesthetic benefits.

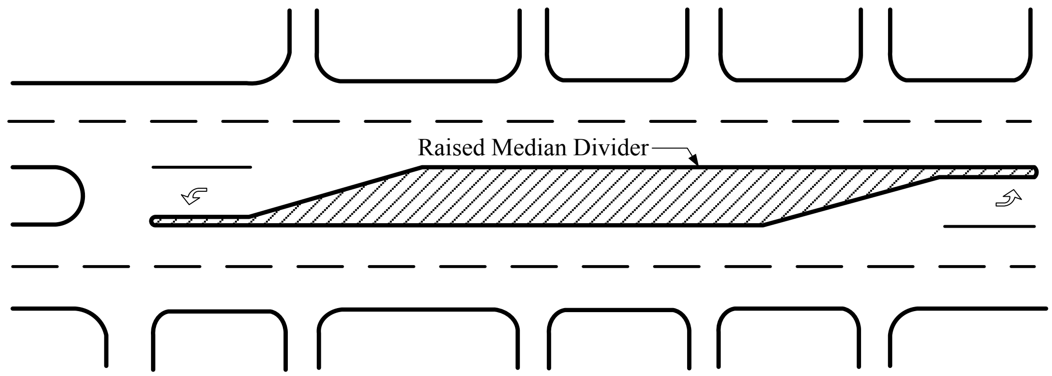


Figure 2-1. Illustration for Raised Medians.

2.1.4 Raised Median Design Elements

With regard to the design of raised medians, there is a series of design elements to be determined based on the geometric, environmental, and traffic conditions. Typically, the elements include (1) median opening placement, (2) median opening spacing, (3) median width, a major contributing factor to U-/left-turn radii, (4) median opening length, and (5) pocket turn lane composed of taper, deceleration, and storage sections. These design elements are illustrated in Figure 2-2.

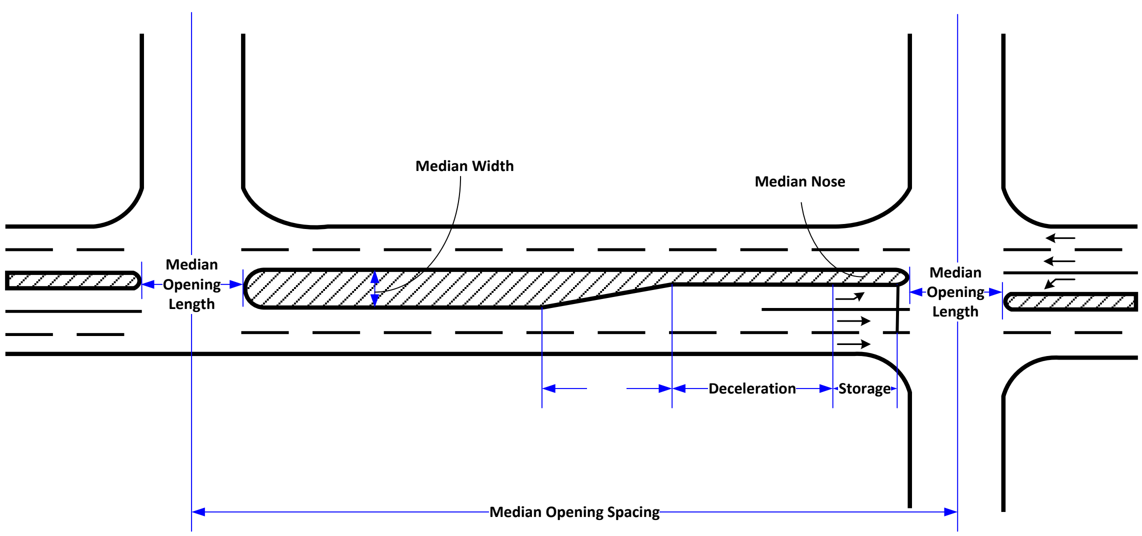
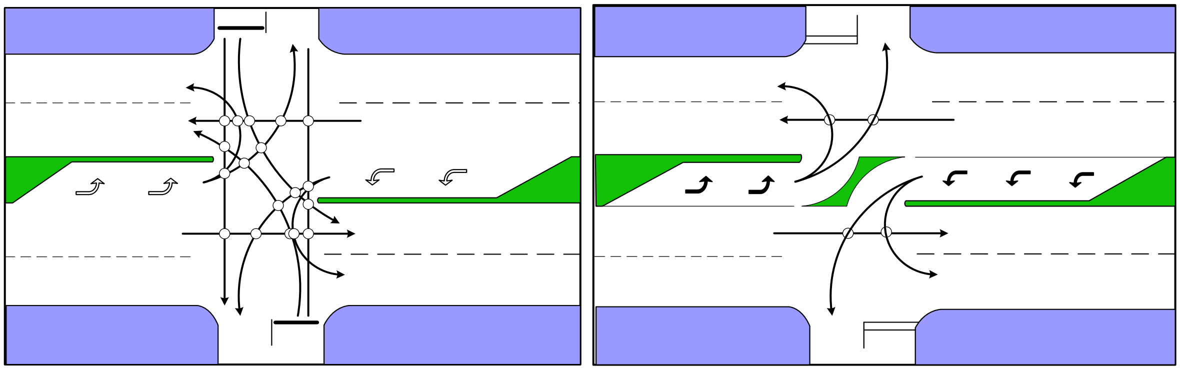
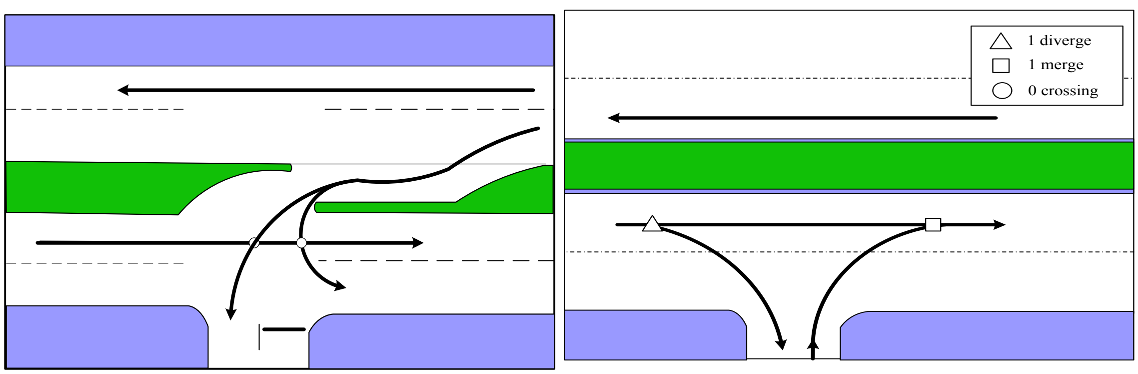


Figure 2-2. Major Raised Median Design Elements.

Median openings are sometimes referred to as “crossovers.” The placement and frequency of median openings is critical for the efficient operation of the roadway. Figure 2-3 illustrates the traffic conflict distributions with various median opening settings. A full median opening allows all turns and has 18 major conflict points (see Figure 2-3 (a)). By providing restrictive medians it can reduce the number of conflict points along arterial roads as shown in Figures 2-3 (b)-(d).



(a) Full Median Opening, 18 Major Conflicts (b) Directional Median Opening, 4 Major Conflicts



(c) Left-in Only Opening, 2 Major Conflicts (d) Restrictive Median, 2 Minor Conflicts

Source: Median Handbook, Florida Department of Transportation, 1997.

Figure 2-3. Conflict Zones with Different Median Opening Settings.

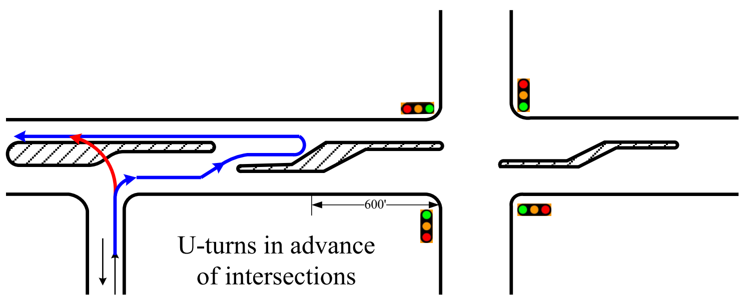
2.1.5 Alternative Movements

Alternative movements, such as RTUTs as an alternative to direct left turns, are increasingly used in order to reduce conflicts and to improve safety along arterial roads. RTUTs make it possible to prohibit left turns from driveway connections or at signalized intersections, which may contribute to more efficient signal operations, reduced congestion, and improved progression along the arterial. Generally, there are three different types of RTUT alternative movements.

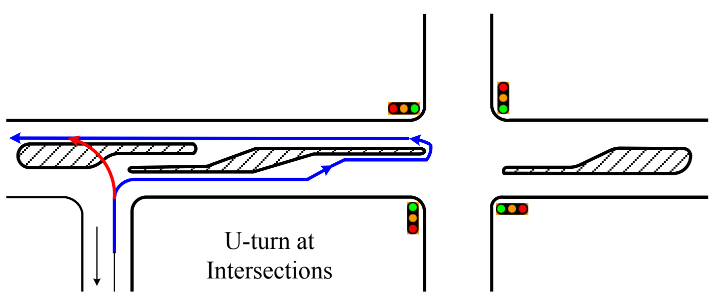
2.1.5.1 Type (1): RTUTs as Alternatives to Direct Left Turns from Unsignalized, Minor Streets/Driveways

Higher volumes along urban arterials (e.g., 700–900 vphpl) would produce high left-turn egress delays. As shown in Figure 2-4 (a) and (b), the red line depicts the hypothesized paths of a direct left-turn vehicle egress from a minor street or driveway, while the blue lines represent the rerouting paths as the alternative movements. Usually, direct left turns from unsignalized minor streets/driveways have to cross two major conflict zones with the two-way major street through movements, which may be particularly difficult for drivers under high traffic volume conditions. Type (1) alternative movements, as shown in Figure 2-4 (a) and (b), may make the maneuver easier by replacing the direct left turn with a U-turn either in advance of or at the signalized intersection.

The case shown in Figure 2-4 (a) removes two major conflict points between direct left turns with through traffic, and presents one minor conflict point (weaving to the left curb) and one major conflict point (making a U-turn). The case shown in Figure 2-4 (b) replaces two major conflict points by one minor conflict point (weaving to the left curb), and a major conflict point that can possibly be removed by using multiphase signal timing. Some operational and safety benefits can thus be gained due to the degradation of conflict zones.



(a) U-turns located in advance of signalized intersections



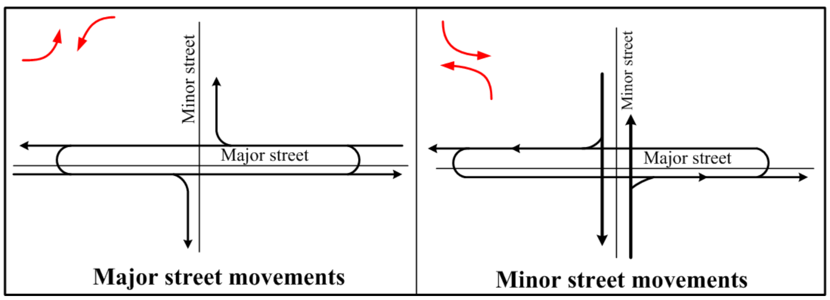
(b) U-turns located at signalized intersections

Source: NCHRP Report 420, Impacts of Access Management Techniques, 1999

Figure 2-4. U-turns as Alternatives to Direct Left Turns from Unsignalized, Minor Streets/Driveways.

2.1.5.2 Type (2): RTUTs as Alternatives to Direct Left Turns at Signalized Intersections—"Michigan U"

As is shown in Figure 2-5, U-turns can also be used as alternatives to direct left turns at signalized intersections, which is commonly referred to as "Michigan U." The "Michigan U" concept for indirect left turns typically places the U-turns about 660 ft downstream of intersections, eliminates all left turns at the main intersection, and allows two-phase signal controls. The removal, or reduction in numbers of left turns and U-turns from the signalized intersection, also allows for shorter signal cycles, improved progression, and increased capacity along the arterial. The U-turn openings can be controlled using traffic signals when it is hard for drivers to correctly estimate the gaps in the through traffic flow because of high speed or high through volume.

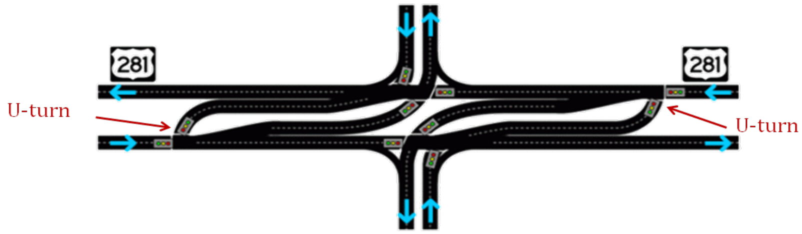


Source: Signalized Intersections: Informational Guide, 2004

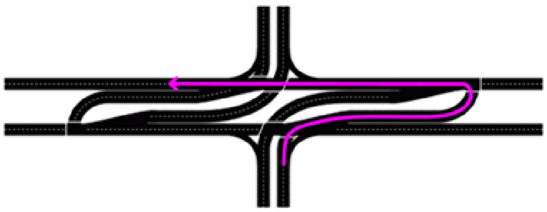
Figure 2-5. U-turns as Alternatives to Direct Left Turns at Signalized Intersections.

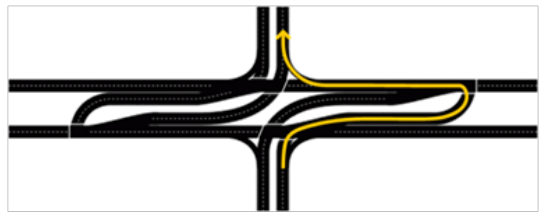
2.1.5.3 Type (3) U-turns as Alternatives to Direct Through Movements from Minor Roads at Rural Highway Signalized Intersections

On rural highway signalized intersections, U-turns can also be used as alternatives to direct through movements on minor streets. A typical application in Texas is known as the Super Street project that has been proposed on U.S. 281, San Antonio Area. As shown in Figure 2-6, besides alternatives to direct left turns, U-turns also serve as alternatives to through movements from minor streets. In this project, U-turns are controlled by signals considering the high speeds on U.S. 281 that cause difficulties in making safe U-turns.



(a) Super-Street crossing design





(b) Rerouted left turns from minor roads (c) Rerouted through movements from minor roads

Source: http://www.texashighwayman.com/us281ss.shtml

Figure 2-6. Concept of Super Street on U.S. 281, Texas.

Likewise, a project named "Restricted Crossing U-Turn Intersection" was initiated by FHWA, proposing the same concept as Super Street on U.S. 281. The spacing from the main intersection to the U-turn crossovers varies in practice. The American Association of State Highway and Transportation Officials recommend spacing of 400 to 600 ft based on signal timing.

In terms of the benefits of alternative movements, some studies indicated that up to a 30% increase in throughput (i.e., the number of vehicles exiting the intersection) and up to a 40% reduction in network intersection travel time were achieved. In addition, previous studies showed that alternative movements will result in significant safety benefits. For example, for the restricted crossing U-turn intersections on the U.S. Route 23/74 corridor in North Carolina, there was a 17% decrease in total crashes, a 31% decrease in total crash rate, a 41% decrease in fatal/injury crashes, and a 51% decrease in fatal injury crash rate.

2.2 EXISTING DOT DESIGN STANDARDS ON RAISED MEDIANS

2.2.1 Texas Guidelines on Raised Median Design

When considering new construction or retrofit of urban public streets, the guidelines in the "TxDOT Access Management Manual" and "TxDOT Roadway Design Manual" are the only official tools available for the design of raised medians. Some representative guidelines and standards in these two manuals are presented as follows:

- Warrants for raised median: ADT exceeds *20,000* vehicles per day or new development is occurring (the Access Management Manual and the Roadway Design Manual).
- Median opening: The frequency of median openings varies with topographic restrictions and local requirements. Spacing is often selected to provide openings at all public roads and at major traffic generators such as industrial sites or shopping centers. Additional openings should be provided so as not to surpass a maximum of one-half mile (about 2,640 ft) spacing. In rural areas, the minimum spacing should be not less than one-quarter mile (about 1,320 ft). Openings should be located where adequate stopping sight distance is available and where the median is sufficiently wide to permit an official design vehicle to turn between the inner freeway lanes (the Roadway Design Manual).
- Urban median widths: Typical median width is 16 ft (12 ft lane plus a 4 ft divider) (the Roadway Design Manual).
- Rural median widths: From 4 ft to 76 ft (the Roadway Design Manual).
- Median opening length: Median opening length should be not less than 40 ft, nor less than crossroad pavement width plus 8 ft. Turning templates for a selected control radius and design vehicle are often used as the basis for minimum design of median openings, particularly for multilane crossroads and skewed intersections (the Roadway Design Manual).
- Left-turn lanes: Left-turn lanes should be provided at all median openings; the minimum length of a left-turn lane is the sum of the deceleration length plus queue storage. In order to determine the design length, the deceleration plus storage length must be calculated for peak and off-peak periods; the longest total length will be the minimum design length (the Roadway Design Manual).

Table 2-1. Lengths of Single Left-Turn Lanes on Urban Streets.

Speed (mph)	Taper Length (ft)	Deceleration Length (ft)
30	50	160
35	50	215
40	50	275
45	100	345
50	100	425
55	100	510

Source: TxDOT Roadway Design Manual

The minimum storage length is 100 ft, as defined as the TxDOT Roadway Design Manual, which shall apply when (1) the required queue storage length calculated is less than the minimum length, or (2) there is no rational method for estimating the left-turn volume.

The queue storage at unsignalized locations is calculated using a traffic model or simulation model or by:

$$L = (V/30)(2)(S) \tag{1}$$

where (V/30) is the left-turn volume in a two-minute interval, and S = queue storage length, in feet (or meters), per vehicle.

At signalized locations, the required storage may be obtained using an acceptable traffic model such as the latest version of the Highway Capacity Software (HCS) or acceptable simulation models. Where such model results have not been applied, the following may be used:

$$L = (V/N)(2)(S) \qquad (2)$$

where V = left-turn volume per hour, vph; N = number of cycles; and 2 = a factor that provides for storage of all left-turning vehicles on most cycles; a value of 1.8 may be acceptable on collector streets.

2.2.1.1 Left-Turn Lane Length Method Suggested by TxDOT Research Report 0-5290-1 (Yu et al. 2007):

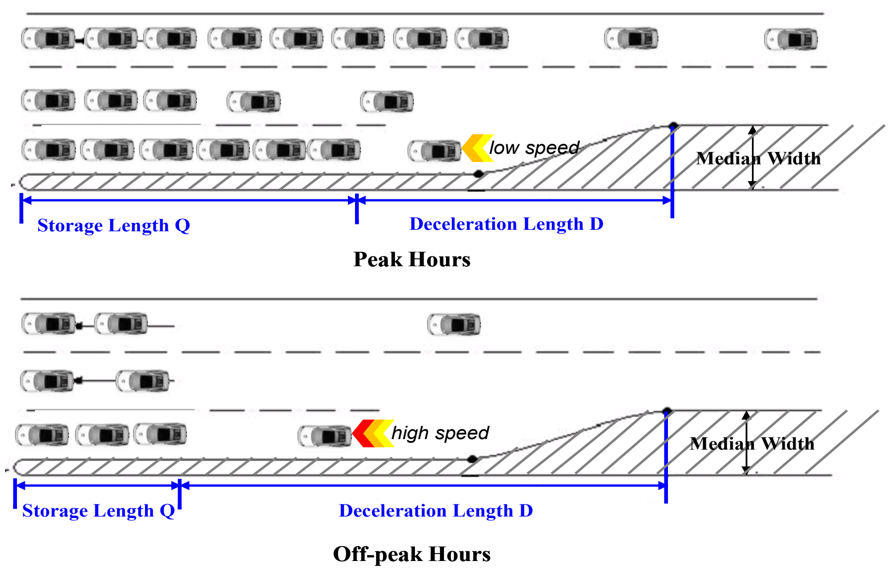
The traffic volume is critical for determining the storage length, and the intersection speed is an important factor for determining the deceleration length. Since the traffic volume and speed conditions during peak and off-peak hours are very different, the total left-turn lane length should be estimated for the peak hour and off-peak hour individually at first. As shown in Figure 2-7, the heavy traffic volume in the peak hours leads to relatively low speeds, so the deceleration length could be shorter during this time period while, at the same time, a longer queue storage length is required. On the other side, in the off-peak hours, the lighter traffic volume usually comes along with higher speeds, which results in relatively lower requirements for queue storage lengths but higher requirements for deceleration lengths. Therefore, the total length of the left-turn lanes can be determined as the maximum of the total lengths estimated for peak hours and off-peak hours. According to the traffic volume, storage queue length could be estimated based on Equations (2) and (3). To estimate the deceleration length, the traffic flow speed needs to be estimated first. For off-peak hours, the speed limits can be adopted. For peak hours, the traffic flow speed is determined by traffic volume, and then applied to Table 2-1. In this study, the Bureau of Public Roads (BPR) equation was recommended for estimating the speed in the congested traffic conditions:

$$S = \frac{S_0}{1 + 0.15(X)^4} \qquad (3)$$

where: S = Average link speed (mph or km/hr)

S_0 = Free-flow link speed (mph or km/hr)

X = Volume to capacity ratio (*v/c*)



Source: TxDOT Research Report 0-5290-1, Yu et al. 2007

Figure 2-7. Impacts of Traffic Conditions in Peak Hours and Off-Peak Hours on Determinations of Left-Turn Lane Length.

2.2.1.2 Summary

While these guidelines provide valuable and useful information for raised median design, they may be unable to address some particular design or access management issues. For example, the requirements for the deceleration and storage of turning vehicles at median openings may often exceed the available length between two openings especially for the arterial roadways with high design speeds and high demand for left-turn movements. On the other hand, when the frequency of median openings is reduced, the demand for mid-block U-turns will increase and will result in longer storage length requirements. Therefore, it is critical and imperative to develop guidelines for operationally effective raised medians on urban roadways that provide implementation-oriented guidelines for Texas design engineers.

2.2.2 Overview of Existing Guidelines on Raised Median Design in Peer DOTs

The peer DOTs' guidelines on raised median design can be valuable resources for developing guidelines dedicated to Texas engineers. Table 2-2 lists the existing, available design guidelines that have been reviewed by the Texas Southern University (TSU) research team. It covers various raised median design elements including median opening spacing, median width, median opening length, and turn lane.

Table 2-2. Reviewed DOT Standards Regarding Raised Median Design.

	Median Opening Spacing	Median Opening Length	Turn Lane at Median Opening	Median Width	References
Texas	√		√	√	TxDOT Access Management Manual TxDOT Roadway Design Manual
California		√		√	Caltrans Highway Design Manual
Colorado				√	CDOT Roadway Design Guide
Connecticut			√	√	CTDOT Highway Design Manual
Delaware			√	√	DelDOT Road Design Manual
Florida	√	√	√	√	FDOT Median Handbook
Georgia				√	GDOT Design Policy Manual Version 2.0
Illinois	√	√	√	√	IDOT Bureau of Design and Environment Manual
Iowa	√				Iowa DOT Design Manual
Kentucky	√				Access Management Implementation in Kentucky
Maine	√		√	√	MaineDOT Highway Design Guide
Massachusetts		√		√	MassDOT Project Development & Design Guide
Michigan	√			√	MDOT Road Design Manual
Minnesota		√	√	√	MNDOT Roadway Design Manual
Mississippi	√				MSDOT Access Management Manual
Missouri	√	√			MODOT Access Management Guidelines
Montana	√	√	√		MDT Road Design Manual
Nebraska		√	√		NDOR Roadway Design Manual
Nevada		√			NDOT Access Management System and Standards
New Mexico	√				NMDOT State Access Management Manual
North Carolina	√				NCDOT Guidelines for Median Separation at Highway/Railway At-Grade Crossings
North Dakota	√				NDDOT Design Manual
Ohio				√	Ohio DOT State Highway Access Management Manual
Oregon	√				DOT Access Management Classification and Spacing Standards
South Carolina	√				SCDOT Access and Roadside Management Standards
South Dakota	√				SDDOT Roadway Design Manual
Utah		√			UDOT Roadway Design Manual of Instruction
Virginia	√				VDOT Roadway Design Manual
Wisconsin	√	√	√		WisDOT Facilities Development Manual

Note: "√" means that relevant guidelines have been available and reviewed

These reviewed guidelines will be presented in detail in the following subsections. The review covers various design elements including general warrants, median opening placement, median opening spacing, median width, median opening length, and turn lane.

2.2.3 Warrants for Raised Medians

2.2.3.1 Georgia (GDOT Design Policy Manual, 2010)

Raised medians shall be constructed on multi-lane roadways at intersections that exhibit one of the following characteristics:

- High ADT volumes of 18,000 vpd (base year) and 24,000 vpd (design year).
- Accident rate greater than the state average for its roadway classification.
- Excessive queue lengths (as determined by district traffic engineer) in conjunction with excessive number of driveways.

2.2.3.2 Connecticut (CTDOT Highway Design Manual, 2009)

Raised medians shall only be used on roadways where the design speed is 50 mph or less.

2.2.3.3 NCHRP Report 395 (by Bonneson and McCoy, 1997)

Besides DOT standards, a set of detailed guidelines were derived by Bonneson and McCoy based on benefit-cost comparisons. Tables 2-3 to 2-6 were presented in NCHRP Report 395, indicating when undivided cross-sections or TWLTLs should be converted to raised medians for business-office and residential land uses. These tables were based on the following assumptions:

- Annual accidents per 0.25 mile were multiplied by $15,000 to obtain annual accident costs for each alternative.
- Annual through and left-turn delays (in hours) were multiplied by $16/hr to obtain annual delay costs.
- The differences in total annual costs (delay costs plus accident costs) between the two options represent the net benefits.

It can be noticed that the guideline assumed a median opening spacing of 1,320 ft, while number of travel lanes, ADT level, access density, and left-turn volumes were taken into account in the development of the guidelines.

Table 2-3. Conversion from an Undivided Cross Section to a Raised Median (Business and Office Land Use).

Through Lanes	ADT	Access Pt. Density (ap/mi)	Left-Turn Percent per 1,320-ft Segment Length					
			0	5	10	15	20	30
4	17,500	30	Stay with existing undivided					
		60	cross section					
		90						
	22,500	30		Site-specific examination required				
		60						
		90						
	27,500	30						
		60						
		90						
	32,500	30						
		60						
		90						
	37,500	30		Consider adding a raised-curb median				
		60						
		90						
	42,500	30						
		60						
		90						
6	26,250	30	Site-specific examination required					
		60						
		90						
	33,750	30						
		60						
		90						
	41,250	30						
		60			Consider adding a raised-curb median			
		90						
	48,750	30						
		60						
		90						
	56,250	30						
		60						
		90						
	63,750	30						
		60						
		90						

Note: Hatching denotes volume levels that may be associated with congested flow conditions.

Source: NCHRP Report 395 (by Bonneson and McCoy, 1997)

Table 2-4. Conversion from an Undivided Cross Section to a Raised Median (Residential and Industrial Land Use).

Through Lanes	ADT	Access Pt. Density (ap/mi)	Left-Turn Percent per 1,320-ft Segment Length: 0	5	10	15	20	30
4	17,500	30						
		60		Stay with existing undivided cross section				
		90						
	22,500	30						
		60			Site-specific examination required			
		90						
	27,500	30						
		60						
		90						
	32,500	30						
		60						
		90						
	37,500	30		Consider adding a raised-curb median				
		60						
		90						
	42,500	30						
		60						
		90						
6	26,250	30						
		60	Site-specific examination reqd.					
		90						
	33,750	30						
		60						
		90						
	41,250	30		Consider adding a raised-curb median				
		60						
		90						
	48,750	30						
		60						
		90						
	56,250	30						
		60						
		90						
	63,750	30						
		60						
		90						

Note: Hatching denotes volume levels that may be associated with congested flow conditions.

Source: NCHRP Report 395 (by Bonneson and McCoy, 1997)

Table 2-5. Conversion from a TWLTL to a Raised Median (Business and Office Land Use).

Through Lanes	ADT	Access Pt. Density (ap/mi)	Left-Turn Percent per 1,320-ft Segment Length					
			0	5	10	15	20	30
4	17,500	30						
		60						
		90		Site-specific examination required				
	22,500	30						
		60						
		90						
	27,500	30						
		60						
		90						
	32,500	30						
		60						
		90	Consider adding a raised-curb median					
	37,500	30						
		60						SWET
		90						
	42,500	30						
		60						SWET
		90						
6	26,250	30						
		60						
		90						
	33,750	30						
		60						
		90		Consider adding a raised-curb median				
	41,250	30						
		60						
		90						
	48,750	30						
		60						
		90						
	56,250	30						
		60						
		90						
	63,750	30						
		60						
		90					SWET	

Note: Hatching denotes volume levels that may be associated with congested flow conditions.
SWET = Stay with existing TWLTL.

Source: NCHRP Report 395 (by Bonneson and McCoy, 1997)

Table 2-6. Conversion from a TWLTL Cross Section to a Raised Median (Residential and Industrial Land Use).

Through Lanes	ADT	Access Pt. Density (ap/mi)	Left-Turn Percent per 1,320-ft Segment Length					
			0	5	10	15	20	30
4	17,500	30						
		60						
		90		Site-specific examination required				
	22,500	30						
		60						
		90						
	27,500	30						
		60						
		90						
	32,500	30	Consider adding a raised-curb median					
		60						
		90						
	37,500	30						
		60						Stay with
		90						TWLTL
	42,500	30						
		60					Stay with existing	
		90					TWLTL	
6	26,250	30						
		60						
		90						
	33,750	30						
		60		Consider adding a raised-curb median				
		90						
	41,250	30						
		60						
		90						
	48,750	30						
		60						
		90						
	56,250	30						
		60						
		90				Site-specific examination reqd.		
	63,750	30						
		60				Stay with		
		90				existing TWLTL		

Note: Hatching denotes volume levels that may be associated with congested flow conditions.

Source: NCHRP Report 395 (by Bonneson and McCoy, 1997)

2.2.3.4 Summary for Existing Warrants for Raised Medians

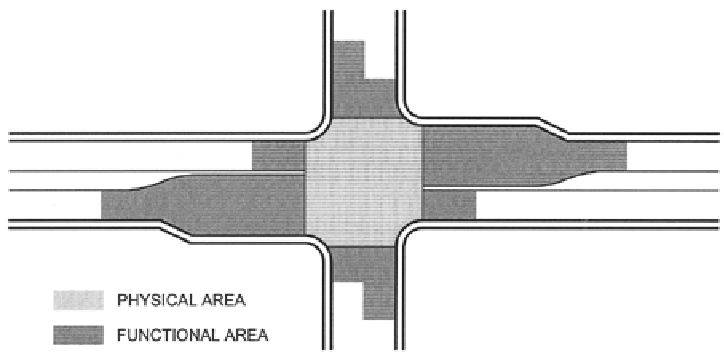
According to the prior research and practices, the raised median treatment is generally associated with fewer accidents than the undivided cross section or TWLTL, especially for average daily traffic demands that exceed 20,000 vpd. An ADT volume around 20,000 vpd typically warrants the consideration for the use of raised medians, which is consistent with the TxDOT guidelines.

2.2.4 Median Opening Placement

2.2.4.1 Florida (FDOT Median Handbook, 2006)

Some median opening placement principles are provided in the Median Handbook by FDOT, including:

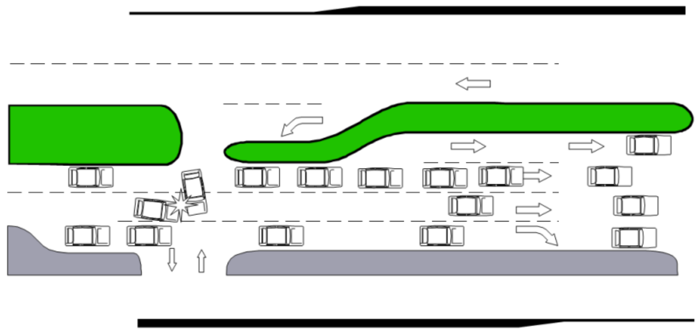
- Follow the spacing criteria as close as possible (see Table 2-7 for FDOT spacing standards).
- Median openings should not encroach on the functional area of another median opening or intersection (see illustration of intersection functional area in Figure 2-8).



Source: Signalized Intersections: Informational Guide, 2004.

Figure 2-8. Illustration of Intersection Functional Area.

- Median openings that allow traffic across left-turn lanes (for nearby signalized intersection) should not be allowed.
- Median openings that allow the following movements should be avoided: (a) across exclusive right turn lanes, and (b) across regularly forming queues from neighboring intersections, as shown in Figure 2-9.



Source: Median Handbook. Florida Department of Transportation, 2006.

Figure 2-9. Unfavorable Median Openings That Allow Inappropriate Turning Movements.

2.2.4.2 Illinois (IDOT Bureau of Design and Environment Manual, 2001)

Desirably, median openings should be provided on divided highways at all public roads and major traffic generators (identical to TxDOT guidelines).

2.2.4.3 West Virginia (Manual on Rules and Regulations for Construction Driveways on State Highway Rights-of-Way, 2004)

No additional median openings will be permitted, and existing openings shall not be lengthened on divided highways to accommodate driveway openings, unless they are (a) proven necessary by a traffic impact study, and (b) proven to not be detrimental to the highway level of service.

2.2.4.4 Michigan (Michigan DOT Road Design Manual, 2004)

Additional openings may be provided for large developments, e.g., shopping centers, as approved by the Traffic and Safety Division.

If constructed on an existing road, the cost of a new opening should be borne by the adjacent property owner or developer requesting the opening, unless the original road construction failed to provide the minimum required spacing.

2.2.4.5 Missouri (MODOT Access Management Guidelines, 2003)

Median openings shall not be allowed under the following circumstances: (a) on interstates or other freeways, (b) within the functional area of an interchange, (c) within the functional area of an intersection between two public roads, (d) at locations that have high accident rates, and (e) where an opening would be unsafe because of inadequate sight distance.

2.2.4.6 Montana (MDOT Road Design Manual, 2006)

Median openings are appropriate (a) at most public streets (site specific), (b) for U-turn movements on long sections of a continuous raised median, or (c) at approaches serving major traffic generators, that is, on approaches serving major shipping centers or special event facilities, not small shopping plazas or single businesses.

Some other relevant, general guidelines on median opening placement also include the following: (a) median openings (both signalized and unsignalized) must not impair the traffic signal coordination of the roadway facility; (b) do not place median openings in areas of restricted sight distance; (c) median openings should only be provided if the full length of a left-turn lane can be provided and if the beginning of the turn lane taper is at least 100 ft (30 m) from the median nose of the previous intersection.

2.2.4.7 South Dakota (SDDOT Roadway Design Manual)

Median openings on divided roadways should be provided at all signalized at-grade intersections, at unsignalized junctions of arterials and collector streets; they may be provided at driveways, where they will have minimum impacts on roadway traffic flow.

2.2.4.8 Iowa (Iowa DOT Design Manual, 2010)

Medians openings' placement on primary highways is governed by the following rules:

- New median openings should not be permitted except to accommodate intersecting local public roads/streets or large traffic generating facilities, such as large shopping centers or industrial plants. Median openings may be permitted in these instances if satisfactorily justified and in the public interest.
- If a median opening exists prior to the construction of a driveway, local public road, or street, the opening may be modified to accommodate the turning movements of the traffic expected.
- Costs incurred for adding or modifying median openings shall not be borne by the department.
- The department reserves the right to close an existing median opening when the department deems it is necessary.

2.2.4.9 South Carolina (SCDOT Access and Roadside Management Standards, 2008)

Median openings should be set far enough back from nearby signalized intersections to avoid possible interference with intersection queues. In all cases, storage of left turns and the necessary deceleration distance must be adequate.

2.2.4.10 Summary for Existing Median Opening Placement Guidelines

The reviewed peer DOT guidelines can be summarized as follows:

- When and where to place a median opening:
  - On divided highways at all public roads and major traffic generators (Illinois, Michigan, Montana, South Dakota, Iowa, and Texas).
  - When a full length left-turn lane can be developed (Montana and South Dakota).

- Where median openings are (a) proven necessary by a traffic impact study, and (b) proven to not be detrimental to the highway level of service (West Virginia).
- When the original road construction failed to meet required opening spacing criteria (Florida, Michigan and Texas).

- When and where not to place a median opening:
  - Within the functional area of an interchange or an intersection between two public roads (Missouri and Florida).
  - At locations that have high accident rates, or where an opening would be unsafe because of inadequate sight distance (Missouri, Montana, and Texas).
  - Where median openings (both signalized and unsignalized) will impair the traffic signal coordination of the facility (Montana).

If constructed on an existing road, the cost of a new opening should be borne by the adjacent property owners or developers requesting the opening, unless the original road construction failed to meet opening spacing requirements (Michigan and Iowa).

2.2.5 Median Opening Spacing

The median opening spacing refers to the distance between the centerlines of two adjacent median openings, as shown in Figure 2-2.

2.2.5.1 Florida (FDOT Median Handbook, 2006)

Table 2-7. Florida DOT Median Opening Spacing Standards.

Access Class	**Minimum Median Opening Spacing (Directional)**		**Minimum Median Opening Spacing (Full)**	
Interstate Highway	1,320 ft	400 m	2,640 ft	800 m
Principal Arterial	1,320 ft	440 m	2,640 ft	800 m
Minor Arterial	660 ft	200 m	2,640 ft over 45 mph 1,320 ft 45 mph or less	800 m over 70 km/h 400 m 700 km/h or less
Collector	330 ft	100 m	660 ft	200 m

Source: Median Handbook. Florida Department of Transportation, 2006

2.2.5.2 Missouri (MODOT Access Management Guidelines, 2003)

Table 2-8. Missouri DOT Median Opening Spacing Standards.

Roadway Classification	In Current and Projected Urban Areas	In Rural Areas
Interstate/Freeway	No median openings allowed	No median openings allowed
Principal Arterial	1,320 to 2,640 ft 1,320 to 660 ft (directional)	2,640 ft (full) when posted speed is over 45 mph 1,320 ft (full) when posted speed is under 45 mph
Minor Arterial	1,320 ft (full) 660 ft (directional)	1,320 ft (full) at all speeds
Collector	Medians generally not used	Medians generally not used

Source: Access Management Guidelines. Missouri Department of Transportation. 2003.

2.2.5.3 Montana (MDT Road Design Manual, 2006)

In no case may the number of median openings exceed three per 1000 ft (300 m).

2.2.5.4 North Dakota (NDDOT Design Manual, 2003)

Table 2-9. North Dakota DOT Median Opening Spacing Standards.

	Functional Purpose	Median Openings
Freeways	High Mobility, Low Access	• Public-use openings not allowed • U-turn median openings for use by authorized vehicles only when need is justified
Expressways	High Mobility, Low to Moderate Access	• Allowed • Alternatives to all-movement openings encouraged Minimum spacing between all-movement openings • 2,000 ft (posted speed limit of greater than 45 mph) or 1,200 ft (posted speed limit of 45 mph or less)
Boulevards	Moderate Mobility, Low to Moderate Access	• Allowed Minimum spacing between all-movement openings • 2,000 ft (posted speed limit of greater than 45 mph) or 1,200 ft (posted speed limit of 45 mph or less)
Thoroughfares	Moderate to Low Mobility, High Access	• Not Applicable

Source: North Dakota DOT Design Manual, 2003

2.2.5.5 South Dakota (SDDOT Roadway Design Manual)

The spacing of median openings for signalized intersections should reflect traffic signal coordination requirements and the storage space needed for left turns. Ideally, spacing of openings should be conducive to future signalization, if it is ultimately needed.

2.2.5.6 Wisconsin (WisDOT Facilities Development Manual, 2006)

Table 2-10. Wisconsin DOT Median Opening Spacing Standards.

Spacing between midblock median openings for a design speed of:	**Minimum**	**Desirable**
25 mph	140 ft	910 ft
30 mph	190 ft	780 ft
35 mph	240 ft	670 ft
40 mph	300 ft	530 ft
45 mph	360 ft	670 ft
50 mph	430 ft	780 ft
55 mph	510 ft	910 ft

Source: Facilities Development Manual. Wisconsin Department of Transportation, 2006.

2.2.5.7 Illinois (IDOT Bureau of Design and Environment Manual, 2001)

The following recommended minimum spacing should be evaluated when determining the location for a median opening:

- Urban Facilities: The desirable minimum spacing between median openings should be approximately one-quarter mile (1,320 ft). However, this may not always be practical. At a minimum, the spacing of median openings should be far enough apart to allow for the development of exclusive left-turn lanes with proper lengths.
- Rural Facilities: Median openings should be at least 0.5 mile (2,640 ft) apart and, desirably, 1 mile (5,280 ft) apart, subject to public service requirements and as determined by an engineering study.

For both rural and urban facilities, the available sight distance in the vicinity of a median opening is also a factor in the determination of its location. In addition, on some facilities, commercial establishments with heavy truck traffic may dictate the location of median openings.

2.2.5.8 Michigan (Michigan DOT Road Design Manual, 2004)

On the premise that an extra travel distance of up to 1/4 mile (1,320 ft) is not excessive when crossing a free access divided highway, the following criteria for opening spacing should apply:

- Medians Less Than 30 ft in Width: Openings may be constructed, as determined by the Traffic and Safety Division, opposite driveways and side roads or streets.
- Medians 30 ft or More in Width: Openings may be provided every 1/8 mile (660 ft) in urban areas and every 1/4 mile (1,320 ft) in rural areas. They may be adjusted 100 ft either way to conform to existing street or road returns or driveways. No two openings should be closer than 500 ft apart. Public roads should take priority over private drives in the event of a location conflict.

2.2.5.9 Mississippi (Mississippi DOT Access Management Manual, 2010)

Table 2-11. Mississippi DOT Median Opening Spacing Standards.

		Minimum Median Opening Spacing (Directional)	Minimum Median Opening Spacing (Full)
Urban Areas	Speed >45 mph	1,760 ft	1,760 ft
	Speed <45 mph	880 ft	1,760 ft
Rural Areas		1,760 ft	1,760 ft

Source: Access Management Manual. Mississippi Department of Transportation, 2010

2.2.5.10 Kentucky (Access Management Implementation in Kentucky, 2008)

Table 2-12. Kentucky DOT Median Opening Spacing Standards.

Access Classification			Speed ≥45		Speed <45	
			minimum spacing (full, ft)	minimum median (directional, ft)	minimum spacing (full, ft)	minimum spacing (directional, ft)
Freeway			N/A			
Urban	Principle Arterial	Volume≥10,000	2400	1200	2400	1200
		Volume<10,000	2400	1200	2400/1200	1200/600
	Minor Arterial	Volume≥10,000	2400	1200	2400/1200	1200/600
		10,000>Volume≥5000	2400/1200	1200/600	2400/1200	1200/600
		Volume<5000	2400/1200	1200/600	600	300
	Collector	Volume≥5000	2400/1200	1200/600	600	300
		Volume<5000	600	300	600	300
	Local		N/A			
Rural	Principle Arterial	Volume≥5000	2400	1200	2400	1200
		Volume<5000	2400	1200	2400	1200
	Minor Arterial	Volume≥5000	2400	1200	2400	1200
		5000>Volume≥2500	2400	1200	2400	1200
		Volume<2500	2400	1200	900	450
	Collector	Volume≥2500	2400	1200	900	450
		Volume<2500	900	450	900	450
	Local		N/A			

Source: Access Management Implementation in Kentucky, University of Kentucky, 2008.

2.2.5.11 Oregon (Oregon DOT Access Management Classification and Spacing Standards, 1996)

Table 2-13. Oregon DOT Median Opening Spacing Standards.

Functional Class	**Level of Importance**	**Area**	**Typical Speed**	**Median Opening Spacing (ft)**
Full Control (Freeway)	Interstate or statewide	Fully developed urban	55 mph	10,559
		Suburban developing urban	55–65 mph	15,839
		Rural	60–65 mph	31,678
Expressway	Statewide	Urban	45–55 mph	2640
		Rural	55 mph	2640
Major Arterial	Multi-lane	Urban	55 mph	2640
		Rural	45 mph	1320
		Fully Developed	35 mph	N/A
	Two-lane	Urban	45 mph	N/A
		Rural	45 mph	N/A
		Fully Developed	35 mph	N/A
Minor Arterial	Multi-lane	Urban	55 mph	660
		Rural	45 mph	330/ N/A
		Fully Developed	35 mph	N/A
	Two-lane	Urban	55 mph	N/A
		Rural	45 mph	N/A
		Fully Developed	35 mph	N/A
Major Collector	Multi-lane	Urban	45 mph	330/ N/A
		Rural	40 mph	N/A
		Fully Developed	35 mph	N/A
	Two-lane	Urban	45 mph	N/A
		Rural	40 mph	N/A
		Fully Developed	35 mph	N/A

Source: Access Management Classification and Spacing Standards, Oregon Department of Transportation, 1996.

2.2.5.12 Summary for Existing for Median Opening Spacing Guidelines

Collectively, the primary determinants of median opening spacing include the type of facility, posted speed limit, traffic volume (e.g., ADT) level, and rural or urban settings. Since this research project focuses on urban roadways, some representative guidelines are listed in Table 2-14, with differentiated spacing values for full and directional median openings, respectively.

Table 2-14. Summary for State DOT Median Opening Spacing Standards Applicable for Urban Areas.

			Minimum Median Opening Spacing (Directional)		Minimum Median Opening Spacing (Full)	
Speed Limit Based	Mississippi	Speed >45 mph	1,760 ft		1,760 ft	
		Speed <45 mph	880 ft		1,760 ft	
	North Dakota	Speed >45 mph	N/A		2,000 ft	
		Speed <45 mph	N/A		1,200 ft	
	Kentucky	Speed >45 mph	1,200/600/300 ft (depends on ADT level)		2,400/1,200/600 ft (depends on ADT level)	
		Speed <45 mph	1,200/600/300 ft (depends on ADT level)		2,400/1,200/600 ft (depends on ADT level)	
	Oregon	Speed >45 mph	N/A		2,640 ft	
		Speed <45 mph	N/A		330 ft	
	Wisconsin	Speed >45 mph	N/A		430 to 510 ft (depends on detailed speed)	
		Speed <45 mph	N/A		360 to 140 ft (depends on detailed speed)	
Rule of Thumb	Michigan	N/A	N/A		500 ft	
	Illinois	N/A	N/A		1,320 ft	
	Montana	N/A	N/A		1,000 ft	
Roadway Functionality Based	Missouri	Principal Arterial	1,320 to 660 ft (dependent variables are not mentioned)		1,320 to 2,640 ft (dependent variables are not mentioned)	
		Minor Arterial	660 ft		1,320 ft	
	Florida	Interstate Highway	1,320 ft		2,640 ft	
		Principal Arterial	Speed >45 mph	1,320 ft	Speed >45 mph	2,640 ft
			Speed <45 mph	660 ft	Speed <45 mph	1,320 ft
		Minor Arterial or Collector	330 ft		660 ft	

2.2.6 Median Width

Median width is measured as the distance between the edges of travel lanes. Median width typically includes inside shoulders if present.

2.2.6.1 Delaware (DelDOT Road Design Manual, 2004)

Typical widths of raised medians range from 4 to 22 ft. A raised median of 4 to 6 ft in width with a paved surface may be used under restricted conditions on urban streets, but they have limited advantages. Although they provide a positive separation between opposing traffic and an opportunity to collect drainage, they offer no opportunity to introduce left turn lanes, are too narrow to provide a desirable pedestrian refuge and do not adequately serve as an area for installing traffic control devices.

The absolute minimum median width is 12 ft for introducing left-turn lanes on low speed arterial streets with restricted conditions and minimal truck use. Any size truck (as well as many passenger car drivers) could not use this lane without infringing on the adjacent travel way.

A median width of 16 ft is the normally accepted minimum in urban areas to adequately serve a mix of drivers and vehicles without having erratic movements. This width provides for a 10 ft turn lane and a 6-ft raised median. This width does not provide any curb offset, so there will be a tendency for drivers to keep away from the median into the adjacent travel lane.

The two preferred urban median widths, where frequent left turns are to be accommodated with a diverse traffic mix, are 20 ft or 22 ft. A 20 ft median width allows for a 12 ft left turn lane, 2 ft clearance from the edge of traffic lanes to the face of the curbed island, and a 4 ft wide island to provide space for traffic control devices. However, in high pedestrian use areas, the preferred width is 22 ft, which will allow for a 6-ft raised median for pedestrian refuge.

2.2.6.2 Connecticut (CTDOT Highway Design Manual, 2009)

The width of a raised median should be sufficient to allow for the development of a channelized left-turn lane. Therefore, the typical width is 22 ft, which provides for a 12-ft left-turn lane, a 2-ft shoulder between the turn lane and raised island, a 2-ft shoulder between the opposing traveled way and the raised island, and a minimum 6-ft raised island.

If practical at an unsignalized intersection, a raised median should be 25 ft in width to permit storage of a vehicle crossing or turning left onto the mainline.

Under restricted conditions, the recommended minimum width of a raised median should be 8 ft. This assumes a minimum 4-ft raised island with 2-ft shoulders on each side adjacent to the through travel lanes.

2.2.6.3 Florida (FDOT Median Handbook, 2006)

Table 2-15. Summary for Florida DOT Median Width Recommendation.

		Minimum Width in Feet	Minimum Width in Meters
Guidance from Plans Preparation Manual	Reconstruction Projects , speed = 40 mph or less	15.5	5
	Reconstruction Projects, Speed >45 mph	19.5	6
	45 mph <Speed < 55 mph	22	7
	Speed> =55 mph	40	12
Recommended	4 lane highways with median expecting significant U-turns and directional median openings with excellent positive guidance	30 for single left turns and 42 for dual lefts	9 for single left turns and 12.6 for dual lefts
	6 lane highways with median expecting significant U-turns and directional median openings with excellent positive guidance	22 for single left turns and 34 for dual lefts	7 for single left turns and 10.6 for dual lefts

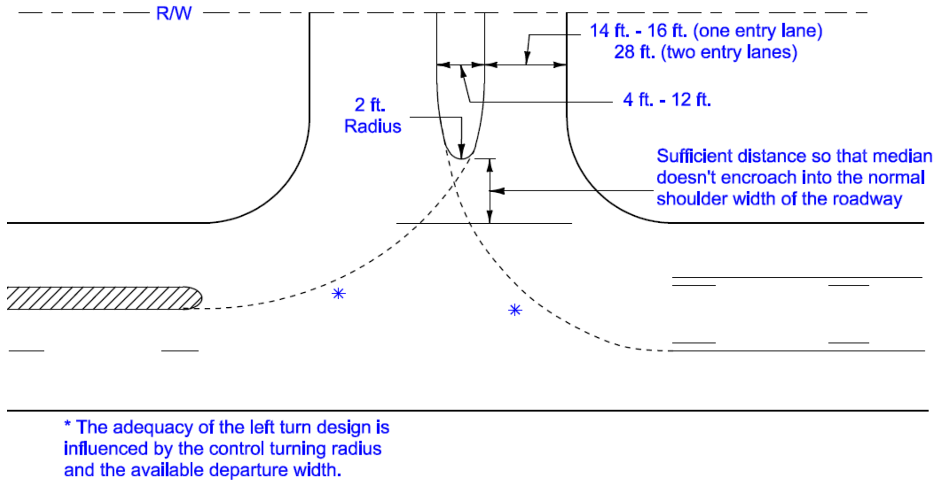
Source: Median Handbook. Florida Department of Transportation, 2006.

The minimum width of a median traffic separator "nose" has commonly been 4 ft (1.2 m). Where the right-of-way is limited, 2 ft (0.6 m) and even as little as 18 in. (460 mm) can be used. The American Association of State Highway Transportation Officials (AASHTO) indicates that "the minimum narrow median width of 4 ft is recommended and is preferably 6 to 8 ft wide" (AASHTO Greenbook).

U-turns should not be permitted from through traffic lanes because of the potential for high speed, rear-end crashes and serious detrimental impact on traffic operations. Rather, all left turns and U-turns should be made from a left-turn/U-turn lane.

2.2.6.4 South Carolina (SCDOT Access and Roadside Management Standards, 2008)

As shown in Figure 2-10, the part of the median within the right-of-way shall have a minimum width of 4 ft and a maximum width of 12 ft. When the median width is larger than 4 ft, the nose shall be defined with a 2-ft radius and the control turning radius. The median nose shall be offset a sufficient distance so that the median does not encroach into the normal shoulder width of the roadway. Landscape plants on the median and within 25 ft of the roadways should be limited to low growing plants not exceeding 2.5 ft in height. These plants shall not negatively affect sight distance.



Source: Access and Roadside Management Standards. South Carolina Department of Transportation, 2008.

Figure 2-10. South Carolina DOT Guidelines on Raised Median and Median Nose Design.

2.2.6.5 Ohio (ODOT State Highway Access Management Manual, 2001)

Urban Roadways: The minimum median width for a four-lane urban freeway should be 10 ft, which provides for two 4-ft shoulders and a 2-ft median barrier. For freeways with six or more lanes, the minimum width should be 22 ft, preferably with a 26 ft wide median when the directional design hourly volume for truck traffic exceeds 250 vehicles per hour to provide a wider median shoulder to accommodate a truck.

Rural Roadways: In flat or rolling terrain, the desirable median width for rural freeways is 60 to 84 ft. The 84-ft wide median allows for a future 12-ft wide lane in each direction of travel, and the 60-ft median. The minimum median width is normally 40 ft. However, in rugged terrain, narrower medians ranging from 10 to 30 ft may be used.

2.2.6.6 Maine (Maine DOT Highway Design Guide, 2007)

The designer should consider several factors when determining the median width:

- The median width should include the width of left-turn lane where it is applicable for providing left-turn bays at the median openings.
- Should be approximately 25-ft wide to allow a crossing passenger vehicle to stop between the two roadways.
- Turning movements at median openings depend on the median width and the width of the opening for cross traffic.
- A uniform median width is desirable; however, variable-width medians may be advantageous where right-of-way is restricted, at-grade intersections are widely spaced (0.5 mile or more), or an independent alignment is practical.
- In general, the widths of the other roadway cross section elements should not be reduced to provide additional median width.

Raised medians, typically with sloping curbs, are often used where it is desirable to control left turns. Desirably, the width of a raised median will be sufficient to accommodate left-turn lanes at intersections. The minimum width of the median nose is 4 ft.

2.2.6.7 Georgia (GDOT Design Policy Manual Version 2.0, 2010)

A 24-ft raised median will require a sloped curb inside the median, and a 2-ft additional paved shoulder offset from the edge of the inside travel lane to the edge of the gutter (for a total of 4-ft inside shoulder width from the edge of travel lane to the face of the curb).

2.2.6.8 Colorado (CDOT Roadway Design Guide, 2005)

The primary determinant of required median width is the type of facility. Width may be limited by aesthetic concerns, economics, right of way limitations, topography, and at-grade intersection signal operations. Median widths less than 4 ft should be considered separators, not medians. Sign width and location should be considered, and sign placement should be discussed with the region traffic engineer.

2.2.6.9 Nevada (NDOT Access Management System and Standards, 1999)

The minimum width for a raised median (edge of gutter pan to edge of gutter pan) is 4 ft. If an existing median is of sufficient width to accommodate the proposed left turn lane(s), the existing median may be used without further widening. When it is necessary to widen the roadway to accommodate left turn lanes, the roadway will be widened symmetrically on both sides of the roadway.

Table 2-16. Minimum Median Widths for Left Turn Lanes.

Single Left Turn Lane	16 ft
Dual Left Turn Lanes	28 ft
Triple Left Turn Lanes	40 ft
Two Way Left Turn Lanes (TWLTL)	14 ft (max)

Source: Access Management System and Standards. Nevada Department of Transportation, July 1999

2.2.6.10 Wisconsin (WisDOT Facilities Development Manual, 2006)

The nose of the median end may be either circular or bullet shaped. The bullet nose is preferred in most instances where the median is wide enough to provide it. The radius used to form the end of the bullet nose should be between 1 ft and 5 ft but desirably should be as near to 3 ft as possible.

2.2.6.11 Summary for Existing Median Width Guidelines

Collectively, the primary determinant of required median width is the type of facility, although the standards may vary state by state. For example, some representative results are shown as follows:

- A shoulder (or shoulders), as a part of the median width, usually has a width of 2 ft each (Georgia and Connecticut), and can be 4 ft each (Ohio).
- A median width of 16 ft is the normally accepted minimum in urban areas (identical recommendations as the TxDOT Roadway Design Manual), while the width include the width of a dedicated left-turn lane. This standard is particularly applicable when dedicated left-turn lanes are considered for intersections or openings (Delaware).
- A raised median of 4 to 6 ft in width with a paved surface may be used under restricted conditions on urban streets, which are too narrow to introduce dedicated left-turn lanes (Delaware).
- In high pedestrian use areas, the median width shall allow for at least a 6-ft raised median for pedestrian refuge (Delaware).
- A median width of 25 ft usually allows a crossing passenger vehicle to stop between the two roadways while keeping away from the travel lanes (Ohio and Maine).

2.2.7 Median Opening Length

2.2.7.1 Florida (FDOT Median Handbook, 2006)

Median opening length is commonly governed by the turn radii, side street geometrics, median (traffic separator) width, intersection skewness, and intersection legs.

An excessively wide median opening will store two or more vehicles in an unsignalized full median opening while they are waiting to complete a maneuver, which results in multiple conflicts for both the turning vehicles and through traffic. This may present both safety and operational problems.

2.2.7.2 California (Caltrans Highway Design Manual, 2006)

For any three or four-leg intersection on a divided highway, the length of the median opening should be at least equal to the width of the crossroads pavement, median width, and shoulders. An important factor in designing median openings is the path of the design vehicle making a minimum left turn at a speed of 8 to 15 km/h. The length of median opening varies with width of median and angle of intersecting road.

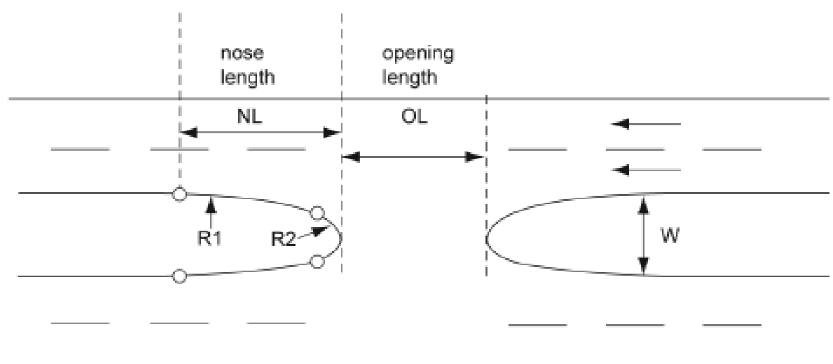
Usually a median opening of 18 m (60 ft) is adequate for 90-degree intersections with median widths of 6.6 m (22 ft) or greater. When the median width is less than 6.6 m (22 ft), a median opening of 21 m (70 ft) is needed. When the intersection angle is other than 90 degrees, the length of median opening should be established by using truck turn templates.

2.2.7.3 Illinois (IDOT Bureau of Design and Environment Manual, 2001)

The median opening length should properly accommodate the turning path of the design vehicle. The minimum length is the largest of the following: (a) approach width plus 8 ft including crossroad median width; (b) approach width plus the width of shoulders, including crossroad median width; (c) the length based on the selected design vehicle; or (d) 40 ft.

2.2.7.4 Massachusetts (MassDOT Project Development & Design Guide, 2006)

Exhibit 6-29
Median Openings



Length of Median Opening (OL, feet)

Width of median (W, feet)	Passenger Car (P)		Single Unit Truck (SU)		Tractor/Trailer Truck (WB-50)	
	Semicircular	Bullet nose	Semicircular	Bullet nose	Semicircular	Bullet nose
4	76	76	96	96	146	122
6	74	60	94	76	144	115
8	72	53	92	68	142	110
10	70	47	90	62	140	105
12	68	43	88	58	138	100
14	66	40 min	86	53	136	96
16	64	40 min	84	50	134	92
20	60	40 min	80	44	130	85
24	56	40 min	76	40 min	126	78
28	52	40 min	72	40 min	122	73
32	48	40 min	68	40 min	118	67
36	44	40 min	64	40 min	114	62
40	40 min	40 min	60	40 min	100	57
50	40 min	40 min	50	40 min	95	48
60	40 min	40 min	40 min	40 min	90	40 min
70	40 min	40 min	40 min	40 min	80	40 min
80	40 min	40 min	40 min	40 min	70	40 min
100	40 min	40 min	40 min	40 min	50	40 min
110	40 min	40 min	40 min	40 min	40 min	40 min
120	40 min	40 min	40 min	40 min	40 min	40 min

Note: R1, R2 and NL determined by design vehicle turning paths.
Source: Adapted from A Policy on the Geometric Design of Streets and Highways, AASHTO, 2004. Chapter 9 Intersections

Source: Project Development & Design Guide, Massachusetts Highway Department, 2006.

Figure 2-11. Massachusetts DOT Guidelines on Raised Median and Median Nose Design.

2.2.7.5 Minnesota (MnDOT Roadway Design Manual, 2004)

The minimum median opening at any crossing should be 40 ft. A school bus shall be the design vehicle for the turning template method at minor roadways with an ADT less than 400 vpd. The same geometric design can be applied to median openings at crossroads with an ADT up to 1000 vpd, if a traffic study shows that the presence of large trucks is only a rare occurrence (5 or fewer per day).

Table 2-17. Lengths of Minimum Median Openings (Minnesota DOT standards).

Median width (ft)	12	14	16	18	20	22	24	26	28	30	greater than 30
Minimum median opening length (ft)	112	96	83	73	65	58	53	47	43	40	40 minimum

Source: Roadway Design Manual. Minnesota Department of Transportation, 2004

2.2.7.6 Nevada (NDOT Access Management System and Standards, 1999)

The turning template method shall be used based on a single unit truck (SUT) and occasional semi-trailer/trucks (WB-50) for perpendicular intersections. The length must be increased for skewed intersections and predominant semi-trailer/truck usage.

Table 2-18. Nevada DOT Standards for Minimal Lengths of Median Openings.

Median Width (ft)	Semicircular (ft)	Bullet Nose (ft)
4	96	96
6	94	76
8	92	68
10	N/A	62
12	N/A	58
14	N/A	53
16	N/A	50
20	N/A	44
24	N/A	40 (min.)
>24	N/A	40 (min.)

Source: Access Management System and Standards. Nevada Department of Transportation, July 1999

2.2.7.7 New Mexico (NMDOT State Access Management Manual, 2002)

Median openings should be designed to accommodate the largest design vehicle anticipated to use the opening. A median opening may be designed to permit U-turn movements. If the opening is too narrow to safely permit a U-turn, based upon storage and vehicle turning characteristics, U-turns should be addressed in design or restricted through signage. Sign use and placement requires the department approval.

2.2.7.8 Nebraska (Nebraska Department of Roads, Roadway Design Manual, 2006)

The median opening length should be a minimum of 72 ft. The turning templates for the appropriate design vehicle shall be used for the final opening width determination.

2.2.7.9 Utah (UDOT Roadway Design Manual, 2007)

Minimum length of median openings is 40 ft. To calculate the need, measure the crossroad pavement width plus 8 ft. Use that measurement if it is greater than the 40 ft minimum.

Do not use a 40-ft minimum length of opening without regard to the width of median or control radius except at very minor crossroads. The 40 ft minimum length of opening does not apply to openings for U-turns.

2.2.7.10 Wisconsin (WisDOT Facilities Development Manual, 2006)

The length of a median opening should be determined by the control radii for left-turn movements of vehicles turning into a driveway or making a U-turn. A 40-ft length should be used as a minimum length.

2.2.7.11 Summary for Existing Median Opening Length Guidelines

A number of states provide, in their roadway design manuals, the minimal median opening length, such as 40 ft proposed by Utah, Wisconsin, Massachusetts, Illinois, Minnesota, and Nevada, and 60 ft by California, and 72 ft by Nebraska.

Particularly, Massachusetts, Minnesota, and Nevada present look-up tables for minimum median openings as a function of median widths. It should be noticed that turning template with appropriate design vehicles should be used for the final decisions on both median width and opening length.

2.2.8 Median Turn Lane

A median turn lane is a critical element involved in raised median design. The lanes provide space for deceleration and storage of turning vehicles, which improve safety performance of the roadway. However, the requirements for the deceleration and storage often exceed the available length along the roadway centerline. This is particularly evident on arterial roadways with design speeds of 45 mph or greater with a high demand for left-turn movements.

Generally, most DOT roadway design manuals provide guidelines on turn lane design, although it may not be specified in the chapters associated with raised medians. It should be also noted that the placement of a median opening can depend on if a full length left-turn lane can be developed.

2.3 SAFETY IMPACTS OF RAISED MEDIANS

2.3.1 Comparison with Other Median Treatments

2.3.1.1 NCHRP Report 395 (by Bonneson and McCoy, 1997)

Table 2-19 compares the results of various existing models that predict safety performance with various median alternatives. An examination of this table indicates that:

- The models show generally consistent results for the relative safety of the three median alternatives, even though they predict somewhat different accident rates for any given set of conditions. The "undivided cross-section" treatment has the highest expected accident frequency over the range of traffic volumes. The model results indicated 30 to 35% accident reduction can be achieved by converting from an undivided cross section to either a TWLTL or nontraversable median).
- The raised median generally has the lowest predicted number of accidents. The main exceptions are the results predicted by the Harwood model that estimates fewer accidents for TWLTLs at all traffic levels.
- The Bowman model consistently predicts fewer accidents on roadways with raised medians than on TWLTLs, and fewer on roadways having a TWLTL than on undivided roadways. This accident model suggests that the number of predicted accidents increases in a linear manner from an ADT of 10,000 to 40,000 vpd, whereas the rate of increase begins to level off from 30,000 to 40,000 vpd.
- The average of the various models generally results in fewer accidents on roadways with raised medians than with TWLTLs.

Table 2-19. Comparison of Safety Model Results on Median Alternatives.

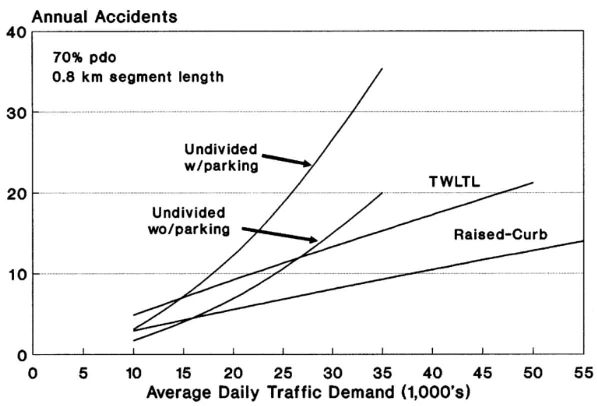
	Expected Accidents / Mile / Year											
ADT:	10,000			20,000			30,000			40,000		
Left-Turn Treatment:	Un-divided	TWLTL	Raised Median	Un-divided	TWLTL	Raised Median	Un-divided	TWLTL	Raised Median	Un-divided	TWLTL	Raised Median
Walton	na	37	na	na	58	na	na	78	na	na	98	na
McCoy	33	31	na	oor	52	na	oor	oor	na	oor	oor	na
Squires	na	ne	37	na	31	56	na	69	75	na	108	94
Parker	na	27	18	na	43	32	na	58	45	na	73	59
Chatterjee	na	55	46	na	90	81	na	125	116	na	oor	oor
Harwood	36	27	36	72	54	72	109	81	108	145	108	144
Bowman	63	43	25	126	85	50	190	128	75	253	170	101
Average Freq.	44	37	32	99	59	58	149	90	84	199	111	100
Std. Deviation	16	11	11	38	21	19	57	39	29	76	36	35
Coeff. of Variation (%)	36	30	34	38	36	33	38	43	35	38	32	35
Excluding Harwood Data												
Average Frequency	48	39	32	126	60	55	190	91	78	253	112	85
Std. Deviation	21	11	12	-	23	20	-	33	29	na	41	23
Coeff. of Variation (%)	44	28	38	na	38	36	-	36	37	na	37	27

Source: Bonneson and McCoy, NCHRP Report 395 (1997)

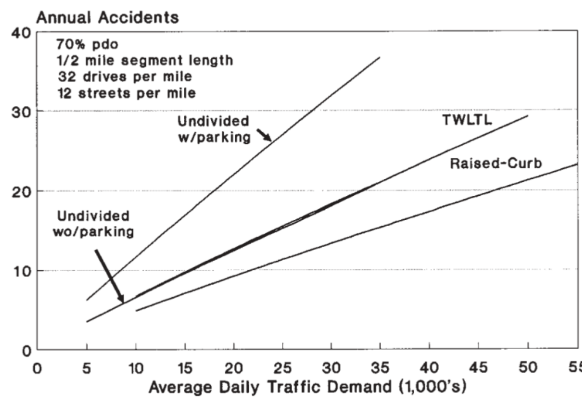
2.3.1.2 NCHRP Report 395 (by Bonneson and McCoy, 1997)

In this paper, the authors proposed a calibrated model to predict the expected annual accident frequency on arterial streets with a specified median treatment. Accident data, geometric data, and traffic data were collected from Phoenix, Arizona, and Omaha, Nebraska. In all, data on 189 street segments were identified and used. Accident data from each city were obtained for 1991, 1992, and 1993. There were 7,125 between-signal (or mid-signal) accidents on the study segments in this 3-year period.

The analysis indicates that the undivided cross section has a significantly higher accident frequency than the TWLTL or raised median treatments when parallel parking is allowed on the undivided street. When there is no parking allowed on either street, the difference between the undivided and the TWLTL treatments is generally small and is negligible for ADT demands of less than 25,000 vpd. The raised median treatments were associated with fewer accidents than the undivided cross section and TWLTL, especially for ADT demands in excess of 20,000 vpd.



(a) Residential and industrial areas



(b) Business and office areas

Source: Bonneson and McCoy, NCHRP Report 395 (1997)

Figure 2-12. Effect of Traffic Demand on Accident Frequency in Residential and Industrial Areas.

2.3.1.3 Self (2003)

In response to the objection from Charlotte citizens against the proposed median-divided road widening project, the Charlotte DOT initiated this study to better understand the safety effects of raised medians. Eleven arterials with 5 raised median-divided roads (7.9 miles in all) and 6 five-lane roads with TWLTL (7.1 miles in all) were selected. Three and a half years of crash data were collected and evaluated. Total crashes, fatalities, injury crashes, and crash types were compared between the two roadway designs.

It was found that on the raised median-divided roads, total crashes were 64% lower, the number of left-turn and angle collisions was 84% lower, and the number of debilitating injuries was 53% lower. The results indicated that median divided roadways are safer than five-lane roadways with TWLTL.

2.3.1.4 Gattis et al. (2005, 2010)

This report examined the effects of four major types of median treatments on roadway safety performance in Arkansas; they are (1) undivided roadways, (2) roadways with occasional left-turn lanes, (3) roadways with continuous TWLTL, and (4) roadways with raised or depressed medians. A total of 326 road segments were involved in this crash history-based study, and the crash reports available from Arkansas State Police were gathered for the years 1998 through 2002. These reports incorporate the crash severity and crash type information. The authors concluded that Type (2) median treatment had the highest mean crash rate, followed by Type (3) and then Type (1). The raised or depressed median had the lowest mean crash rate.

2.3.2 Major Contributing Factors to the Safety of Raised Median-Divided Roadways

2.3.2.1 Gattis et al. (2005, 2010)

As part of the research efforts, the results of a statistical analysis identified the following attributes regarding raised medians as significant contributing factors to roadway safety.

- Median Width: Among the segments with TWLTL and raised or depressed medians, the median widths ranged from 8 to 84 ft. For these segments, as the median width increased, both overall crash rate and fatal crash rates decreased. The impacts on the overall crash rate were statistically significant, while the impacts on the fatal crashes were not.
- Median Opening Density: For segments with raised or depressed medians, the median opening density had a statistically significant positive relationship with crash rate. As the median opening density increased, the crash rate increased significantly.

2.3.2.2 Hadi et al. (1995)

The study estimated the effects of roadway design attributes on crashes for Florida DOT. The divided roadway median categories involved were depressed, raised, crossover resistance, and TWLTL. Roadway categories included:

- Four-lane, non-freeway urban divided roadways with an average annual daily traffic (AADT) between 10,000 and 50,000 vpd.
- Four-lane, non-freeway urban undivided roadways with AADT between 5,000 and 40,000 vpd.

Crashes over a four-year period were categorized by severity and as mid-block (non-intersection) or intersection related. The study reported the following key findings related to raised medians:

- Median Type: For divided roadways, there was a significant relationship between the mid-block crash frequencies and the depressed, raised, and crossover resistance median types. The depressed median had the lowest crash frequency, followed by raised median, crossover resistance, and TWLTL.
- Median Width: For divided roadways, as the median width increased, the total and mid-block crash frequencies decreased significantly.
- Intersection Frequency: For both divided and undivided roadways, as the intersection frequency increased, the crash frequency increased significantly for both total and mid-block crashes.

2.3.2.3 NCHRP Report 395 (by Bonneson and McCoy, 1997)

The data used in this report were analyzed by analysis of variance (ANOVA) method to determine attributes that have significant effects on accident frequency. The analysis of the accident data indicates that median type and driveway density significantly correlate with accident frequency. In general, accidents are more frequent on street segments with higher traffic demands, higher driveway densities, or higher public street approach densities.

2.3.3 Full Median Opening vs. Directional Median Opening

2.3.3.1 Levinson et al. (Transportation Research Record, No. 1912, 2005)

The paper summarized the existing comparisons of safety performance between full and directional median openings.

Table 2-20. Safety Benefits between Full and Directional Median Openings.

Location	Treatment	Difference in Accident Rate (%)
Grand River Blvd, Detroit	Bi-directional (full) crossover replaced by directional crossover	-61
Detroit, Michigan	Bi-directional (full) crossover replaced by directional crossover	-15
Michigan	Bi-directional (full) crossover replaced by directional crossover on unsignalized roadway segment	-14
Michigan	Bi-directional (full) crossover replaced by directional crossover with nearby signalized intersections	-36 to 52

Source: Levinson et al., 2005.

Overall, the accident rate decreased after replacing full median openings with directional median openings.

2.3.3.2 Castronovo et al. (1995)

The safety effects of directional vs. full median openings in Michigan were analyzed for 123 boulevard segments containing 226 miles of highways. The segments were separated into those with either full or directional median openings, and then further stratified by the number of signals per segment. The results indicated that on divided highway sections without traffic signals, the directional U-turn median crossovers had a 14% higher accident rate than those with full median openings. However, as the density of traffic signals increased, divided highways with only directional median openings had significantly lower accident rates (-36% to -52%) compared to full median openings.

Table 2-21. Impacts of Signal Spacing and Directional Median Openings on Safety Performance.

Signals Per mile	Completely Full	Completely Directional	Percent Difference
0	420	480	+14
>0–1<	533	339	-36
1–3	1,685	856	-49
> 3	2,658	1,288	-52

Source: Castronovo et al., 1995.

2.3.4 Summary for Safety Impacts of Raised Medians

Collectively, it is widely accepted that raised medians, if properly designed, tend to bring a better safety experience over TWLTL or undivided median treatments. More importantly to this research project, the existing research has identified a series of contributing factors that may significantly affect the roadway safety performance when raised median treatments are used. These factors (Gattis et al., 2005, 2010; Hadi et al., 1995) include:

- Raised median design elements: median opening density, median width.
- Other factors: ADT demand, speed limit, adjacent land use, parallel parking allowed or not, travel lane width, outer shoulder width, presence of curb or shoulder.

Additionally, it can be generally concluded that roadway safety can be improved by replacing full median openings with directional median openings in typical urban roadway settings (Levinson et al., 2005; Castronovo et al., 1995).

2.4 OPERATIONAL CHARACTERISTICS OF RAISED MEDIANS

2.4.1 Operational Impacts of Raised Medians

2.4.1.1 NCHRP Report 395 (by Bonneson and McCoy, 1997)

Based on the HCM procedures for analyzing unsignalized and signalized intersections, a set of models were proposed to address the operational effects of midblock left-turn treatments on traffic flows. The direct impacts of median treatments considered by the proposed model include (a) through lane blockage, (b) through vehicle slow-down resulting from turns, and (c) through vehicle slow-down resulting from traffic volume. The proposed model is sensitive to access point density, left-turn treatment type, intersection signal timing, traffic volumes at each access point, frequency of left-turn bay (or lane) overflow, and platoons formed by upstream signals. The primary outputs are the major-street left-turn delay and through movement travel speed.

This study contributed a series of useful findings as follows:

- Raised-curb medians and TWLTLs experience similar delays to arterial drivers; an undivided cross section yields significantly higher delays than the two mentioned above.
- Any of the median treatment types can function without creating congestion within the major-street movements at ADT demands of 40,000 vpd or less.
- The performance of an unsignalized access point often is degraded by the close proximity of another intersection.

2.4.1.2 NCHRP Report 420 (1999)

Based on the analytical methods developed in NCHRP Report 395 (1997), an example was presented to illustrate a roadway carrying 32,500 vehicles per day, with left turns per 1,320-ft segment accounting for 10 percent of the daily traffic. For a TWLTL with 90 access points per mile, there would be 3,200 annual hours of delay. Conversion to a raised median with 30 driveways per mile would result in 3,100 annual hours of delay. Note that for an undivided cross section with 90 driveways per mile, there would be 8,000 annual hours of delay.

By examining the data presented in Table 2-22, it can be concluded that TWLTLs and raised medians may experience similar delay levels over a range of access density and ADT level.

Table 2-22. Annual Delay to Major Street Left-Turn and Through Vehicles.

Driveways/Mile	Undivided	TWLTL	Raised Median
	ADT 22,500		
30	2,200	1,300	1,300
60	2,200	1,400	1,400
90	2,200	1,400	1,400
	ADT 32,500		
30	7,100	3,000	3,100
60	7,800	3,200	3,500
90	8,000	3,200	3,400

Note: Assumes 10 percent Left Turns/1320-foot segment.

Source: NCHRP Report 395 (1997)

2.4.1.3 Eisele and Frawley (Transportation Research Record, No. 1931, 2005)

This paper aimed to assess combined impacts of raised medians and driveway consolidation on both traffic operations and safety performance. Micro-simulation in VISSIM was used for investigating the operational effects (e.g., on travel time, delay, and travel speed).

As model inputs, the data collected from the field include:

- Aerial photographs of the sites.
- Geometrics: lane configurations, lane widths, driveway widths, distance between driveways, and lengths of dedicated lanes.
- Traffic volumes on the main lanes, and turning movement counts at signalized intersections and driveways along the corridor.
- Signal timing.
- Travel time (floating-car method)—the criterion used to calibrate the VISSIM model.

Before and after studies were conducted to quantify the effects of the conversion from TWLTL to raised median. The driveway spacing, ADT level, and number of lanes in each direction vary with scenarios. In addition to real-world scenarios, theoretical corridors, hypothesized 1-mile corridors with typical land uses, were designed to supplement the simulation experiments. The typical land uses considered include drive-in bank, pharmacy-drugstore, fast food restaurant with a drive-through, and gas station.

The measures of effectiveness used were "different in number of conflict points" and "difference in travel time." Collectively, the micro-simulation experimental results indicated that the operational impacts on real-world scenarios are case-specific, with the travel times changing by -11% to 57% when replacing TWLTLs with raised medians. The theoretical corridor cases exhibited slightly lower speed results when replacing TWLTLs with raised medians, while the travel times increased by 1%–44%.

2.4.1.4 Venigalla and Margiotta (Transportation Research Record, No. 1356, 1992)

In this paper, TWLTLs and nontraversable medians (raised or depressed) on four-lane roads were compared for operational efficiency under identical traffic and development situations. Through TRAF-NETSIM model, delay and fuel consumption were obtained.

The treatment types were examined on a 2,640-foot street with access points at uniform spacing of 165 ft or 330 ft in this paper. Raised median openings were provided every 660 ft. Numerous unsignalized intersections with short left-turn bays were used to model the TWLTL. The raised median treatment was modeled by reassigning the left-turn volume at selected access points to the next downstream intersection having a median opening.

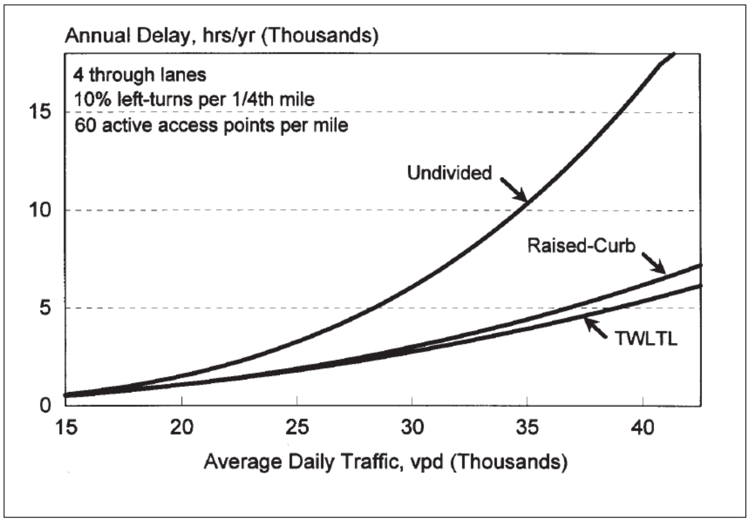
The comparison results suggested that driveway density, traffic volume, and the type of design (TWLTL or nontraversable medians) had significant effects on the performance measures such as total delay, fuel consumption, and delay to left-turning traffic and through traffic on the arterial. Total delay for the TWLTL was more than 32 percent lower than that for the nontraversable medians. When driveway density was low and traffic volume was low, there was no significant difference in total delay between TWLTLs and nontraversable medians. When driveway densities were higher, delay to left-turning traffic on the arterial was not significantly different between the two design alternatives. However, TWLTL design was found to cause less delay to through traffic and be more fuel efficient at all levels of driveway density and traffic volume.

2.4.1.5 Bonneson and McCoy (ITE Journal, 1998)

This paper studied the operational and safety impacts of alternative median treatments on urban and suburban arterials and described the cost-effective conditions where one treatment type can convert to another. The three alternative treatments that were considered include the raised-curb median, TWLTL, and undivided cross section.

The operational analysis indicated that the undivided cross section could result in significantly higher delay than either the raised-curb median or TWLTL, as shown in Figure 2-13. This result is due to the turbulence caused by left turns from the inside through lane.

When the left turn and through volume are high, the raised median treatment has slightly higher delay than the TWLTL treatment, as shown in Figure 2-13. This trend may be because of bay overflow for the raised median treatment under high-volume conditions, due to the fact that the left-turn bay length with a TWLTL is larger than the bay length with a raised median treatment.



Source: Bonneson and McCoy, ITE Journal, No. 3, 1998

Figure 2-13. Average Annual Delay to Major-Street Left-Turn and Through Vehicles.

2.4.2 Summary for Operational Impacts of Raised Medians

There are fewer existing research studies associated with operational impacts than safety impacts of raised medians. Collectively, the available research findings are consistent: it is not conclusive if a raised median presents a better or worse operational performance than a TWLTL, since the measures of effectiveness depend on a wide range of factors. Some representative findings are listed as follows:

- Any of the treatment types can function without creating congestion within the major-street movements at ADT demands of 40,000 vpd or less (NCHRP Report 395).
- Raised medians and TWLTLs experience similar delay levels to arterial drivers (NCHRP Report 395, Bonneson and McCoy 1998); undivided cross section yields significantly higher delays than the two mentioned above, particularly under high traffic volume conditions (NCHRP Reports 395 and 420). Raised median treatments may result in slightly lower speeds compared with the TWLTL treatments (Eisele and Frawley, 2005).
- The changes in travel times due to conversion from TWLTLs to raised medians can be case specific. A study performed by Venigalla and Margiotta (1992) showed that total delay for the TWLTL could be more than 32 percent lower than that for the raised medians when driveway density was high and traffic volume was heavy; otherwise, there was no significant difference in total delay between TWLTLs and raised medians.

2.5 ECONOMIC AND ACCESS IMPACTS OF RAISED MEDIANS

2.5.1 NCHRP Report 420 (1999)

The economic impact associated with installing a raised median (limiting certain access points to right turns only) will depend upon the following factors:

- The size and type of each abutting land use at the locations where left-turn access will be reduced.
- The reliance of each land use on pass-by traffic.
- The number of vehicles turning left into the activity or land use.
- The average purchase per vehicle (or person).
- Economic trends for the surrounding areas.

For any site where left-turn access is denied, the maximum adverse impacts can be represented by the product of (1) the number of left-turn entrants, and (2) the proportion of those turns that represent pass-by trips, given that the pass-by customers may give up the visit to the store due to the inconvenience associated with the restrictive raised medians. The loss would be equal to the average dollars per purchase multiplied by the number of trips involved. The proportion of the pass-by trips differs with different business types as Table 2-23 shows.

Table 2-23. Pass-by Customer Percentage by Various Land Uses.

Land Use	% Pass-by	Estimated Left Turns As % of Total Entering Traffic	
1 Gasoline Service Station Convenience Mart Small Retail < 50,000 sq. ft.	55	ADT 5,000 10,000 20,000 30,000 or more	% 43 40 30 15
2 Fast Food Restaurant with Drive Through Window Supermarkets Shopping Center 50,000 - 100,000 sq. ft.	45		
3 High Turnover sit-down restaurant	40		
4 Shopping Centers 250,000 - 500,000 sq. ft.	30		
5 Shopping Centers Over 500,000 sq. ft.	20		

Source: NCHRP Report 420, Impacts of Access Management Techniques, 1999

2.5.2 NCHRP Report 395 (by Bonneson and McCoy, 1997)

The overall objective of this study is to develop a quantitative methodology for evaluating alternative midblock left-turn treatments on urban and suburban arterials, where midblock left-turn defines the turning movement at the section of street between, but exclusive of, the bounding signalized intersections. The involved median treatments include raised median, flush median with TWLTL delineation, and undivided cross section. As part of this study, the access impacts of alternative midblock left-turn treatments have been quantified, and a more subjective approach was used based on a questionnaire survey.

The nature of the economic impact depends on two factors: (1) whether the treatment provides a storage area for the arterial left-turn movement, or (2) whether the treatment increases or decreases access to the adjacent property. The extent of the impact depends on whether the land use of the adjacent property is auto-related or non-auto-related.

According to the survey, the access concern is ranked much lower in importance than either service or quality. This finding indicates that businesses, particularly those non-auto-related, may be able to overcome the reduced accessibility if they offer good, reliable services.

Table 2-24. Ranking of Factors Influencing Customer's Decision.

Ranking of factors influencing customer's decision	**Reponses**	**Factor Rank**		
		High (8-10)	**Medium (4-7)**	**Low (1-3)**
a. Price	24	62%	38%	0%
b. Quality		87%	13%	0%
c. Service		96%	4%	0%
d. Hours Open		42%	50%	8%
e. Accessibility		46%	33%	21%

Source: Bonneson and McCoy, NCHRP Report 395, 1997.

An access impact index, AI, for the subject arterial with a specified midblock left-turn treatment was proposed as:

$$AI = \frac{\sum_{i=1}^{N_p} U_{i,(k,L)} m_i}{\sum_{i=1}^{N_p} m_i} \tag{4}$$

where $U_{i,(k,L)}$ = weighted utility index of property i based on a change in left-turn storage L and access k; m_i = mass of property i (i.e., number of driveways, frontage length, or square footage); and N_p = number of individual properties along both sides of subject arterial.

The index can be used to represent the relative impact of a change in left-turn treatment and property access on a business property. This impact is measured in terms of traffic conditions, property access, and business operations. The calibrated access impact model provides a method for predicting which alternative midblock left-turn treatment is best in terms of its impact on adjacent land uses, from a business owner's or manager's perspective. The associated findings in this report include the following:

- From a business owner's perspective, the undivided cross section should be avoided and median openings should be provided as frequently as possible if a raised-curb median treatment is provided.
- The survey indicated that business representatives believe that customers rank property accessibility much lower in importance than either service or product quality.

2.5.3 Eisele and Frawley (1999)

This report described the research effort to address the increasing concerns of the businesses and property owners on the effects of raised medians on their businesses and property values.

Two survey instruments were designed: in-person interview survey and mail-out survey. The in-person interview survey finally received 197 responses, while the mail-out survey got a total of 34 returns.

The results showed that from the business owners' standpoints, they generally ranked "accessibility to store" below customer service, product quality, and product price. The results also noted that some types of businesses valued accessibility higher than the average. For example, specialty retail located mid-block and at street intersections as well as sit-down restaurants at street intersections ranked accessibility as first, while fast-food restaurants ranked it as the third most important factor contributing to their business. A majority of customers indicated that while the raised median made access more difficult, they would still frequent the five businesses where customer surveys were performed.

In this study, surveys were conducted with both the current and the previous business owners who closed their business after the construction. The results showed that the current business owners believed that property values would have an increase of 7.7% after the raised median installation, while the perception of the previous business owners indicated that there would be a decrease, pessimistically.

The construction phase appears to have the most detrimental impacts on businesses. Suggestions to alleviate these impacts include 1) ensuring that adequate access is provided to businesses during construction, 2) reduced construction time, and 3) performing construction in smaller roadway segments.

2.5.4 Dixon et al. (2000)

TWLTLs and raised medians are two typical median treatment options. This paper summarizes three case studies on public perception on median treatment options. Data came from three roadway improvement projects at Shallowford Road, Sandy Plains Road, and Wade Green Road, in Cobb County in the Greater Atlanta Region. The authors studied the public comments on two types of median treatments during the public hearings. Generally, most residents prefer the raised medians, especially those landscaped medians, although many property owners (both commercial and residential) with direct access onto the subject roadway prefer the TWLTL alternative. The commercial property owners prefer the TWLTL treatment, because this option provides unlimited access to their properties.

2.5.5 Summary for Economic and Access Impacts of Raised Medians

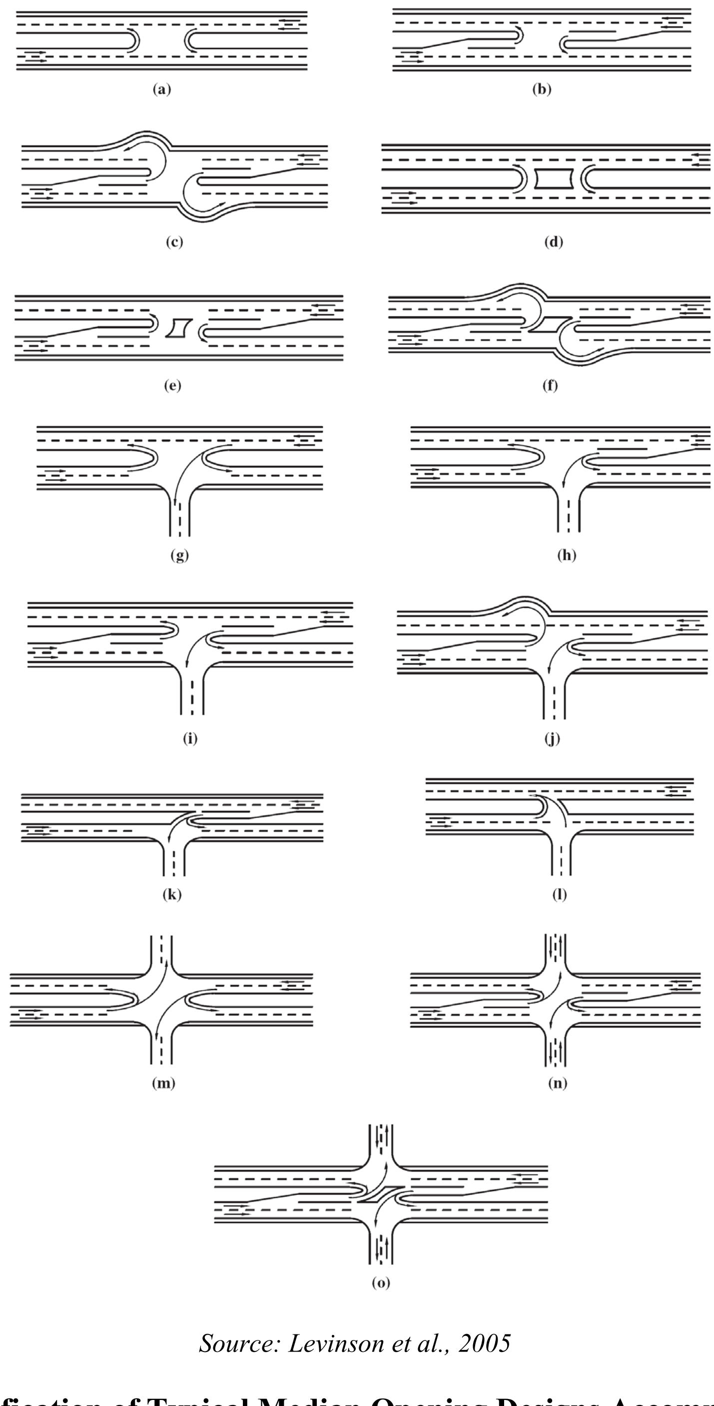
The existing research has proposed several equations to either measure the adverse impacts on business (NCHRP Report 420, 1999) or quantify the changes in accessibility to the established business along the roadways (NCHRP Report 395, 1997).

In light of the survey responses (Eisele and Frawley, 1999 and NCHRP Report 395, 1997), "accessibility to store" is commonly ranked below customer service, product quality, and product price. However, different types of land uses will be subject to different extents of impacts associated with raised medians, e.g., sit-down restaurants and gas stations may recognize accessibility as a key factor to their business. This generally explains why the commercial property owners prefer the TWLTL treatment, because this option provides unlimited access to their properties (Dixon et al., 2000).

2.6 OPERATIONAL AND SAFETY IMPACTS OF ALTERNATIVE MOVEMENTS

2.6.1 Typical U-Turn Median Opening Designs

2.6.1.1 Levinson et al. (Transportation Research Record, No. 1912, 2005)



Source: Levinson et al., 2005

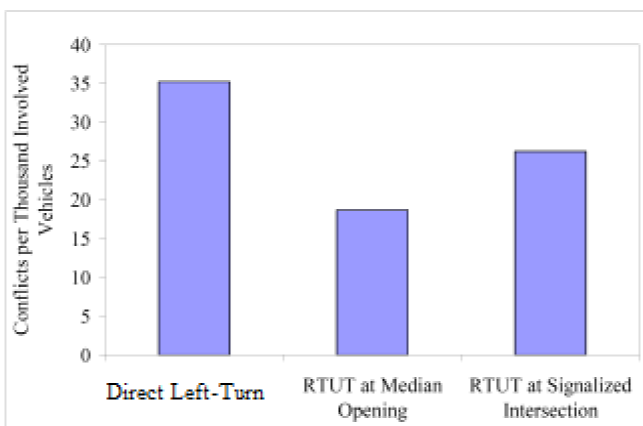
Figure 2-14. Classification of Typical Median Opening Designs Accommodating U-Turns.

This paper presents typical median opening designs accommodating U-turns, as shown in Figure 2-14. Overall, loons, as depicted in Figure 2-14 (c), (f), and (j), are good design practice for facilities with narrow medians. With the use of loons, design agencies can achieve the safety and operational benefits of a divided roadway with alternative movements, without incurring the significant cost of acquiring enough land along the entire corridor to provide sufficient median width.

2.6.2 Safety Impacts of Alternative Movements

2.6.2.1 Liu et al. (TRB 3rd Urban Street Symposium, 2007)

This paper described the research results on right turns followed by U-turns, which was defined as Type 1 (a) alternative movements in this report (see Figure 2-4 (a)). A traffic conflict study was performed based on more than 500 hours of traffic conflict data that were collected at sixteen selected sites. A total of 2,873 conflicts were observed and involved in the analysis. The field traffic conflict study indicates if U-turn location is provided at an unsignalized median opening, vehicles making an alternative movement will generate 47% fewer conflicts than those egress vehicles making direct left turns from a driveway. If a U-turn location is provided at a signalized intersection, as is shown in Figure 2-15, vehicles making an alternative movement will generate around 26% fewer conflicts than direct left turns from a driveway (Type 1 (b) alternative movements, see Figure 2-4 (b)).



Source: NCHRP Report 420, Impacts of Access Management Techniques

Figure 2-15. Conflict Rates for Direct Left Turns and RTUT Movements.

2.6.2.2 Levinson et al. (Transportation Research Record, No. 1912, 2005)

A comprehensive review on existing field studies was conducted in this paper. The results indicate that alternative movements that increase U-turn volumes at unsignalized median openings can be used safely and effectively. Analysis of accident data found that accidents related to U-turn and left-turn maneuvers at unsignalized median openings occurred infrequently. In urban arterial corridors, unsignalized median openings experienced an average of 0.41 U-turn or left-turn related accidents per median opening per year. In rural arterial corridors, unsignalized median openings experienced an average of 0.20 U-turn and left-turn accidents per median opening per year. On the basis of these limited accident frequencies, there is no evidence that U-turns at unsignalized median openings present a major safety concern.

Table 2-25. Accident Rate of Driveway Left Turns vs. Alternative Movements (Right Turn/U-Turn).

Location	**Treatment**	**Difference in Accident Rate (%)**
US-1, Florida	Driveway egress left turns replaced by right turn/U-turn	-22
Florida	Left turns replaced by Michigan U	-18

Note: Also presented in NCHRP Report 420, Impacts of Access Management Techniques, 1999

2.6.2.3 Carter et al. (2005)

The paper focused on operational and safety effects of U-turns at signalized intersections. As described by Figure 2-4 (b), U-turns at signalized intersections are part of the Type 1 (b) alternative movements. This paper analyzed safety effects of U-turns at signalized intersections on median-divided roadways.

Seventy-eight sites were studied in the 3-year study period, and only 13 sites had U-turn collisions. From the 13 sites with U-turn collisions, 41 U-turn collisions were noted. The most common U-turn collision observed was the angle collision (22 out of the 41 collisions), followed by rear-ends (11 of 41) and sideswipes (8 of 41). Overall, U-turns do not have the large negative effects at signalized intersections that many have assumed. The safety impact of Type 1 (b) alternative movements was considered to be minimal in this study.

2.6.2.4 Maki (1996)

The author evaluated the safety benefits of replacing existing conventional signalized intersections with the Michigan U concept (see Figure 2-5), on Grand River Avenue in Wayne County, Michigan. The 0.43-mile study segment on Grand River Avenue was from the east of Poinciana to west of Delaware Street. The analysis period for the before-after study was 1990 to 1995. The crossroads in all cases were undivided with crossroads intersecting at either 90 degrees or on a skew. Crash data for the years 1986–1990 were obtained for each site.
Table 2-26 shows the safety performance of the Michigan U turns in comparison to conventional intersections. The statistics showed a reduction of crash rates from 9% to 30% by using Michigan U to replace direct left turns.

Table 2-26. Safety Comparison of Michigan U and Conventional Intersections.

Dataset	Crash Type	Group	Mean Crash Rates (crashes/MVE)	Standard Deviation
Corridor	All	MUTIT (*Reduction*)	1.554 *(14%)*	0.784
		Conventional	1.806	0.679
Intersection Related	All	MUTIT (*Reduction*)	1.388 *(16%)*	0.593
		Conventional	1.644	0.643
	PDO	MUTIT (*Reduction*)	0.982 *(9%)*	0.392
		Conventional	1.077	0.467
	Injury	MUTIT (*Reduction*)	0.407 *(30%)*	0.266
		Conventional	0.58	0.252

Note: MUTIT=Median U-turn Intersection Treatment (typically referred to as "Michigan U"); PDO = Property Damage Only

2.6.2.5 Summary for Safety Impacts of Alternative Movements

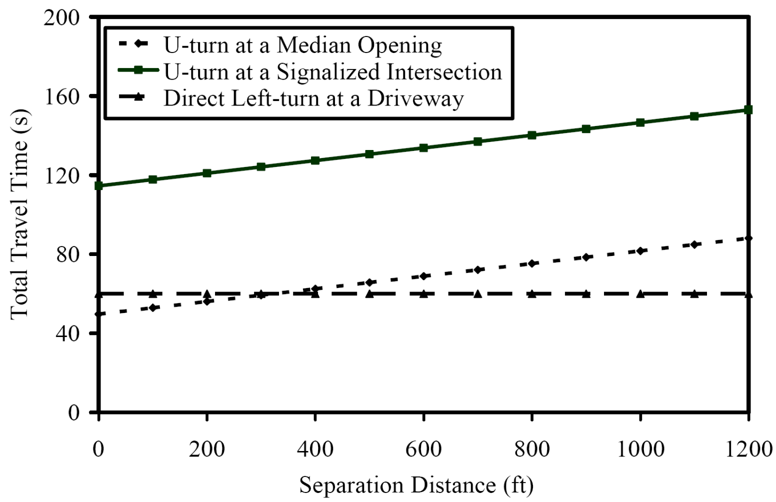
All the researches reviewed support that the use of alternative movements (Type 1 either (a) and (b) for egress left turns from minor streets) can potentially improve roadway safety performance compared to direct left turns. According to Carter et al. (2005), U-turns do not have the large negative effects at signalized intersections that many have assumed. The findings of Maki (1996) indicate that Michigan U (Type 2 alternative movements) will reduce the overall crash rates compared with the direct left turns.

It should be noted that there are relatively few research studies focusing on safety impacts of alternative movements, and the conclusions may be limited in scope and applicability.

2.6.3 Operational Features of Alternative Movements

2.6.3.1 Liu et al. (TRB 3rd Urban Street Symposium, 2007)

This paper discussed the potential operational effects of alternative movements as compared to direct egress left turns. In this study, separation distance defines the distance between the driveway and the downstream median opening. Out of the 179 roadway segments, the largest separation distance is 1150 ft, and more than 85% of the sites have a separation distance between 150 ft and 750 ft. Within this distance range, vehicles making right turns followed by U-turns at a downstream median opening will not result in much longer travel time than those making direct left turns at a driveway. The "travel time," which refers to the total time used for finishing the direct left turns or the counterpart through alternative movements, were collected from the field and presented in Figure 2-16.



Source: Liu et al., 2007

Figure 2-16. Travel Time Comparison for Different Driveway Left-Turn Alternatives.

Additionally, a total of 2,997 observations were used to compare vehicle delays. Each observation represents a vehicle delay data sample with a 15-min time interval collected in the field, as shown in Table 2-27. We can see that Type 1 (a) alternative movements, which place U-turns at unsignalized median openings, can reduce the average waiting delay. However, Type 1 (b) alternative movements, characterized by "U-turns at signalized intersections" may result in significant delay increases due to the signal delays.

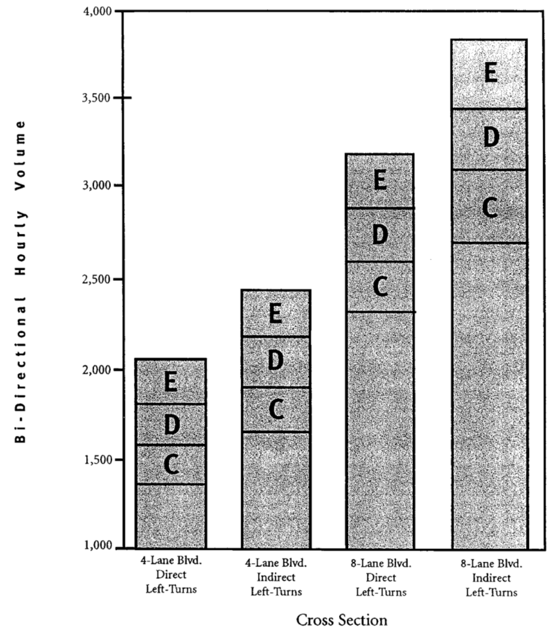
Table 2-27. Delay Comparison for Various Driveway Left-Turn Alternatives.

# Of Lanes	Traffic Volume (veh/hr)		Average Waiting Delay (s)		
	Driveway	Major Street	Signal U-turn	Median U-turn	Direct Left turn
4 lanes	0-50	1000-2000	77	15	18
		2000-3000	83	19	25
		3000-4000	83	24	37
	>= 50	1000-2000	76	18	19
		2000-3000	83	21	28
		3000-4000	83	30	37
6 to 8 lanes	0-50	2000-3000	77	18	27
		3000-4000	82	33	36
		4000-5000	92	35	48
	50-100	2000-3000	79	26	28
		3000-4000	97	35	50
		4000-5000	103	41	55
	>= 100	2000-3000	N/A	29	30
		3000-4000	N/A	36	57
		4000-5000	N/A	40	64

Source: Liu et al., 2007

2.6.3.2 Maki (1996)

The study conducted in Michigan claimed that arterial capacity (measured in bi-directional hourly service volume) will gain 20 to 50% by using U-turns as an alternative to all direct left turns, as Figure 2-17 shows.



Source: Maki, 2006

Figure 2-17. Divided Highways Level of Service Comparison, Michigan.

2.6.3.3 Koepke and Levinson (2003)

In this study, the traffic simulation based method was used for analyzing the impacts of Michigan "U" on the arterial capacity. It found that the use of Michigan "U" as an alternative to direct left turns at signalized intersections provided about 14 to 18% more capacity than the conventional dual left-turn lane designs, as shown in Table 2-28.

Table 2-28. Estimated Capacity Gains by Michigan "U" Compared to Dual Left-Turn Lanes.

Capacity	Arterial*	
	6 Lanes	8 Lanes
Artery Only 60-40 directional split vs. 45% through 15% left-turn 40% cross traffic	+14%	+18%
Arterial Plus Cross Street 60-40 directional split vs. 45% arterial through 15% arterial left-turn 30% cross street through 10% cross street left turn	+16%	+18%

Source: Koepke and Levinson, 2003

2.6.3.4 Carter et al. (2005)

The paper mainly focused on operational and safety effects of U-turns at signalized intersections. As described by Figure 2-4 (b), U-turns at signalized intersections are part of the Type 1 (b) alternative movements. As part of the research, this paper analyzed the effects of U-turns on left-turn saturation flow rate.

The field study covered 14 intersection approaches that have exclusive left-turn lanes with protected phasing. Each site was studied for an average of 7.5 h with an average of 400 eligible queues observed per site. Statistical analysis using regression and t-tests indicated that only the presence of protected right-turn overlap and the number of left-turn lanes affect the left-turn saturation flow rate.

The resulting regression equation indicates a 1.8% saturation flow rate loss for every 10% increase in average U-turn percentage, and an additional 1.5% loss per 10% U-turns if the U-turning movement is opposed by protected right-turn overlap from the cross street. This adjustment factor should be used for exclusive left-turn lanes with protected phasing. In the case of double left-turn lanes, this factor applies only to the inside left-turn lane because that is the only lane affected by U-turns. To analyze the left-turn-lane group as a whole, the analyst will need to calculate a weighted average adjustment factor by using known or assumed values of lane utilization.

2.6.3.5 Liu et al. (Transportation Research Record, No. 2130, 2009)

The primary objective of this paper is to estimate the potential capacity of U-turns at unsignalized median openings on six-lane streets. To achieve the research objective, data were collected at seven unsignalized median openings in the Tampa Bay area of Florida. In total, the research team recorded the rejected and accepted headways for 290 U-turning vehicles. The observed largest rejected headways vary from 0.5 to 7.9 s, with an average of 3.8 s. The accepted headways are from 4.5 to 33.3 s, with an average of 8.8 s. By using the maximum likelihood method and the Siegloch method, the research team estimated the critical headway and follow-up times for U-turns on six-lane streets.

Critical headway is defined as the minimum gap in the major street traffic stream that allows intersection entry for one minor-street vehicle. In HCM, follow-up time is defined as the time between the departure of one vehicle from the minor street and the departure of the next vehicle using the same major street headway, under the condition of continuous queuing on the minor street. Thus, follow-up time is the headway that defines the saturation flow rate for the approach. The estimated critical headways are presented in Table 2-29.

Table 2-29. Critical Headway and Follow-Up Times for Different Turning Movements.

Vehicle Movement	Base Follow-up Time, $t_{f,base}$ (s)	Base Critical, $t_{c,base}$ (s)
Left turn from major (4-lane)	2.2	4.1
U-turn (6-lane)	2.3	5.6
U-turn (4-lane, wide median)	2.5	6.4
U-turn (4-lane, narrow median)	3.1	6.9
Through traffic on minor (4-lane)	4.0	6.5
Left turn from minor (4-lane)	3.5	7.5

Source: Liu et al., 2009

With the estimated critical headway and follow-up time obtained, Harders' model was used for estimating the potential capacity of U-turns.

As compared to the four-lane situations, U-turns at median openings on six-lane streets have the following characteristics:

- Median openings on six-lane streets usually have large turning radii to accommodate U-turning vehicles. Accordingly, U-turning vehicles on six-lane streets have higher turning speeds than those on four-lane streets. Field observations show that U-turning drivers on six-lane streets have more confidence to accept smaller headways in the major street traffic stream.
- On six-lane streets, drivers have more options to select lanes on the major street to complete U-turn movements. Thus, it is more difficult to determine the conflicting traffic flow for U-turn movement on six-lane facilities.

2.6.3.6 Liu et al. (Transportation Research Record, No. 2027, 2007)

This research analyzed the headway acceptance characteristics of U-turning vehicles at unsignalized intersections on four-lane divided roadways. More specifically, the objectives of this study are twofold: (1) to estimate the critical headway for U-turning vehicles; 2) to evaluate the impact of median width on critical headway. For these purposes, the maximum likelihood method (Miller and Pretty, 1968) was used to estimate the critical headway for U-turning vehicles, while the binary logit model was used to evaluate the impact of median width on critical headway.

Based on the observation at 3 wide and 3 narrow median-divided roadways, the results of this study indicated that median width at a median opening significantly affects the critical headway. The critical headway at an unsignalized intersection with a wide (≥21 ft) median is 6.4 s, which is smaller than that (6.9 s) with a narrow (<21 ft) median. The estimated critical headways can be directly used in Harders' model to estimate the capacity of U-turn movement at unsignalized intersections.

2.6.3.7 Summary for Operational Impacts of Alternative Movements

The reviewed research on operational impacts of alternative movements is summarized in Table 2-30 as follows.

Table 2-30. Summary of Reviewed Research on Operational Impacts of Alternative Movements.

Operational Aspects Investigated	**Studies**	**Major Results**
Travel time and delays for Type 1 (a) alternative movement	Liu et al. (TRB 3rd Urban Street Symposium, 2007)	Positive results for alternative movement Type 1 (a)
Capacity for Type 1 (a) alternative movement	Maki (1996)	Positive results for alternative movement Type 1 (a)
Capacity for Type 2 alternative movement (Michigan U)	Koepke and Levinson (2003)	Positive results for alternative movement Type 1 (b) compared to dual left-turn lane designs
Effects of U-turns on the left-turn saturation flow rate at signalized intersection for Type 1 (b) alternative movement	Carter et al. (2005)	Left-turn saturation flow reduction factors were suggested
Critical headway and capacity of median U-turn	Liu et al. (Transportation Research Record, No. 2130, 2009)	Critical headway values and equations for estimating capacity were suggested
Critical headway of median U-turn	Liu et al. (Transportation Research Record, No. 2027, 2007)	Critical headway values were suggested

Source: Liu et al., 2007

2.7 SUMMARY

To develop a full context for this project, the state-of-the-art/practice associated with raised median and alternative movements has been documented and synthesized in this chapter. The chapter summarizes the basic concepts, definitions, and backgrounds; presents existing DOT design standards; and provides available research results on safety, operational, and economic impacts of raised medians and alternative movements. Collectively, the review on the prior research has further justified the critical needs for this research project, as the operational benefits of raised medians depend on a wide range of design and operations parameters.

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CHAPTER 3: SURVEY

To collect information, both within Texas and nationally, about current practices and implementations related to raised medians and alternative movements on arterial roadways, a survey of transportation professionals at state departments of transportation has been conducted. This chapter presents the results of the survey, which was conducted in such a manner as to capture responses nationally and within Texas.

3.1 SURVEY DESIGN

The survey of traffic engineers was developed to gather information about current practices and implementations of raised medians and alternative turning movements on arterials. The survey included questions related to both of these topics, some of which were open-ended and some multiple choice.

The survey began with an introduction to the project. It continued with a figure describing typical elements of raised median roadways and two examples of designs for operations where U-turns would be required.

Several questions regarding raised medians were presented. These questions attempted to illicit guidance as to when raised medians would be considered, where median openings would be placed, and preferred median widths. Additionally, questions were asked about factors affecting traffic safety and major obstacles expected to be encountered when installing new medians.

The second set of questions related to alternative movements. First was an open-ended question (for those with experience with alternative movements) regarding whether or not they have been effective and accomplished their goals. The survey moved on to asking about the types of impacts expected from implementing alternative movements and which median opening designs are used by the agencies represented by survey respondents.

The final questions were open-ended and asked how respondents would deal with issues of balancing the number of median openings with deceleration and storage requirements, how respondents would handle median treatments where median width would be limited in providing adequate U-turn radii, and what other challenges have been encountered in implementing raised medians or alternative movements. Additionally, the last question asked for suggestions for further reducing/minimizing overall delay at signalized intersections. The full survey document is available as Appendix A.

3.2 SURVEY RESULTS

The survey was conducted through a website beginning April 11, 2011, and was closed June 21, 2011. Invitations were emailed to traffic engineers at state transportation departments throughout the country. Invitations were also emailed by Rick Castaneda, project director, to relevant staff he identified within TxDOT.

Ultimately, 43 responses were received. Two surveys were submitted by the same individual, so they were considered to be one response, bringing the total to 42 unique respondents. Of those, seventeen were from within Texas and 25 were from states other than Texas. The responses outside of Texas came from the following states:

- Alabama.
- Arkansas (2).
- Arizona.
- Colorado.
- Connecticut.
- Florida.
- Georgia.
- Illinois.
- Iowa.
- Kansas (2).
- Louisiana.
- Maine.
- Michigan.
- Minnesota (2).
- Mississippi.
- Montana.
- New Hampshire.
- New Mexico.
- Ohio.
- South Dakota.
- Tennessee.
- Wyoming.

The following sections contain the results of each question. Note: Respondent spellings were deliberately not edited, in order to retain their real statements.

3.2.1 PART I: Questions Regarding Raised Medians

Eight questions were included in this portion of the survey.

Question 1: Under what circumstances would the installation of a raised median be an option for consideration?

In this question, respondents were asked to select which of the given circumstances would allow for consideration of a raised median and then specify the threshold or other guidance for those circumstances.

High ADT volume

Texas respondents who selected this choice (11 of 17, 64.7%) gave a wide range of requisite daily traffic volumes between 10,000 and 30,000 vehicles. Respondents from other states (11 of 25, 44.0%) tended toward the higher end of that range, with the range being between 20,000 and 30,000 vehicles.

Texas	Usually start looking at it as an option with traffic volumes in excess of 20,000
Texas	15000
Texas	20,000 ADT with two way left turn lane
Texas	Roadway Design Manual
Texas	>20,000
Texas	Usually should be considered when ADT exceeds 30,000
Texas	when ADT is above or approaching 20,000 vpd within 20 year horizon
Texas	10000 vpd
Texas	10,000ADT or greater
Texas	1500/lane
Texas	20,000 ADT - TxDOT Roadway Design Manual
Other	Construction/Reconstruct projects in Urban areas with projected ADT > 30,000
Other	Typically the threshold which requires multi-lane cross section.
Other	Case by case basis.
Other	30000
Other	Low speed or urban roadways
Other	above 30-35,000 ADT
Other	20,000 VPD + where possible
Other	6-lane urban facilities (for safety)
Other	Engineering Judgment.
Other	Design Speed less than or equal to 45 mph and, >18,000 ADT (Base Year) and, > 24,000 ADT (Design Year).
Other	No Specific Guidance, considered project by project.
No Response Given	20 (6 Texas, 14 Other)

High midblock left-turn volume

There was no consensus from respondents regarding the threshold for high midblock left-turn volumes to influence consideration for the installation of a median. If anything, the consensus may be that this is not a significant factor as responses came from only seven Texas respondents (41.2%) and nine respondents from outside Texas (36.0%).

Texas	Use the raised median in a worm configuration in an effort to reduce the number of potential conflict points.
Texas	300
Texas	Roadway Design Manual
Texas	50 vehicles per hour
Texas	If there is considerable left turn activity at many mid-block locations on the corridor in an uncontrolled manner, then raised medians should be considered.
Texas	100 vph
Texas	When combined with heavy through volumes - TxDOT Roadway design Manual
Other	Raised Medians may be considered
Other	Case by case basis.
Other	Low speed or urban roadways
Other	Access management - county guideline is 1/4 mile spacing.
Other	Raised median would get rid of the left turn and traffic can do right turn only
Other	Engineering Judgement.
Other	Design engineer's judgement
Other	If we have an opportunity to provide access to an intersection.
Other	No Specific Guidance, considered project by project.
No Response Given	26 (10 Texas, 16 Other)

Excessive number of driveways

Like the previous option, few respondents indicated that there were guidelines for an excessive number of driveways being cause for median installation (Texas: 4 of 17, 23.5%; Others: 9 of 25, 36.0%).

Texas	Less than 250' spacing.
Texas	30 drives per mile, both sides
Texas	case by case
Texas	10 or more entrances per mile - TxDOT Roadway Design Manual
Other	Raised Medians may be considered
Other	case-by-case basis
Other	Usually considered as an access management technique, either in conjunction with combining/eliminating drives, or instead of impacting drives for cost reasons.
Other	Case by case basis.
Other	No specific density threshold - based on crash history.
Other	Raised median can control and help access control
Other	Engineering Judgment.
Other	Another option would be to consider a TWLTL(flush median) depending upon all the factors associated with a location.
Other	No Specific Guidance, considered project by project.
No Response Given	29 (13 Texas, 16 Other)

High accident rate

A common theme among respondents regarding high accident rates was that the type of recurring accident would be significant in any discussions regarding median installation. Four of 17 (23.5%) Texas respondents and 14 of 25 (56.0%) respondents from other states gave responses to this option.

Texas	Consideration should be given to the types of accidents. We have found that left turns out of sidestreets and drives account for higher % of crashes on some corridors.
Texas	3-4 collisions per year
Texas	Threshold depends on accident types and severity.
Texas	Per cost/benefit analysis.
Other	Raised Medians may be considered
Other	if access management can be used to eliminate the high crash location.
Other	May be recommended as a result of a safety study where crashes could be reduced by installing a raised median.
Other	Case by case basis.
Other	No specific threshold. Performance measure goal to be at or below state average for county highways
Other	Boulevards has proven in Michigan as one of the safest design
Other	We develop a list of locations with higher than expected accident rates, based on statewide accident rate analysis. If a location showed up on that list, a raised median would be a candidate if the accidents were preventable with a raised median
Other	Above the critical rate for the segment type.
Other	Engineering Judgment.
Other	Design engineer's judgment
Other	This would be directly related to crashes that are addressable by a raised median.
Other	Desire to implement access management.
Other	No Specific Guidance, considered project by project.
Other	We would consider corridors with accident rates double or more the average rate for that class of highway. However, along with that we must also have patterns of mid block collisions susceptible to correction with medians.
No Response Given	24 (14 Texas, 10 Other)

High design speed

There were very few responses to this option, possibly indicating that high design speed would not normally be something to spur discussion of raised median installation. Three of 17 (17.6%) Texas respondents and 8 of 25 (32.0%) respondents from other places provided guidance, which varied from indicating that high speed could be a factor to indicating that raised medians would only be appropriate for low-speed roadways.

Texas	50-55 MPH
Texas	>40mph
Texas	Would look more at operating speeds. Design speed may change if medians are introduced.
Other	Case by case basis.
Other	45 mph or higher
Other	Not a threshold, but as a rule of thumb, roads with design speeds of 50MPH or higher would be a candidate for a raised median.
Other	Engineering Judgement.
Other	Design Speed less than or equal to 55 mph, 24-ft wide raised median is an option.
Other	Raised median not appropriate for speeds of 45 mph or greater. Depressed medians could be used in this case.
Other	No Specific Guidance, considered project by project.
Other	If the accident rate and number of mid block collisions is only slightly above average a high design speed may also be considered.
No Response Given	31 (14 Texas, 17 Other)

Others

Respondents provided a number of circumstances where raised medians may be considered, including for six-lane roadways, areas where pedestrian activity may be significant, and areas with poor sight distances on approaches to unsignalized intersections and driveways.

Texas	1. Corridor is designated as a high mobility corridor. 2. Six lane roadways, especially with a continuous left turn lane.
Texas	High volume urban intersection, particularly in business/shopping areas
Texas	Would a raised median induce a significant number of "U" turn movements? Is there adequate roadway space to make a "U" Turn? What is the percentage of large trucks making "U" Turns? Are we really solving the problem? What is the adjacent land use internal cross-access issues?
Texas	Presence of pedestrians in areas which development patterns have changed over the years. Presence of transit lines which may have been added to the corridor over the years.
Texas	poor sight distance on approach to an unsignalized intersection or driveway. When driveways are located within close proximity to a major intersection (such as a freeway frontage road) in order to prevent left turns # of lanes. Raised would be highly considered on all 4 lane urban arterials. Even stronger consideration would be given on a 6 lane facility.
Texas	close proximity of left-turning roadway to the cross street. < 250 ft.
Other	considered on a case by case basis, depending on available right of way, traffic volumes, turning movement conflicts and crash history.
Other	Complete Streets type projects often utilize medians, sometimes for vegetation placement (aesthetics), to allow for pedestrian staged crossings of streets, or for perceived traffic calming.
Other	functional classification
Other	Multi - Lane Highways (4 or 6 lane) will have medians.
Other	Raised median can help pedestrians
Other	Where a raised median might be useful as a pedestrian refuge area, it might be used, but generally it is preferable to cross pedestrians at signalized locations.
Other	Engineering Judgment.
Other	The type of channelization (flush or raised) is determined on a case-by-case evaluation.
Other	Required on any multi lane roadway
No Response Given	27 (11 Texas, 16 Other)

Question 2: Under what circumstances will your agency consider the placement of a new median opening? Select all that are applicable.

Surveyed individuals were presented with four common conditions where median openings may be considered and asked to select any that were used by their respective agencies. They were then given the option of submitting any other conditions that may apply.

On divided highways at all public roads and major traffic generators

A majority of all respondents (58.8% in Texas, 72.0% elsewhere) selected this choice.

	Selected	Unselected	Total
Texas	10	7	17
Others	18	7	25
Total	28	14	42

Where a full length left-turn lane can be developed

A majority of Texas respondents (58.8%) and a slight minority of out-of-state respondents (48.0%) chose this option.

	Selected	Unselected	Total
Texas	10	7	17
Others	12	13	25
Total	22	20	42

Where median openings are proven necessary by traffic impact study

A clear majority of all respondents (94.1% in Texas, 88.0% elsewhere) selected this option.

	Selected	Unselected	Total
Texas	16	1	17
Others	22	3	25
Total	38	4	42

When the original road construction failed to meet required opening spacing criteria

Though Texas respondents were unlikely to choose this option (only 13.3% did), a slight majority of out-of-state respondents did select this choice (52.0%).

	Selected	Unselected	Total
Texas	2	15	17
Others	13	12	25
Total	15	27	42

Others. Please specify.

Several respondents mentioned public/political pressure being involved in the positioning of median openings.

Texas	If senator calls and requests it.
Texas	Need to consider the total access to the major generator. Need to find a way to provide safe access and provide safety to the highway traveling public.
Texas	If you are installing medians on a corridor, the above are general guidelines, you must also consider delivery truck access, whether streets have back access to other thoroughfares, and balance access with design guidelines. Sometimes lesser standards must be allowed to provide reasonable access to local businesses.
Texas	Prior to considerable development to try to allow land planning to develop around the raised median and openings.
Other	Political pressure. The above are places we would consider. This is not to infer a median opening is provided in each situation.
Other	Median openings in general would be considered if necessary turn lane lengths could be provided, a traffic study warrants full movement, and a median break meets spacing requirements of the Ohio Access Management Manual. http://www.dot.state.oh.us/Divisions/ProdMgt/Roadway/AccessManagement/Pages/default.aspx
Other	Public pressure/economic development accompanied by a traffic impact study.
Other	At pre-determined locations thru access management plan developed with communities. At 1/4 mile spacing generally.
Other	where needed for emergency vehicle access
Other	According to guidelines set in an access management plan developed by the AHTD, City, and MPO.
Other	Engineering Judgment.
Other	Again median openings will be determined on a case-by-case basis. Just because it is a public road does not guarantee that a median opening will be provided.
No Response Given	30 (13 Texas, 17 Other)

Question 3: Does your agency limit the spacing of median openings in any way? Has your agency noticed any operational effects related to median opening spacing?

This was a free-response question. Aside from one Texas respondent and one respondent from elsewhere, all other respondents gave answers to this question. Most responses indicate some level of limitations in the spacing of median openings, though the spacing requirements vary largely.

Texas	Does your agency limit the spacing of median openings in any way? Only to provide adequate left turn lane storage and adequate decel lengths. Has your agency noticed any operational effects related to median opening spacing? Definitely, increase in median openings increases conflict points decreasing operational efficiency.
Texas	We try to comply with the spacing in the Roadway Design Manual.
Texas	No.
Texas	0.25 mi. for full openings in a suburban area with the possibility of some directional turns in between .
Texas	In our TxDOT district, we used a guideline of 1/2 mile spacing between full openings and 1/4 mile spacing for directional openings. The closer the spacing the more operational issues are encountered.
Texas	Yes.
Texas	Yes. We have found it improves thru traffic movement in areas of high ADT and high midblock left turn potential.
Texas	Yes, to street or highway intersections. Thru traffic speed is lowered due to turning (crossing) vehicles
Texas	We started at the desirable and then apply based on the current land use, that I can not change.
Texas	See comment above in No. 2. This is usually a balance between access, aesthetics, local traffic patterns, and proximity to major thoroughfares where you must get long left turn storage bays at signals.
Texas	When possible 1/4 mile spacing assists with forcing signals to have this desirable spacing. Otherwise it is based on an operational analysis/case by case.
Texas	yes. a reduction is the accident rate has been observed and reported
Texas	YES
Texas	Yes. Spacing is held to a minimum distance. More decel/storage space is required.
Texas	Try to use 1/4 min
Texas	Yes. The TxDOT Roadway Design Manual provides minimum and maximum spacing guidelines. If openings are signalized, then minimum spacing requirements between signals must also be met.
Other	Spacing of median openings may be limited. Excessive median openings has a negative effect on Safety and LOS.
Other	We do not have any formal policy regarding median openings.
Other	We limit median openings. Effects? the less median openings the better operations of the corridor and less crashes.
Other	Yes, State access manual defines the spacing.
Other	Median opening spacing is established by the Ohio Access Management Manual based on the roadway's access category. http://www.dot.state.oh.us/Divisions/ProdMgt/Roadway/ AccessManagement/Pages/default.aspx
Other	Yes, 1760' in rural areas, 880' in urban areas. Yes, absolutely. too many conflict points if too many median openings
Other	no
Other	Yes, preferably 660 ft., but subject to a traffic impact study. From observation, frequently spaced median openings tend to negate the purpose of the median.
Other	Yes. No.
Other	Yes. Guidance is place for spacing median openings on divided highways to provide uniform spacing and to control having an excessive number of openings.

Other	urban - quarter mile spacing minimum rural - half mile spacing minimum
Other	Yes. Generally, when present, we allow median openings at 1/4 mile spacing. This is the goal. In practice this is often not met - however we strive to get as close as possible. Medians have had an overall positive effect on operations: Better signal timing and progression Fewer Crashes Higher Capacity - less friction Improved pedestrian safety - they know where to cross highway
Other	Our guide calls for the opening to be 600 ft away from signalized intersection in urban area and twice that in rural setting
Other	Median openings are limited to the extent practical, but no spacing limitations have been set. It is generally accepted that the more openings, the more chances for accidents and operational concerns, but this has not been documented with a formal study, to my knowledge.
Other	Our guidelines provide minimum distances for rural and urban. Guidelines only - not policy.
Other	urban - quarter mile spacing minimum rural - half mile spacing minimum
Other	The spacing between median openings at intersections shall not be less than 330 feet.
Other	Every 1300'
Other	Yes; GDOT has adopted 1000-ft as the preferred minimum spacing between median openings in urban areas, and 1320-ft as the preferred minimum spacing between median openings in rural areas. In urban areas, median openings may be spaced less than 1000-ft, and greater than 660-ft if it can be demonstrated that left turning volumes are nominal. Yes, refer to the GDOT Design Policy Manual, Chapter 7.3 at internet address: http://www.dot.ga.gov/doingbusiness/PoliciesManuals/roads/DesignPolicy/GDOT-DPM-Chap07.pdf
Other	In no case may the number of median openings exceed three per 1000 feet. If openings are too closely spaced, storage for turn lanes can be too short and may have queue spillback in the through travel lanes.
Other	At minimum, access is allowed to be 0.25 mile. Ideally, we would like greater spacing.
Other	Access is controlled on some facilities according to state law.
Other	We have had a policy in place since 2008 limiting full access median openings on new construction to 1/2 mile.
Other	We do not limit the spacing of openings at this time. openings are considered on a case by case basis.
No Response Given	2 (1 Texas, 1 Other)

Question 4: What guidelines and standards are in place for your agency regarding arterial median width? Is preference given to designing medians wide enough to allow for vehicle refuge between the travelways?

This was also a free-response question and drew responses from all respondents, except for one out-of-state individual. The responses given display a wide range of median width standards, and there was no consensus regarding preference for the provision of sufficient width to allow for vehicle refuge.

Texas	What guidelines and standards are in place for your agency regarding arterial median width? Standard median widths are identified in the TxDOT roadway design manual in addition there have been several studies on offset left-turn sight distance which affect operations. Is preference given to designing medians wide enough to allow for vehicle refuge between the travelways? No the median is should not be used as a refuge between travelways.
Texas	Roadway Design Manual. Yes.
Texas	Roadway Design Manual and AASHTO Green Book
Texas	For full openings at unsignalized locations, it would be critical to have enough room to allow for refuge. On a signalized intersection, it may not be as critical, since they will be utilizing their specific signal phase to get across. As far as traffic parallel to the median, left turn bays with adequate queuing capacity will suffice.
Texas	TxDOT Roadway Design Manual states 16' median width is desirable. On depressed median facilities we ensure that they are wide enough to accommodate vehicle storage.
Texas	Unknown. Sometimes.
Texas	It is desirable to provide medians wide enough for vehicle refuge.
Texas	16' minimum desirable, to allow refuge area for vehicles and pedestrians
Texas	20 ft. desired. No.
Texas	We use a minimum of 14 to 16 feet. Usually that is all we can reasonable provide given existing development.
Texas	Yes, usually 14 feet minimum.
Texas	Desirably raised medians are 14' to allow for a turn lane at intersections providing refuge for vehicles.
Texas	TxDOT Roadway Design Manual. Medians are designed greater than 30' if ROW allows
Texas	Standard turning Radius
Texas	14' urban
Texas	Design Manual
Texas	TxDOT Roadway Design Manual provides guidance regarding median widths. Widths should allow for refuge of pedestrians in the median. Normal widths usually allow refuge for turning traffic but not crossing traffic. Arterial median width normally based upon proposed Right of Way requirements.
Other	Per SDDOT Road Design Manual in... Chapter 7 - Cross Sections at http://www.sddot.com/pe/roaddesign/docs/rdmanual/rdmch07.pdf Chapter 12 - Intersections at http://www.sddot.com/pe/roaddesign/docs/rdmanual/rdmch12.pdf
Other	We have very few examples, or even possible locations, so we have not adopted any formal policies.
Other	For urban arterials, we use 30 foot, 22 foot, or 18 foot barrier medians. 16 foot mountable medians. 10 foot to 14 foot flush medians. If you mean by "refuge", perpendicular to traffic, only the 30 foot offers a suitable refuge.
Other	AASHTO and state access manual. Yes
Other	Median width is established in the Ohio Location and Design Manual, Section 304.3.2 http://www.dot.state.oh.us/Divisions/ProdMgt/Roadway/roadwaystandards/Pages/locationanddesignmanuals.aspx Also considered is left turn lane offset described in Section 401.6, Approach Lanes
Other	None at present
Other	At least 4 feet for raised

Other	Minimum of 5 ft. back to back of curb and gutter is preferable. In urban areas, we do not typically allow for vehicle refuge.
Other	Yes. Provide positive offset for left turners.
Other	TDOT allows varied median widths due to ROW considerations. Forty-eight foot medians are preferred on divided highways.
Other	Our standard is 15', 50' and 60'.
Other	Goal for minimum width (at the intersection) is 6 feet. This is based on state of Minnesota standard width necessary for a pedestrian refuge. We have gone narrower in some situations. County minimum is 4 feet.
Other	The median width depends on the vehicles you designing for, to allow for indirect left turn.
Other	We follow AASHTO guidelines to the extent possible. Vehicle refuge is typically not a consideration.
Other	In Minnesota the State Aid Rules for Operation provide a minimum width. We determine median width based upon roadway lane configurations and corridor width.
Other	15' raised medians 50' and 60' depresses medians
Other	Engineering Judgment.
Other	No guidelines. ALDOT tries to provide medians wide enough to allow vehicle refuge on rural arterials but not necessarily on urban arterials.
Other	GDOT guidelines on the subject are located in Chapter 6.12 of the GDOT DPM, at internet address: http://www.dot.ga.gov/doingbusiness/PoliciesManuals/roads/DesignPolicy/GDOT-DPM-Chap06.pdf On planned rural and suburban roadways with a significant number of un-signalized intersections, preference is given to designing medians wide enough to allow for vehicle refuge.
Other	The median nose has a minimum width of 4' from face of curb to face of curb. The median width has a minimum of 16' from face of curb to face of curb with a 2' shy distance. This is ideal conditions but these are not always met.
Other	I believe we want medians to be at least 12 ft in width. But we can go narrower depending on the situation.
Other	No Specific Guidance, considered project by project.
Other	For new construction we have a set of design standards which can be located on our website. Retro fits are more difficult and its a road by road decision.
Other	We strive for a 4 foot minimum. In the Denver metro area we have very few arterials with medians large enough to provide a vehicle refuge.,
No Response Given	1 (0 Texas, 1 Other)

Question 5: Does your agency have a preference regarding full median openings versus directional median openings? If so, why?

Most agencies seem to prefer full median openings over directional openings, unless there exist specific circumstances for which directional openings may be helpful.

Texas	No real preference simply based on operations. Although much easier to design directional medians initially than to retrofit facility later.
Texas	No preference.
Texas	Full median openings justified by cross street volumes and left turning volumes are the most important to address, but providing some directional turns to minimize intersection congestion at those full opening can help with the efficiency and safety.
Texas	Full median openings should be placed desirably at 1/2 mile spacing and located at major public roadways and major traffic generators. Directional median openings should be located at approximately mid-point between full openings and desirably located at public roadways or significant traffic generators.
Texas	Haven't used directional median openings.
Texas	Not that I am currently aware of.
Texas	Don't know.
Texas	No.
Texas	We have used directional median openings a "T" intersections and where cross-access is being denied because of the proximity to an intersection.
Texas	We usually do not implement directional median openings on on corridors with only 4 lanes total (2 in each direction), because the resulting U turns can not be accomplished well without more than 2 lanes.
Texas	This is usually case by case. If the openings are required to be more closely spaced due to existing development the directional median openings are typically used to prohibit certain movements such as a "left out". Sometimes the directional openings are used where an intersection or major driveway T-s into a roadway, the directional opening would be constructed to prevent a full directional intersection from going in on the other side.
Texas	The use of full median openings are preferred, however their use is discouraged when ADT's and turning movements begin creating detrimental operational effects.
Texas	Yes. Conflicts in turning vehicle movements.
Texas	no
Texas	Dependent upon situational characteristics of roadways and access locations.
Other	When openings are provide typically full movements are provided. Directional medians may be provided on a case by case situation.
Other	No, but our limited experience is with full median openings.
Other	If your meaning of directional opening is prohibiting some movements, this is usually provided where we preferred total closure, but were forced to provide some access due to political pressure.
Other	No, depends of the intend of the design.
Other	Directional median openings are used rarely, and only when a specific reason such as restricting left turns out are desired.
Other	Yes, to cut down on the conflicts associated with mainline turning traffic and side-road traffic crossing the median
Other	no
Other	Generally prefer full openings, but both may be acceptable, depending on the traffic movements.
Other	Yes. We don't have directional openings because we have very few medians.
Other	Most median openings designed and constructed are full median openings. Directional median openings are specified for sight specific locations.
Other	no
Other	Full median openings are provided at 1/4 mile spacing. We have used directional median openings in various scenarios - when appropriate. We consider directional

	median openings a tool to be used when other options (no median opening) cannot be achieved.
Other	In the state of Michigan we only allow for directional median opening.
Other	Preference would be to allow left turns from the arterial road but prevent left turns from the side street, for safety and operational reasons, however typically median openings are full openings.
Other	Preference is for full median opening because we experience a degree of violation by motorists who feel shortchanged by the lack of full movement options.
Other	No.
Other	No.
Other	No preference
Other	GDOT prefers to limit the number of median openings to public roads and major traffic generators, so preference is given to full median opening design. Directional median openings are considered on a case-by-case basis when turning volumes warrant an opening but adequate dimensions for weaving, taper lengths, deceleration lengths, and storage lengths may not be available to satisfy the traffic volumes.
Other	We use both full median openings and directional median openings. This is determined based on the needs of the highway corridor.
Other	Case by case and depends on what we are trying to accomplish. We have installed medians which restrict side street left and through but allows all other movements.
Other	We have done very few directional openings at this time. There is often public opinion against this type of access.
Other	yes Directional medians are preferred due to the safety and capacity benefits.
Other	If accident patterns suggest a directional median opening can be done safely then we strive for this. Directional openings can be very affective in reducing accidents.
No Response Given	3 (2 Texas, 1 Other)

Question 6: Are median-specific guidelines in place regarding turn lanes, or are the same turn-lane guidelines used for roadways with or without medians? If there are median-specific guidelines, how do they differ?

In general, respondents indicated that the guidelines are the same (or that there are no median-specific guidelines), but it is important to exercise care in designing the length of a turn lane adjacent to a median, as modifying the concrete median is not a simple process.

Texas	Are median-specific guidelines in place regarding turn lanes, or are the same turn-lane guidelines used for roadways with or without medians? If there are median-specific guidelines, how do they differ?
Texas	Same guidelines.
Texas	N/A
Texas	Some requirements would be the same, such as justification for protected movements especially at signalized intersections. Continuous left turn lanes may work to a point until the number of driveways and ADT on the road makes it less efficient and safe. At that point a concrete median would be more justifiable.
Texas	No median-specific guidelines for turn-lane lanes on raised median facilities.
Texas	Same
Texas	Guidelines appear to be the same with or without.
Texas	Refer to Design Manual.
Texas	No
Texas	They are basically the same, but more care must be given to designing the length of the turn lane with a raised median due to the lack of flexibility as compared to just restriping if changes in travel patterns/traffic increases occur for instance.
Texas	Same
Texas	No
Texas	Same guidelines.
Other	The same. Refer to SDDOT RDM Chapter 12 - Intersections
Other	No median-specific guidelines.
Other	For the narrower medians we use a slotted left turn design. As the median widens we bury the LTL to off-set the opposing LTL's for sight distance.
Other	No
Other	Turn lane design is not changed by use of raised medians. If insufficient space remains for raised medians, then they are not used.
Other	No
Other	same other than 1 foot curb offset needed for lanes adjacent to median
Other	Same used for roadways with or without medians.
Other	No.
Other	Guidelines are in place for placement of turn lanes for signalized intersections with medians.
Other	there is no difference. We design all left turn lanes parallel with o' offset.
Other	Same general guidelines. Many 4-lane highways have dual left turn lanes - this adds additional taper length. Typical storage length = 300 feet Typical taper length - 15:1
Other	It is the same.
Other	Providing adequate storage and taper lengths is more critical with raised medians. With undivided roads, drivers can usually drive over the painted centerline if the left turn lane is full, without significantly affecting through traffic in either direction. With raised medians, a full left turn lane means additional vehicles are queued in the through lanes.
Other	Median is desired over merely painted separation. Where paint is used, the distances tend to be shorter because of the urban condition. At the higher speeds we try to separate traffic.
Other	Same turn-lane guidelines are used for roadways with or without medians.
Other	Yes. All median openings shall be designated to include median storage lanes for both directions of travel.
Other	ALDOT does not have median specific guidelines for turn lanes.
Other	Yes; GDOT has guidelines specific to the design of turn lanes along planned multi-lane

	divided highways. Refer to Chapter 7.2.3. and 7.3 of the GDOT DPM at internet address: http://www.dot.ga.gov/doingbusiness/PoliciesManuals/roads/DesignPolicy/GDOT-DPM-Chap07.pdf
Other	If we have width of the median we will provide a turn lane if feasible regardless of volume. If the roadway needs to be widened to provide a turn lane we use the same guidelines with or without medians.
Other	Our District personnel prefer not to have raised medians due to maintenance. We like raised medians for access management purposes.
Other	No specific guidance.
Other	All new median openings shall have turn lanes. Other roadways are dependent upon volume.
Other	We use the same guidelines
No Response Given	5 (4 Texas, 1 Other)

Question 7: Which of the following factors do you think would significantly affect traffic safety performance of raised medians? Select all that are applicable.

In this question, surveyed individuals were presented with seven choices for factors that may affect the traffic safety performance of raised medians. They were asked to select any that they thought were relevant to traffic safety on these types of roadways. Additionally, they had an opportunity to suggest any factors not listed.

<u>Median opening density</u>

Most respondents in Texas (88.2%) and elsewhere (92.0%) believed that median opening density affected traffic safety.

	Selected	Unselected	Total
Texas	15	2	17
Others	23	2	25
Total	38	4	42

<u>Median width</u>

A slight majority of Texas respondents (52.9%) and a greater majority of respondents elsewhere (60.0%) believe median width to be a significant factor.

	Selected	Unselected	Total
Texas	9	8	17
Others	15	10	25
Total	24	18	42

ADT demand

All Texas respondents and most elsewhere (72.0%) felt that traffic volumes impact the traffic safety performance of raised medians.

	Selected	Unselected	Total
Texas	17	0	17
Others	18	7	25
Total	35	7	42

Speed limit

Simple majorities in both Texas (58.8%) and elsewhere (64.0%) selected speed limit as a significant factor.

	Selected	Unselected	Total
Texas	10	7	17
Others	16	9	25
Total	26	16	42

Adjacent land use

A large majority of Texas respondents (70.6%) believed adjacent land use to be a factor in the traffic safety performance of raised medians, while only a slight majority (56.0%) elsewhere agreed.

	Selected	Unselected	Total
Texas	12	5	17
Others	14	11	25
Total	26	16	42

Travel lane number and width

A majority of respondents in each group (70.6% in Texas, 60.0% elsewhere) agreed that the number of lanes and widths of those lanes impacted the safety of roads with raised medians.

	Selected	Unselected	Total
Texas	12	5	17
Others	15	10	25
Total	27	15	42

Presence of curb or shoulder on a raised median

This was the only option where a majority of respondents in both geographic groups did not think the listed item affected the safety of the median. Only 41.2% of Texas respondents and 28.0% elsewhere selected the presence of curb or shoulder on a raised median as being significant.

	Selected	Unselected	Total
Texas	7	10	17
Others	7	18	25
Total	14	28	42

Others. Please specify.

Few responses were received suggesting other factors.

Texas	Pedestrians & transit.
Other	Signalized or Non-signalized
Other	I am not sure of what you are asking.
Other	left turn lane offset design
Other	Having a consistent median width - horizontal alignment is straight = more safe Median Width only in the sense of pedestrian refuge safety and a traffic calming effect.
No Response Given	37 (16 Texas, 21 Other)

Question 8: When installing a new raised median, the major obstacle(s) you encounter/expect is/are (Select all that are applicable):

This question consisted of four factors from which respondents could choose that may be obstacles to installing new raised medians. Additionally, there was a space for offering additional obstacles.

Objection from abutting business owners

Nearly all respondents (100.0% in Texas, 96.0% elsewhere) expect to receive objections from business owners along roadways where a raised median is proposed.

	Selected	Unselected	Total
Texas	17	0	17
Others	24	1	25
Total	41	1	42

Objection from abutting residents

Most respondents (64.7% in Texas, 76.0% elsewhere) expect objections from neighboring residents when a raised median is proposed.

	Selected	Unselected	Total
Texas	11	6	17
Others	19	6	25
Total	30	12	42

High construction costs

High construction costs were not cited as a concern in Texas (0.0%) but were a concern to some, though not many, of respondents elsewhere (32.0%).

	Selected	Unselected	Total
Texas	0	17	17
Others	8	17	25
Total	8	34	42

Limited land availability

Limited land availability was not a concern for most respondents in Texas (17.6%) but was a factor for almost half (48.0%) of the respondents elsewhere.

	Selected	Unselected	Total
Texas	3	14	17
Others	12	13	25
Total	15	27	42

Others. Please specify.

Most respondents opted not to offer any additional substantial obstacles.

Texas	Objection from law enforcement.
Texas	Effect on travel patterns. Increase in the number of uncontrolled "U" Turns. Political
Texas	It is best to have multi-govt support, local business chambers, civic groups, homeowners associations, etc participate in studies, then keep constant communication during whole project implementation. You also must be aware of changes in development on the corridor after study complete and be willing to consider changes if needed. Also better get your emergency responders in discussions during the study process. Public safety issues can defeat a project.
Other	design of opposing left turn lanes at signalized and unsignalized intersections
Other	Typically, municipalities want medians to be landscaped. This creates a maintenance issue. On non-expressway roads, we try to get the towns to take over maintenance of any landscaped areas.
Other	Political
No Response Given	36 (14 Texas, 22 Other)

3.2.2 PART II: Questions Regarding Alternative Movements

Three questions were included in this portion of the survey.

Question 1: In addition to the examples shown in Figure A-2 in Appendix A, alternative movements may include such arrangements as restricted-crossing U-turn intersections, continuous flow intersections, diverging diamond interchanges, and others. Some of these types of intersections (or portions thereof) may or may not be signalized. If you and your agency have experience with alternative movements, do they work well? What operational objectives led to their installation and have they accomplished these goals?

This was a free-response question. Of the respondents having experience with alternative movements, several are implementing restricted crossing U-turns, with one individual reporting "positive results and good feedback." Another respondent reports having tried restricted crossing U-turn intersections and ultimately removed them (or some of them) due to complaints. Several agencies are trying diverging diamond interchanges and others report that roundabouts (which are outside the scope of this study) may provide some of the desired benefits often found with other alternative movements.

Texas	No experience.
Texas	N/A
Texas	No experience with these other optional treatments.
Texas	Our district has not implemented these type of measures.
Texas	Don't know where our agency has used these.
Texas	Design of a Super Street.
Texas	The Alamo RMA working with the TxDOT SAT district has implemented a restricted-crossing u-turn intersection corridor project on U.S. 281 north of Loop 1604 as a result of congestion on the corridor. There have been very positive results and good feedback from the public regarding this project. TxDOT is currently implementing another restricted-crossing u-turn intersection corridor on Loop 1604 from SH 151 to Braun Road. This project is under construction, but is expected to improve operations on this corridor.
Texas	Not aware of any
Other	We are looking at diverging diamonds in one or more locations, but expect that there will be some push back before we are able to implement them.
Other	We frequently design for u-turns to allow access to the opposing side of the road. They work fine although the public is sometimes unaware of the u-turn option.
Other	We do not have alternative movement designs
Other	Ohio's first DDI interchange is still in development. The first CFI intersection recently opened and seems to work satisfactorily with respect to traffic channelization. Only a few restricted movement median openings exist and I have heard no reports of problems with them.
Other	N/A
Other	Our use of alternative (indirect) movement intersections is minimal. We have our first DDI under design at present.
Other	None on the ground yet.
Other	TDOT has constructed one Diverging diamond interchange and is satisfied with the

	operation of the interchange. Due to budget and other considerations, the department is open to alternative designs as a way of better utilizing limited resources and providing better traffic operations and safety.
Other	NA
Other	We have used 3/4 intersections with good success.
Other	The state of Michigan allows indirect left down stream of the signalized intersection. This would increase the capacity of the intersection by having a two phase signal. We also been active in constructing roundabouts.
Other	Low-speed modern roundabouts have been demonstrated to be a marvelous, pretty, efficient and VERY SAFE method for solving many of the problem situations depicted in this survey. FHWA says modern roundabouts reduce fatalities by 90% -- unlike any of the solutions you depict in this survey.
Other	We have used the example in Figure A-2 (including at the driveway to our Headquarters building, where we allow lefts in but not lefts out and lefts out can make a U-turn a short distance away) and restricted crossing u-turn intersections, with good results. This was used to improve traffic flow by limiting the traffic signal to two phases (an artery green phase and a left turn in/right turn out phase).
Other	N/A
Other	We have considered alternative movements as part of planning studies, but have not incorporated these into any of our designs at this point in time.
Other	No experience
Other	GDOT has experience with restricted crossing u-turn intersections and they have worked well in situations where operating speeds are at 55 mph or less, adequate advanced signing, and decision sight distance is adequate. GDOT has several diverging diamond interchanges under development so our experience is limited at this time.
Other	We have considered alternative movements but have not provided any to date. We have on one corridor used roundabouts instead of traffic signals at the full movement openings. These allow the U-turn capability at the intersections. These have provided the ability to provide access with the raised median. The full movement approaches were located at the 1/2 mile spacing.
Other	We do not use the medians for U-Turns. U-Turns have been allowed at intersections signalized. We have used what we call a 3/4 intersection which allows all mainline movements but only allows right in / right out movements from the side street.
Other	No significant experience
Other	restricted crossing u-turn–tried some had to pull them up due to complaints, some still in place and crashes have decreased CFI- put in for congestion, too difficult to modify
Other	N/A
No Response Given	12 (9 Texas, 3 Other)

Question 2: The "indirect left turn" treatment is shown in Figure A-2. Based on your experience/judgment, what kind of impacts will it bring? Please select all that are applicable.

Improved safety for left-turn vehicles egress from a driveway

A majority of respondents (82.4% in Texas, 72.0% elsewhere) believe that "indirect left turn" treatments improve safety for vehicles making left turns onto roadways from driveways.

	Selected	Unselected	Total
Texas	14	3	17
Others	18	7	25
Total	32	10	42

Increased travel time for left-turn vehicles egress from a driveway

A minority of respondents (41.2% in Texas, 32.0% elsewhere) indicated that increased travel time for left-turn vehicles exiting a driveway could be expected.

	Selected	Unselected	Total
Texas	7	10	17
Others	8	17	25
Total	15	27	42

Reduced delay for left-turn vehicles egress from a driveway

A minority of respondents (41.2% in Texas, 32.0% elsewhere) indicated that reduced travel times could be expected for left-turn vehicles exiting a driveway.

	Selected	Unselected	Total
Texas	7	10	17
Others	8	17	25
Total	15	27	42

Negative effects on mainline traffic flows

A minority of respondents (35.3% in Texas, 20.0% elsewhere) felt that negative effects on mainline traffic flows would be likely.

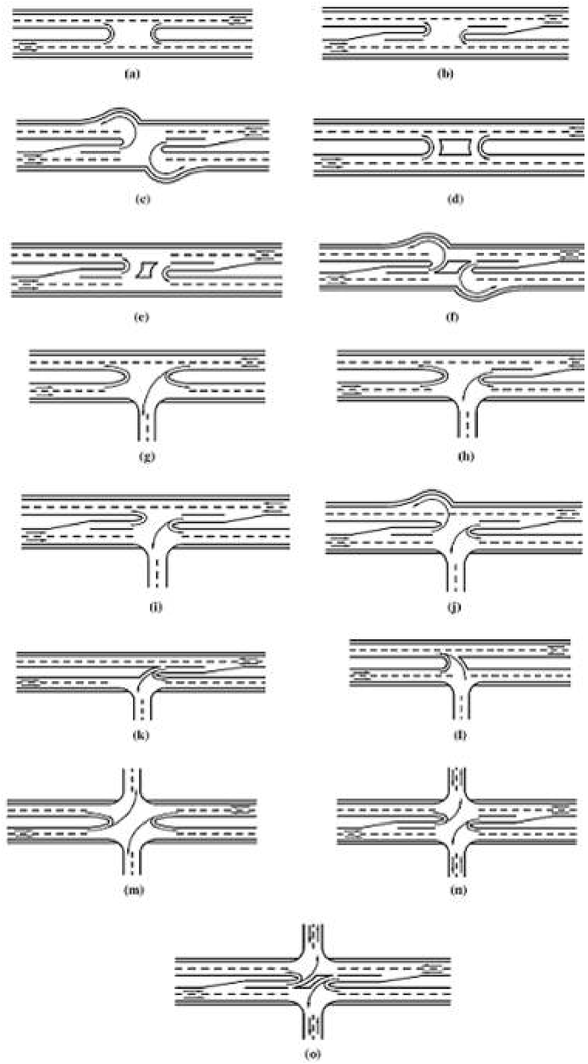
	Selected	Unselected	Total
Texas	6	11	17
Others	5	20	25
Total	11	31	42

Others. Please specify.

Texas	Too narrow a channel opening can cause single vehicle crashes hitting the median.
Texas	Works well if implemented on a long corridor consistently.
Texas	improved mainlane traffic flows.
Other	Don't have any experience, but would expect that it would increase delay during off peak traffic periods, but could decrease delay during peak traffic periods.
Other	Your impacts imply a comparison. I am assuming a comparison to no median full access.
Other	None used
Other	Space for left turns is always a concern (loons).
Other	Unfamiliar driver errors.
Other	Weave distance and design vehicle will be a challenge.
Other	Negative effects on mainline traffic flows will occur only if you do not provide a dedicated turn lane.
Other	No significant experience with indirect lefts.
Other	reduced delay and better progression for main line
Other	While the data suggests u turns are as safe or safer than left turns this is not universally accepted by the public. Therefore, taking away a direct left turn and forcing traffic into a u turn situation will usually be perceived by the public as a diminishment of the roadway safety.
No Response Given	29 (14 Texas, 15 Other)

Question 3: Which of these typical median opening designs are used by your agency (if any) to accommodate U-turns? Please select all that are applicable.

Every option was selected by at least one person in Texas and two people elsewhere. Designs A, B, H, I, and N were each selected by majorities of Texas respondents. Designs B, H, I, K, and N were each selected by majorities of respondents from outside Texas.



A

	Selected	Unselected	Total
Texas	10	7	17
Others	12	13	25
Total	22	20	42

B

	Selected	Unselected	Total
Texas	13	4	17
Others	14	11	25
Total	27	15	42

C

	Selected	Unselected	Total
Texas	4	13	17
Others	9	16	25
Total	13	29	42

D

	Selected	Unselected	Total
Texas	1	16	17
Others	2	23	25
Total	3	39	42

E

	Selected	Unselected	Total
Texas	5	12	17
Others	5	20	25
Total	10	32	42

F

	Selected	Unselected	Total
Texas	2	15	17
Others	4	21	25
Total	6	36	42

G

	Selected	Unselected	Total
Texas	8	9	17
Others	11	14	25
Total	19	23	42

H

	Selected	Unselected	Total
Texas	11	6	17
Others	14	11	25
Total	25	17	42

I

	Selected	Unselected	Total
Texas	11	6	17
Others	15	10	25
Total	26	16	42

J

	Selected	Unselected	Total
Texas	3	14	17
Others	8	17	25
Total	11	31	42

K

	Selected	Unselected	Total
Texas	8	9	17
Others	13	12	25
Total	21	21	42

L

	Selected	Unselected	Total
Texas	5	12	17
Others	5	20	25
Total	10	32	42

M

	Selected	Unselected	Total
Texas	6	11	17
Others	12	13	25
Total	18	24	42

N

	Selected	Unselected	Total
Texas	13	4	17
Others	17	8	25
Total	30	12	42

O

	Selected	Unselected	Total
Texas	9	8	17
Others	9	16	25
Total	18	24	42

3.2.3 PART III: General Questions

This portion of the survey consisted of three open-ended questions (one with two parts) regarding how respondents would handle several issues related to raised medians, providing for U-turn movements, and a request for suggestions in further reducing/minimizing overall delay at signalized intersections.

Question 1: Do you have any suggestions for addressing the following specific issues in raised median design:

(a) The requirements for the deceleration and storage of turning vehicles may exceed the available length between two openings, especially for the arterials with high design speeds and high demand for left-turn movements. On the other hand, if the frequency of median openings is reduced, the demand for mid-block U-turns will increase and will result in longer storage length requirements. How did/will you deal with the median treatment under this circumstance?

Respondents provided a number of options for consideration, with some stressing the need for flexibility when it comes to designing these types of corridors. Several responses indicated that storage requirements trump a desire for frequent openings.

Texas	We do not have raised medians on high design speed areas.
Texas	We adopted reduced storage lengths for private drives and low volume county roads.
Texas	Extend storage.
Texas	We tried to optimize the spacing based on the demand and capacity of the signalized full openings, if applicable.
Texas	We compromised. We shortened the storage and deceleration lengths.
Texas	Design waivers for deceleration/storage length
Texas	Place fewer openings and force the driver to plan ahead to approach their destination, so that they do not cross traffic.
Texas	In arterial, high land use development, I do not think deceleration lanes are a significant requirement. Storage is essential. I would rather reduce the deceleration lane length and increase the storage length.
Texas	Each corridor must be studied carefully and decisions made based on the characteristics of the corridor. There is not a set approach that works for all corridors, and flexibility in design is important.

Texas	The application of median openings is a balancing act of all the items mentioned above. Typically, as long as the storage requirements are met the assumption can be made that the operating speed of the vehicles in the through lanes are much less when the peak conditions are present, and therefore much less deceleration length is required. This would, of course need to be applied on a case by case basis. Sometimes it might be a better situation to allow u-turns and provide for a mid-block u-turn at a strategic location.
Texas	Use available lengths
Texas	Signalization
Texas	Select cross overs at critical locations far enough apart to accommodate acel and decel lanes.
Texas	Design waivers are required if the minimum deceleration or storage lengths cannot be met. Generally use less numbers of median openings with longer storage lengths.
Other	Mid block u-turns are not typical in SD.
Other	No experience in this area.
Other	We give priority to minimizing median openings.
Other	Typically the number of median openings is reduced. Restricted movements are also considered to improve operation and reduce queuing.
Other	We would probably, and have in the past, extend the turn lanes all the way between the median openings. We would also try to add dual lefts if at all possible.
Other	We don't do a lot of the continuous turn treatments like you have above, outs are more intersection related, very few uses of continuous islands.
Other	Each location must be evaluated individually. We would attempt to balance the number of openings and storage length needs. A TWLTL might be an option to be evaluated. If a signalized intersection is warranted, perhaps it would provide gaps.
Other	We don't have high volume roads in our state.
Other	Provided median opening spaced equally between intersections with as much storage as possible based on the sight conditions.
Other	Our guide is our median opening spacing requirements. Adequate taper and storage is designed based on projected demand.
Other	In this order: 1) Try to space openings to avoid shortened storage/decel 2) If not 1 – then reduce turn lane taper to as little as 5:1 – keep storage 3) If not 1 or 2 – reduce taper and reduce storage Note – 2 & 3 will require left turning vehicles to start deceleration in thru lanes.
Other	If the demand is high at the opening ,then a dual left turn lanes would be constructed. The opening would be signalized.
Other	Eliminate the median openings and thus the conflicts, crashes, injuries and fatalities associated with them. Low-speed modern roundabouts provide safe, comfortable U-turns and provide right turns into driveways after the turn – so much better than median cuts to get to that driveway on the other side of the median.
Other	We typically use median openings only at signalized intersections, where the queues can be controlled with signal timing. If queues were to extend beyond the next median opening, and we could not adjust the signal timing to prevent this, we would likely prevent left turns from the side street, so that vehicles were not stuck trying to cross the artery. This has not been a common problem.
Other	Not had this problem.

Other	We require a minimum of about 1/4 mile between median breaks, so we have not had a problem with requirements exceeding the available lengths. We have utilized dual left turn lanes at some intersections to reduce the storage length needed at some signalized intersections.
Other	Engineering Judgment.
Other	Dual lefts to reduce storage length requirements
Other	Where practical, the total length of turn lane should be determined based on the design speed and the storage requirement for the turn lane and adjacent through-lane queue. The applicable design vehicles should be considered in this assessment.
Other	This would be looked at on a case by case basis and balancing the needs in each corridor.
Other	We do not promote mid block U-Turn movements. We have closed medians and enhanced features at intersections we want movements to funnel through.
Other	NA
Other	moved the opening
Other	We will not build a median opening that can not support and storage needs of that turn. We feel queuing cars into the through lanes will cause additional safety issues.
No Response Given	4 (3 Texas, 1 Other)

(b) In areas of restricted rights-of-way, the median width is limited to provide adequate U-turn radii for vans or trucks (especially on four-lane arterials). How did/will you deal with the median treatment under this circumstance?

For this question, responses varied widely. In some places, the preference may be not to build a median if U-turn movements could not be provided for larger vehicles. Elsewhere, trucks may be expected to find alternate routes via adjacent streets that would then allow for right turns into destinations. Additionally, where medians could not be made wide enough to allow for larger vehicles to make U-turns in the normal limits of the roadway, it may still be possible to acquire right-of-way for loons.

Texas	We only have raised medians on roadways with sufficient right-of way to provide a minimum of 16 ft. median. We purchase right of way at intersections to provide "loons for u-turn movements if we do not have sufficient right-of-way.
Texas	Most of these situations are on rural roads, so ROW has not been a factor. Very few raised medians in our urban areas.
Texas	Restrict trucks on that facility.
Texas	We have utilized left turn bays with narrow median dividers in order to maximize the room for them to utilize the majority of the pavement in order to maneuver the turn. In most cases tried to leave some kind of a shoulder which could be used as a buffer for vehicles to clear their turns.
Texas	Having as wide a divider as possible provided the most room possible for left turn movements.
Texas	Use hooded left turn bays and prohibit u-turns
Texas	Disallow U-turns at these locations. Force vehicles to find alternate route.
Texas	These vehicles can use local intersecting road networks to make a series of 90-

	degree turns instead of a u-turn.
Texas	Narrow ROW is a challenge and could be a hindrance to a median treatment. One does not want to solve one concern, but create another.
Texas	Usually we do not use channelized median openings, we leave them fully directional on 4 lane roads.
Texas	This depends on the adjacent street network. There may be adequate network to allow trucks/buses/vans the ability to “backtrack” on a parallel roadway. If there is not adequate street network we have provided “bubble-out” areas of additional pavement on the outside of the pavement to allow for the turnaround. Usually an area of slightly wider ROW can be found to accommodate this.
Texas	Development of parallel routes
Texas	Signage for no truck traffic in median
Texas	Use normal radii that will fit within right of way. Large trucks would be expected to make turns along street system until a right turn into the property could be made.
Other	If ROW is restricted and roadway width is not sufficient for u-turn movements vehicles will need to adjust their route (i.e. go around the block). In some locations providing a shoulder or bump-out at the intersection allows for u-turns.
Other	We may prohibit u-turns for all vehicles if there is a documented concern with trucks/vans blocking through vehicles.
Other	we typically do not design for u-turns of trucks. We assume they will be directed to roadways which allow a right turn to their destination.
Other	Restrict u-turn
Other	We are considering use of loons. None are in place yet, but are in consideration in several locations.
Other	We would probably try to widen the shoulder at the least or use a jug handle.
Other	If large radii –turns are allowed, the “bulb out” on the receiving end may be considered.
Other	The bulbout idea looks good. We don’t have midblock median breaks at this time because we have very few median islands.
Other	Restrict u-turns. Provided additional shoulder width for encroachment by larger vehicles.
Other	we allow U-turn movements only where the design vehicle can make the maneuver.
Other	Use style like (j) above – called “loons” in Minnesota. Will require purchase of ROW to build loon.
Other	We build truck turn around as shown in your figure(f).
Other	Prohibit u-turns by vehicles larger than those that can make the turn.
Other	Have used mountable curb to allow vehicle tracking of rear wheels.
Other	We widen the roadway at the intersection (bubble out) enough to accommodate the u-turn radius of the design vehicle. This is like accommodate in the typical median opening designs shown above.
Other	Engineering Judgment.
Other	Would not allow U-turns
Other	Additional pavement for U-turns at median openings should be considered where there is a demand for access and where practical. In some cases, pavement for truck U-turns such as jug-handles may be necessary at strategic locations along the roadway to satisfy truck access to private property between successive median openings.
Other	Determined on a case by case basis depending on the conditions at each site.

Other	We do not handle this well. If medians can not handle U-Turns for vans or trucks, we do not expect those vehicles to make U-Turns.
Other	NA
Other	longer route for trucks or bulb outs
Other	We do not build them in these situations.
No Response Given	5 (3 Texas, 2 Other)

Question 2: What other challenges have you encountered in implementing raised medians and/or alternative movements?

Respondents provided a number of issues they have encountered when attempting to implement raised medians and alternative movements. Most objections seem to come from politicians and abutting property owners (particularly businesses wanting direct access).

Texas	Nighttime and or inclement weather visibility issues.
Texas	None
Texas	Limited rights of way which could prevent you from developing the optimum typical section in order to clear obstructions to turning vehicles.
Texas	Public opposition, especially from businesses.
Texas	Political pressure to provide median openings.
Texas	None.
Texas	Drivers and landowners prefer continuous two-way left-turn lanes.
Texas	Existing land use may not be supportive of a raised median. Tracts of land developed as individual islands of access for only themselves does not lend itself to a raised median.
Texas	Politics.
Texas	Inconsistent support from local government and business owners.
Other	The main challenges is working with property/business owners.
Other	Very difficult to get past opposition from abutting property owners. If they even consider medians, they generally want an elaborate sign plan to direct traffic back to their facility. They tend not to be worried about traffic returning to the highway after doing business with them.
Other	Political influence is the worst obstacle.
Other	Most significant issue has been reaction of adjacent property owners who object to the restricted movements where median breaks are not provided.
Other	You have pretty well covered the subject. More pressure is placed to increase access points which degrade the overall traffic flow. Some movements need not be allowed.
Other	Pedestrian treatments and decorative items in the median.
Other	Access concerns from adjacent residences and businesses.
Other	dealing with individual large property owners whose left turn access is being removed
Other	Primarily opposition from business and elected officials.
Other	Right of way cost Business
Other	The biggest challenge is usually opposition from businesses. We have found that they are especially concerned with the ability of their customers to enter the site and are less concerned with any difficulty they may have leaving the site. Therefore, if left

	turns from the artery can be reasonably accommodated, but left turns out of the site are made via a downstream u-turn movements, business owners will object less.
Other	Most frequently – perceived access reduction and related complaints.
Other	Design of raised medians in superelevated roadways can be a little tricky at times.
Other	Drainage can be an issue in some cases
Other	In Georgia, raised medians are typically planned for urban areas where there is mixed commercial and residential access, significant pedestrian and bicycle demand, a need to reduce crash rates related to mid-block turning movements, and overall restrictive right-of-way conditions. A re-occurring challenge has been when we convert undivided or flush medians to the raised median treatment; and convincing the public of the advantages, particularly when U-turns are introduced.
Other	Our maintenance forces oppose raised median due to the difficulty of snow plow operations. Raised median adds another obstacle in the roadway. Drainage issues.
Other	Support from businesses that do not like restricted access. In some instances, funding.
Other	Public opinion
Other	buy in
Other	Our experience is the largest challenge is in commercial areas with local businesses. They all perceive medians as bad for business and are reluctant to believe statistics from studies performed outside of Colorado. Unfortunately we do not have any local studies.
No Response Given	12 (7 Texas, 5 Other)

Question 3: What suggestions could you offer for the handling of signalized intersections to further reduce/minimize overall delay?

For this question, responses varied, but several people mentioned that dual left turns should be considered where feasible. Additionally, signals should be synchronized to promote progression along the major arterial.

Texas	Positive offsets that help facilitate turning movements during green ball cycle.
Texas	Plan early for late life facility modifications . . . like raised medians.
Texas	Consider Dual Left turns if possible in order to clear as many vehicles as possible and consider alternate left turn phasing such as Lead-Lag, etc depending on demand or directional distribution for time of day.
Texas	Try to synchronize them if possible, or provide as much green time on the major roadway as possible. Also, make the protected left turn phases permissible on steady green signal indications as opposed to steady red.
Texas	In urban areas on high ADT roadways, synchronize the signal timing along the primary roadway. Do not disrupt the primary flow to accommodate side streets (using vehicle detectors).
Texas	The best is to provide a raised median prior to development occurring, working with the local government and their major thoroughfare plan to provide reasonable future intersection openings that develop can use for new public streets.
Texas	Increase turn bay storage. Spend some money on signal improvements and re-timing right after medians are placed.

Texas	Additional turn lanes
Texas	Stagger u-turn lanes behind intersections.
Texas	Ensure the signals are synchronized.
Other	*(Two separately submitted responses from the same individual) 1)* Replace them with modern roundabouts to reduce/minimize delay as well as fuel consumption, GHGs, injuries and severity of injuries. Plus, FHWA says modern roundabouts reduce fatalities "by more than 90%." *2)* Replace them with low-speed modern roundabouts, which can improve rush-hour capacity 20-30%, provide LOS A&B much of daylight hours, and provide free-flow most of the rest of the time. Dramatically shortened queues can bring life back to the corner properties, too.
Other	Good luck?
Other	1. Eliminate turns 2. Add through lanes. 3. Provide an interchange.
Other	Adaptive systems
Other	We are open to many new and innovative designs such as CFIs, Superstreet, and multi-lane roundabouts. Roundabouts, in conjunction with raised medians, can provide convenient locations for u-turns for indirect lefts without impacting driveways.
Other	open to suggestions
Other	Coordinate adjacent signals for optimal progression.
Other	Put in roundabouts.
Other	There are many. Eliminate left turn movements. Construct parallel offset left turn lanes. Install adaptive traffic control.
Other	Coordinated, traffic responsive signal timing.
Other	The Michigan indirect left is one of these solutions and the roundabouts.
Other	The use of raised medians with roundabouts at the intersections instead of signals (where volumes and space allow) can be an excellent way of preventing left turns while still providing a safe and efficient way to make a u-turn.
Other	Make sure there is a zero or negative offset for opposing left turn movements. Also, make sure the median break is wide enough to allow opposing left turn movements to be made simultaneously.
Other	Provide right turn lanes with right turn arrows during the protected left turn phase of the intersecting roadway.
Other	Consider alternative intersection design, such as roundabouts. Have an operations program in place to synchronize signals on corridors with multiple access points.
Other	Would a roundabout be a better alternative? If in a corridor with other signals need to make sure you are in a coordinated plan and optimize the signal timings. Balance the safety of the intersections with the operations of the intersections. May considered fully actuated intersection with dilemma zone protection; extension of the green on the mainline.
Other	Coordination if necessary. Proper intersection geometry for expected traffic.
Other	NA
Other	restrict turns at the signal
Other	Our experience is that the most efficient signal is one that operates to its full potential. Which means you need good comm., efficient detection, accurate ped times and up to date coordination plans. It also helps to have visual contact with the signal at your operations center for quick response to complaints.
No Response Given	12 (7 Texas, 5 Other)

3.3 SUMMARY

The major findings of the survey are summarized as follows:

- 64.7% of Texas respondents and 44.0% elsewhere have guidelines for considering median installation based upon ADT volume, generally varying between 10,000 and 30,000 vehicles per day (out-of-state responses often were at the higher end of that range, at least 20,000 vehicles per day).
- 41.2% of Texas respondents and 36.0% elsewhere have guidelines for considering median installation based upon high mid-block turning volume.
- 23.5% of Texas respondents and 36.0% elsewhere have guidelines for considering median installation based upon an excessive number of driveways.
- 23.5% of Texas respondents and 56.0% elsewhere have guidelines for considering median installation based upon a high accident rate.
- 58.8% of Texas respondents and 72.0% elsewhere install median openings at all public roads and major traffic generators.
- 94.1% of Texas respondents and 88.0% elsewhere install median openings when proven necessary by traffic impact studies.
- Several respondents commented that there can be pressure from the public and politicians to have more median openings provided than would be preferred for operations.
- When asked about median opening spacing, respondents gave answers that varied between 1/16 mile and 1/2 mile, though they were normally at least 1/8 mile. A recurring comment was that a greater number of openings can lead to operational challenges and a greater likelihood of collisions.
- There was no consensus regarding whether or not medians should be wide enough to provide for vehicle refuge, though 14′-16′ (and up to 20′) standard widths were given.
- Most agencies seem to prefer full openings, rather than directional openings, but will look at directional openings to solve specific issues.
- Very few respondents indicated that there were median-specific guidelines regarding turn lanes, but several noted that great care must be taken in their design, as modifications later are difficult.
- 88.2% of Texas respondents and 92.0% elsewhere reported that median opening density may affect traffic safety performance of raised medians.
- 52.9% of Texas respondents and 60.0% elsewhere felt that median width affected traffic safety performance.
- 100.0% of Texas respondents and 72.0% elsewhere reported ADT demand impacting traffic safety performance.
- 58.8% of Texas respondents and 64.0% elsewhere felt that speed limit impacted the traffic safety performance of raised medians.
- 70.6% of Texas respondents and 56.0% elsewhere reported that adjacent land use may be a significant factor in the safety performance of raised medians.

- 70.6% of Texas respondents and 60.0% elsewhere felt that travel lane number and width were a factor in the safety performance of raised medians.
- The presence of a curb or shoulder on a roadway with a raised median was selected by only 41.2% of Texas respondents and 28.0% elsewhere as affecting the traffic safety performance of the median.
- 100.0% of Texas respondents and 96.0% elsewhere believed objections from abutting business owners to be a major obstacle to the installation of medians.
- Objections from abutting residents were less of a factor than objections from businesses, with this option selected by 64.7% of Texas respondents and 76.0% elsewhere.
- High construction costs were not a significant obstacle, being selected by none of the Texas respondents and 32.0% of respondents elsewhere.
- Restricted crossing U-turn arrangements have been used by several respondents with mixed success. One individual noted positive results, while another indicated that some of the arrangement was later removed due to complaints.
- 82.4% of Texas respondents and 72.0% elsewhere agreed that indirect left turns may improve safety for left-turn egress from a driveway.
- 41.2% of Texas respondents and 32.0% elsewhere felt that indirect left turns would increase travel time for left-turn egress from a driveway. The same proportions thought that this arrangement would reduce delay for these vehicles.
- 35.3% of Texas respondents and 20.0% elsewhere thought that indirect left turns would present negative impacts to mainline traffic flow.
- Of the fifteen designs presented for median openings, five were selected by a majority of Texas respondents as existing in the state (A, B, H, I, and N), while five were also selected by a majority of respondents elsewhere (B, H, I, K, and N). Every design was selected by at least one Texas respondent and two respondents from elsewhere. (See the figure in Part II Question 3.)
- A request for suggestions regarding balancing the need for median openings with deceleration and storage lengths yielded responses that storage requirements are generally more important, but flexibility is important when designing these types of corridors.
- There were three common responses when asked about medians not wide enough to accommodate turn radii for vans and trucks: don’t build the median, build the median and expect trucks to reroute themselves, and attempt to locate sections where additional rights-of-way could be procured that would allow for the construction of loons.

CHAPTER 4: FIELD STUDY

In this project, field studies were conducted for two purposes: (1) to collect field data for the following simulation-based studies and the case studies, and (2) to further identify issues related to raised medians through field observation.

4.1 FIELD STUDY SITES

4.1.1 Location #1: Jones Road—between FM 1960 and Fallbrook

The purpose of conducting a field study at this location is to help the researchers understand the benefits and shortcomings of closely spaced median openings with turn bays shorter than TxDOT standards.

Figure 4-1. Jones Road—between FM 1960 and Fallbrook.

Following are the basic roadway and traffic conditions at this site:

- It is designed and operated by Harris County, TX.
- Its length is about 3,000 ft with signalized intersections (FM 1960 and Fallbrook) on each end.
- Six-lane arterial road connecting Texas State Highway 290 and Texas State Highway 249.
- Posted speed limit is 45 mph (relative high).
- Full median openings provided along the road.
- A mixture of residential and business areas along this road. Jones Square Shopping Center and Cypress Fairbanks Medical Center are beside the road segment.
- Frequent presence of driveways and the left-turn traffic volumes from driveways are heavy.

This location was selected because it has the following potential design and operational issues:

- Closely spaced median openings—There are five full median openings (allowing all movements including crossing movement from one side street to the opposite). The opening spaces are between 160 ft to 800 ft (from north to south: 500 ft, 160 ft, 500 ft, 800 ft, 280 ft, and 650 ft).
- Compromised left-turn bay length (relative to TxDOT standards)—According to the TxDOT Roadway Design Manual, the minimum turn lane length is typically 445 ft with a speed limit of 45 mph. However, in this location, there are nine dedicated left-turn lanes installed with all the lengths less than this TxDOT standard. The existing left-turn bay lengths from north to south are 270 ft, 250 ft, 185 ft, 250 ft, 280 ft, 200 ft, 130 ft, 220 ft and 200 ft. Please see Figure 4-2 for an example turning bay.
- Relative high traffic volumes at many driveways.

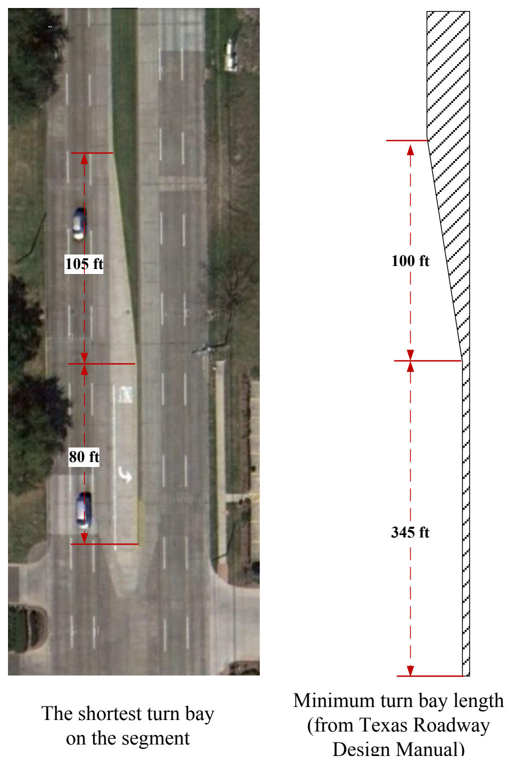


Figure 4-2. An Example of Compromised Left-Turn Bay with Shorter Storage and Deceleration Lengths.

4.1.2 Location #2: U.S. 281 at Evans Rd., San Antonio

The purpose of conducting a case study at this location is to evaluate the effects of geometry design elements on the performance of a representative alternative movement, i.e., RCUT (or Super Street). These design elements include the U-turn crossover distances, the number of turning lanes, etc.

Figure 4-3. U.S. 281 at Evans Rd., San Antonio.

Following are the basic roadway and traffic conditions at this site:

- It is designed and operated by TxDOT.
- Rural highway generally with 3 travel lanes.
- Posted speed limit is 65 mph.
- Superstreet concept has been applied—U.S. 281 is well known for the Super Street in the San Antonio District. In this design, the U-turn is used as an alternative to direct through movements departing from minor streets. The U-turns are controlled by signals considering the high speeds and the resulting difficulty for drivers to judge the gaps.
- High traffic left-/U-turn demands from both U.S. 281 and Evans Rd.

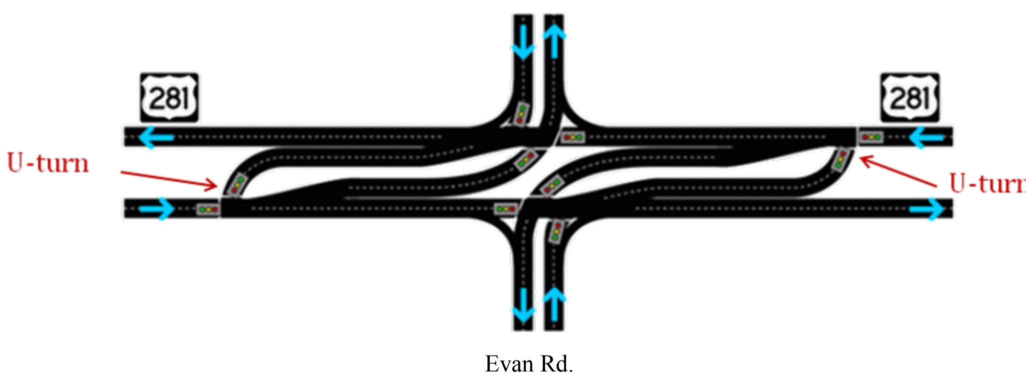


Figure 4-4. Concept of Super Street on U.S. 281, Texas.

4.1.2.1 Potential Design Issues

During the field observation, complaints were heard from some residents in this neighborhood; most of them were from senior citizens about the complex lane configurations.

4.2 DESCRIPTION OF THE FIELD OBSERVATION

4.2.1 Time Period for Field Observation

U.S. 281 & Evans Rd., San Antonio: November 9-11, 2011. 3 weekdays, 6 hours per day during 6:00-9:00 AM (or 7:00-10:00 AM) and 4:00-7:00 PM (or 3:00-6:00 PM).

Jones Rd. between FM 1960 and Fallbrook Dr., Houston: November 16-18, 2011. 3 weekdays, 6 hours per day during 6:00-9:00 AM (or 7:00-10:00 AM) and 4:00-7:00 PM (or 3:00-6:00 PM).

4.2.2 Observational Methods

AutoScope Van: The AutoScope Van owned by TSU is a mobile traffic-data collecting system. It is equipped with two Autoscope cameras that are mounted on a 42-ft mast. By connecting with the computer and video recording equipment inside the van, these two cameras can simultaneously record traffic videos.

Video Cameras: Video camcorders will be set up inside a passenger car with a focus on the selected field study locations. The recorded videos will be replayed in the laboratory to collect traffic data as needed.

Figure 4-6 and 4-7 show the position and coverage of the AutoScope van cameras and video camcorders at both sites.

Probe Car Survey: As a probe car, a Volkswagen Jetta was driven by the researchers. At each of the locations, the researchers spent approximately 6 hours on driving through the road segments. A stop watch was used to record the travel times between reference points.

(a) AutoScope Van

(b) Video Cameras Based on Tripod

(c) Probe Car Survey

Figure 4-5. Observational Methods.

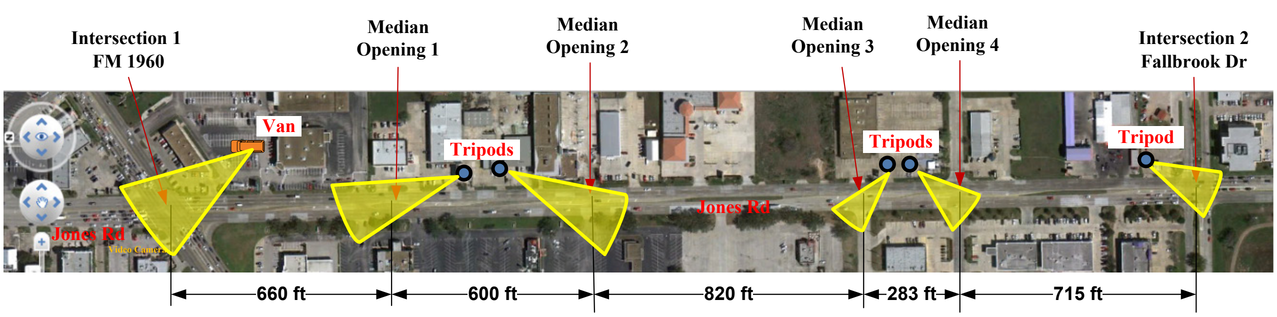


Figure 4-6. Positioning of Camcorders at the Jones Rd. Location.

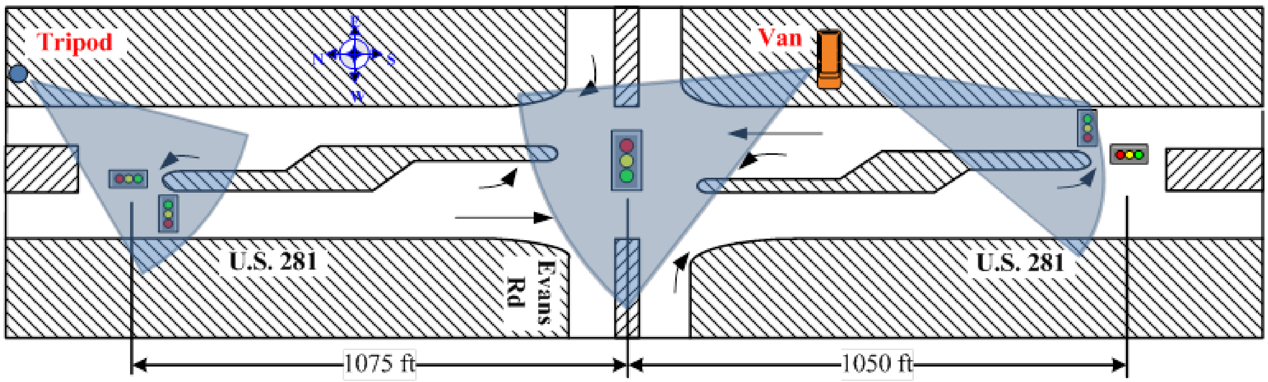


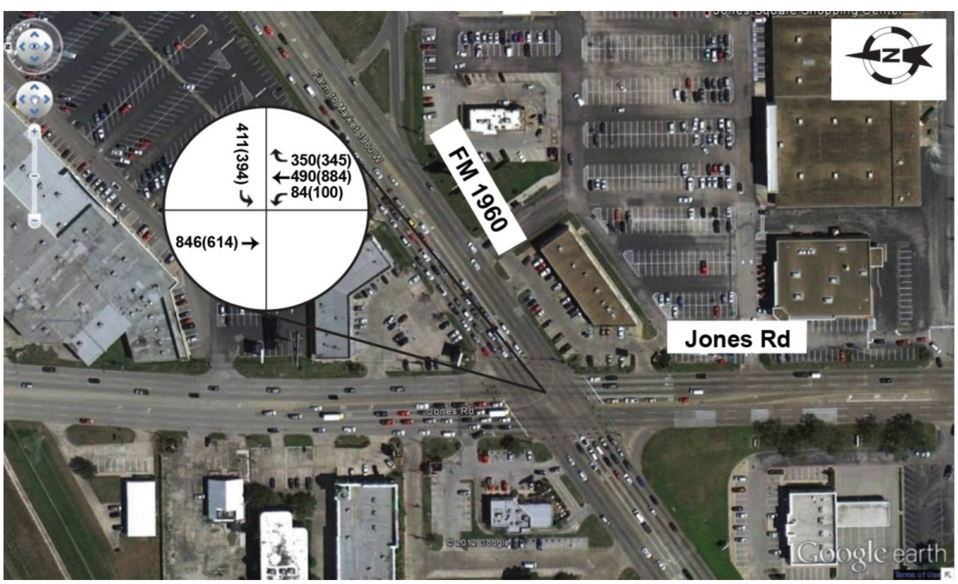
Figure 4-7. Positioning of Camcorders at the U.S. 281 Location.

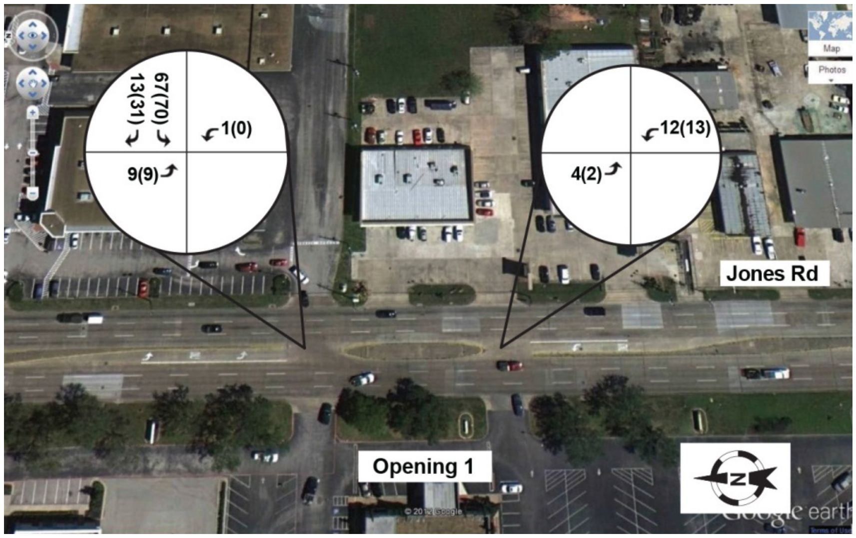
4.3 TRAFFIC DATA COLLECTED

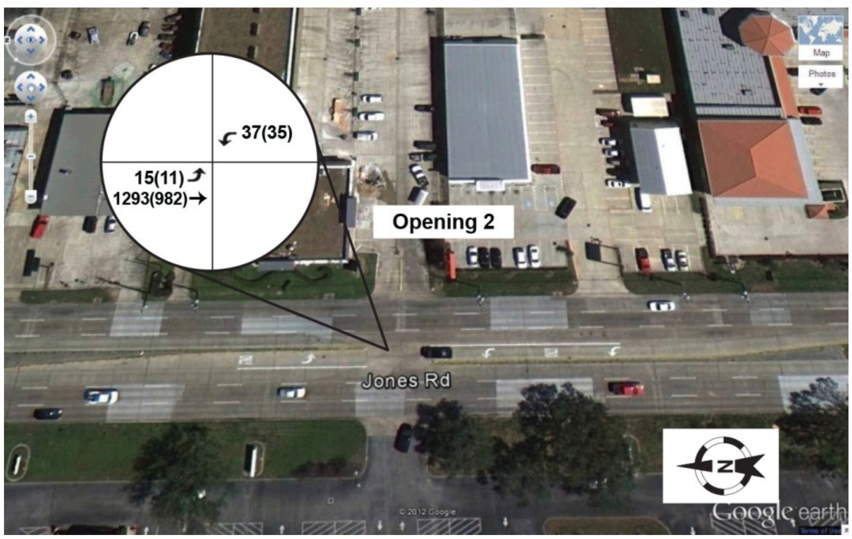
4.3.1 Traffic Volumes

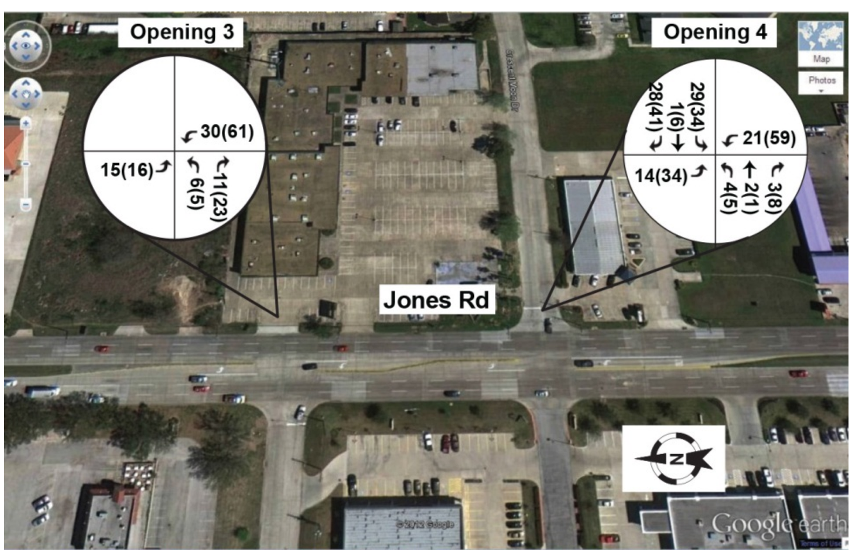
Traffic volumes were observed during the observational periods and averaged for both the morning and afternoon peak periods, respectively.

For the Jones Rd. location in Houston, the observed volumes are shown in Figure 4-8. For each of the movements, the morning-peak-period volumes are presented as well as the afternoon-peak-period volumes shown in parentheses.




67(70)
13(31)
1(0)
9(9)
12(13)
4(2)
Jones Rd
Opening 1


37(35)
15(11)
1293(982)
Opening 2
Jones Rd


Opening 3
Opening 4
30(61)
15(16)
6(5)
11(23)
29(34)
1(6)
28(41)
21(59)
14(34)
3(8)
2(1)
4(5)
Jones Rd

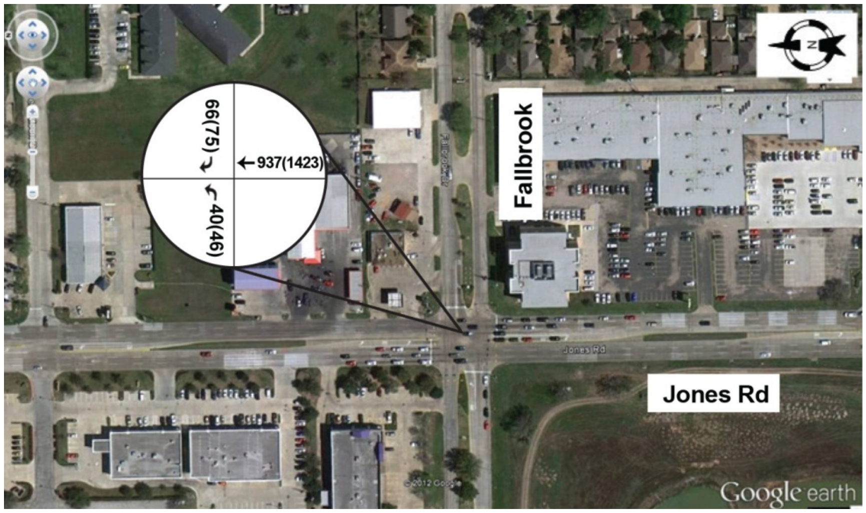
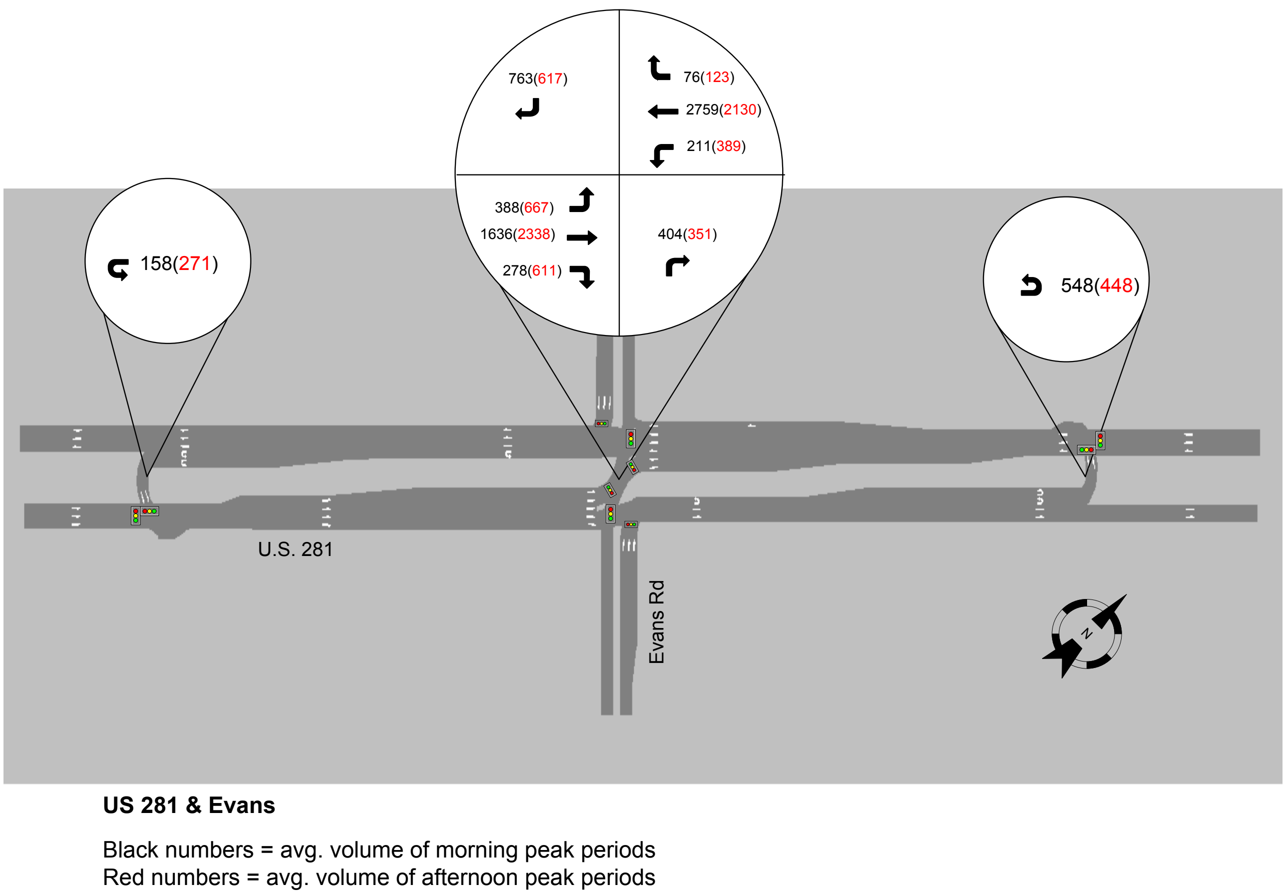


Figure 4-8. Traffic Volumes Observed at Jones Rd. between FM 1960 and Fallbrook Dr., Houston.

For the U.S. 281 Super Street location in San Antonio, the observed volumes for each of the movements are shown in Figure 4-9.



4.3.2 Travel Time Based on Floating-Car Surveys

Travel times and delays were collected based on a floating car driven by a researcher. The data will be used to calibrate the simulation models in the following Chapters 5 and 7.

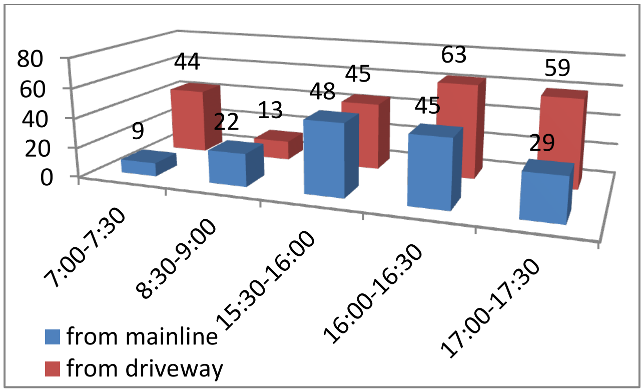
4.3.2.1 The Jones Rd. Location in Houston

For the Jones Rd. location, the travel times were observed along the entire segment of Jones Rd, as shown in Figures 4-10. The red lines in Figure 4-10 are the reference lines for measuring the times. Along the segment, the average northbound and southbound travel times are measured for the morning peak hours and the afternoon peak hours, as shown in Figure 4-10.

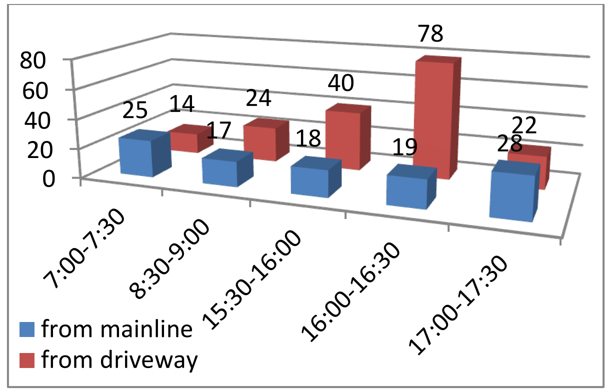
Directions	FM 1960 to Fallbrook (SB)		Fallbrook to FM 1960 (NB)	
Time of Observation	Travel Time (s)	Sample size	Travel Time (s)	Sample size
7:00-8:30	282	4	150	4
8:30-10:00	121	3	82	3
16:00-17:30	170	4	381	4
17:30-19:00	159	2	865	2

Figure 4-10. Travel Times along the Segment at the Jones Rd. Location, Houston.

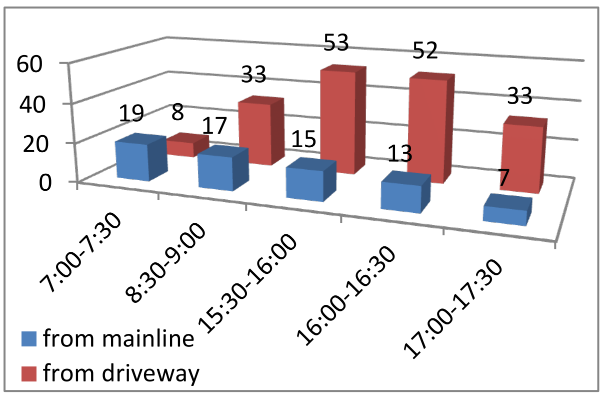
To further calibrate the simulation models, the left-turn delays observed at two selected openings were collected, as shown in Figure 4-11. The left-turn delays were collected from the time when a vehicle arrived at the stop line to the time when the vehicle finished the left-turn maneuvers, either entering the target driveway from the mainline, or merging onto the mainline travel lanes from a driveway.



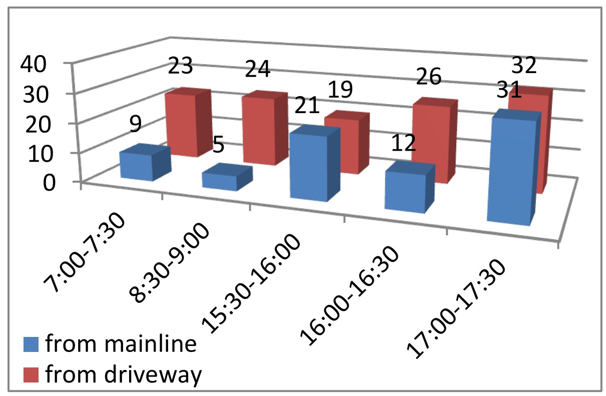
Delay for Opening 1 (Southbound)



Delay for Opening 4 (Southbound)



Delay for Opening 4 (Northbound)



Delay for Opening 1 (Northbound)

Figure 4-11. Delay at Selected Openings at the Jones Rd. Location, Houston.

4.3.2.2 The U.S. 281 Super Street Location in San Antonio

Travel times and delays were also collected at this location. Four reference points were pre-set (A, B, C, and D) for measuring the travel time between them. For example, the travel time from A to C was measured from when the floating car passed point A to when it passed point C (signal delay at the main intersection included). The travel time from B to D was composed of the time from B to opening C (including signal delay at the main intersection), the delay at opening C, and the time from C to D (including signal delay at the main intersection).

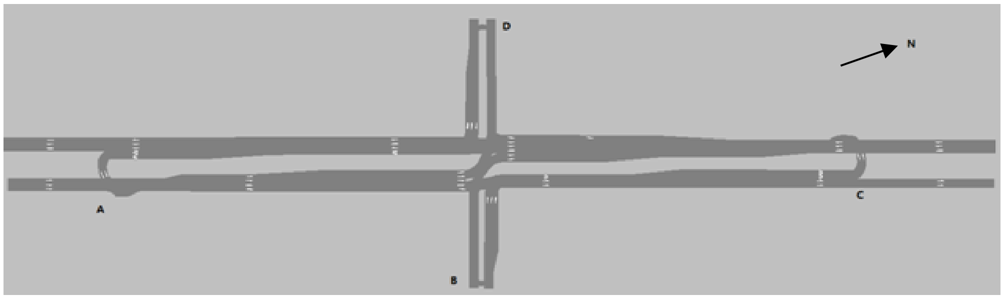


Figure 4-12. Four Reference Points for Floating-Car Measurements at U.S. 281 & Evans Rd., San Antonio.

The results between all of the four reference points are presented in Tables 4-1 and 4-2. The delays at median openings are shown in Table 4-3.

Table 4-1. Average Travel Times during Morning Peak Hours (in Seconds).

From \ To	C	A	D	B
C		70.4	74.1	78.6
A	61.2		88.6	45.9
D	199.8	107.3		184.4
B	96.7	218.1	221.7	

Table 4-2. Average Travel Times during Afternoon Peak Hours (in Seconds).

From \ To	C	A	D	B
C		59.9	75.4	98.5
A	79.6		64.4	57.8
D	264.9	74.6		243.0
B	160.3	269.7	285.2	

Table 4-3. Average U-Turn Delays at Two Median Openings.

	Delay (in seconds)	
	Morning peak hours	Afternoon peak hours
North Opening (point C)	50.9	49.6
South Opening (point A)	31.2	98.6

Note: U-turn delay is measured from the time when the floating car stopped joining the queue at the opening to the time when it was discharged from the stop line at the opening.

The observed travel time data were compared with "before conditions" as shown in Table 4-4. The results indicated that 34% of northbound travel times and 42% of southbound travel times were saved along the mainline, measured from one U-turn crossover to the other crossover.

Table 4-4. Mainline Travel Time at U.S. 281 & Evans Rd.

Sources	**Average Travel Time (s)**		
	PM NB	**AM SB**	**Study Time**
"0-6644"—After	79.6 s (-34%)	70.4 s (-42%)	Nov. 2011
TxDOT/ARMA—After	55.8 s (-54%)	93.6 s (-23%)	Feb. and Mar. 2011
TxDOT/ARMA—Before	121.2 s	122.1 s	Feb. 2010

TxDOT/ARMA data were adapted from U.S. Highway 281 Superstreet—Project Summary Report by Alamo Regional Mobility Authority (ARMA)

The observed travel time data showed that the vehicles from the side streets experienced excessive delays, which is up to 200 seconds for a left-turn/crossing maneuver.

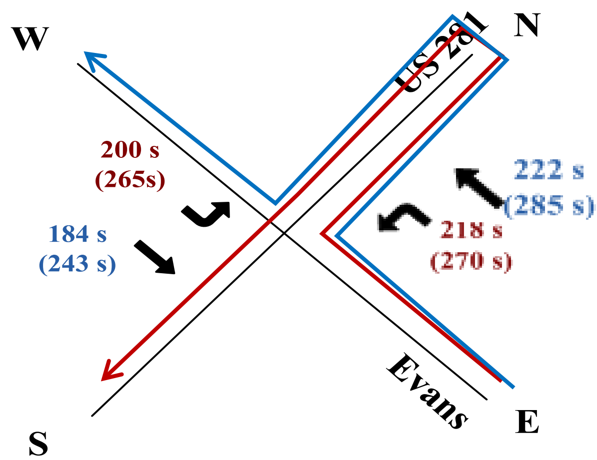


Figure 4-13. Travel Time from Evans Rd. (the Side Streets).

4.4 SAFETY ANALYSIS

The safety problems at these two study sites were analyzed based on the collected traffic conflicts and historical crash data at both sites.

4.4.1 Jones Rd. in Houston

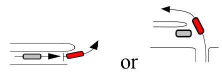
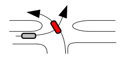
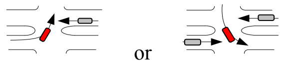
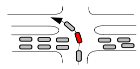
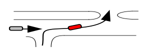
4.4.1.1 Traffic Safety Data at Jones Rd. in Houston

4.4.1.1.1 Traffic Conflict Data.

Traffic conflicts are defined as the interaction between two or more road users (e.g., vehicles, pedestrians, and bicycles), where one or more users take evasive action to avoid a collision. For this study site, there were four observers along Jones Rd. Each of the observers covered one median opening. The researchers observed both southbound and northbound traffic and recorded the different types of conflicts that occurred.

Totally, there were 29 conflicts observed and identified though three-day field observations. As shown in Table 4-5, the conflicts were classified into five different types. The red vehicles define the left-turn vehicle involved in the conflicts.

Table 4-5. Traffic Conflicts Observed on Jones Rd. in Houston, TX.

Types of traffic conflicts and events	Illustrations	Opening ID				Total
		I	II	III	IV	
Type 1: Conflict between through vehicles and LT [1] stored in the opening		4	3	N/A	N/A	7
Type 2: Conflict between driveway LT & mainline LT		2	0	2	1	5
Type 3: Conflict between LT & opposing through traffic on the mainline		4	3	2	N/A	9
Type 4: Gridlock due to aggressive LT from driveway (peak hours)		4	1	N/A	1	6
Type 5: Weaving conflict [2]		N/A	2	N/A	N/A	2
Total		14	9	4	2	29

Note: 1. LT=left-turn.
2. Near opening II, there are two driveways that are not aligned to the full openings, thus, no direct left-turn maneuvers can be made from these two driveways.

Type 1—Conflict between through vehicles & left turn stored in the opening occurs (a) when a leading left-turn vehicle from the mainline slows down at an opening without a dedicated left-turn lane (shown as Type 1.A), or (b) when a left-turn vehicle from either mainline or driveway stops at an opening, waiting to cross, but the opening cannot fully accommodate the length of the left-turn vehicle (shown as Type 1.B). Both of these situations place a follow-up mainline vehicle in danger of a rear-end collision.

Type 1.A Type 1.B

Figure 4-14. Illustration of Type 1 Traffic Conflicts.

The occurrence of Type 1 traffic conflicts pinpoints the need for refuge space at a median opening, e.g., providing a dedicated left-turn lane at the opening or sufficient median width to shelter the left-turn vehicles from the mainline traffic.

Type 2—Conflict between driveway left turns & mainline left turns occurs when a left-turn vehicle from the mainline and a left-turn vehicle from the driveway at a median opening are turning at the same time. Conflicts of this type are a result of unclear priority between the two left-turn movements inside the median opening. Under heavy traffic conditions, the excessive waiting time at the median opening may cause this type of traffic conflict.

The occurrence of Type 2 traffic conflicts may indicate that problems may appear where a full median opening is provided to allow all the movements. More importantly, drivers' sight distance will be impaired if two left-turn vehicles appear at the opening at the same time and block each other's view.

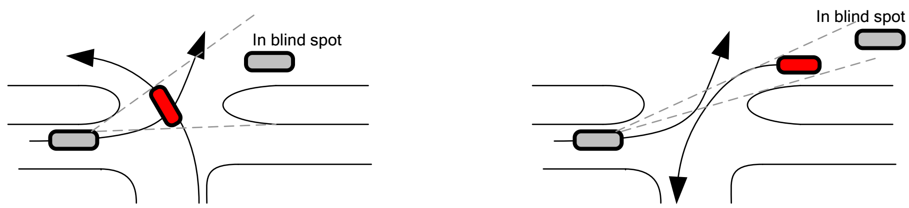


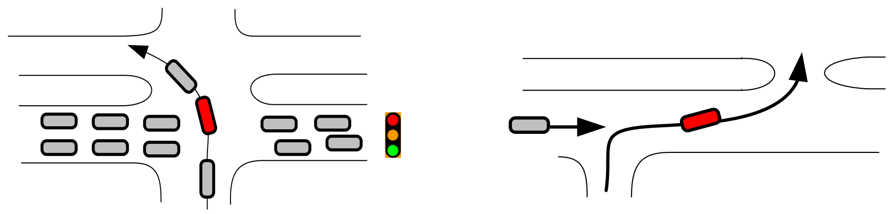
Figure 4-15. Impaired Sight Distance When Two Left-Turn Vehicles Appear at a Full Opening at the Same Time.

Type 3—Conflict between left turns & opposing through traffic on the mainline occurs when a left-turn vehicle from the mainline or a left-turn vehicle from the driveway makes an aggressive turn at a median opening by taking risky gaps.

The occurrence of a Type 3 traffic conflict is generally a result of aggressive left-turn drivers. The excessive waiting time at a driveway under heavy traffic conditions may be a cause of this type of aggressive left-turn maneuver.

Type 4—Gridlock due to aggressive left turns from a driveway (peak hours) occurs under heavy traffic conditions where a driveway and the aligned median opening are within the functional area of a signalized intersection. When the egress left turns from the driveway have to cross the queue of the downstream signalized intersection, the mainline traffic normally stops during a red interval to keep the driveway clear. However, when the signal of the downstream intersection turns green, the egress left turns, which aggressively enter the mainline but cannot be cleared, may block the mainline traffic and cause gridlock in the middle of the road (see Figure 4-16).

The occurrence of a Type 4 traffic conflict indicated that operational problems may appear where a median opening is located in the functional area of a signalized intersection.



Type 4 Type 5

Figure 4-16. Traffic Conflicts of Types 4 and 5.

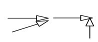
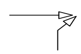
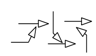
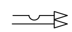
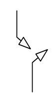
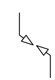
Type 5—Weaving conflict occurs where there are no full openings that are aligned to the driveways, and thus no direct left-turn maneuvers can be made from the two driveways. As a result, left-turn maneuvers have to quickly weave to the most left side lane to make left turns at a closely spaced opening downstream (see Figure 4-16).

4.4.1.2 Traffic Crash Data

For collecting crash data, the research team looked up a five-year period (from Jan 2006 to Dec 2010) of police reports. A total of 100 crash reports had been identified, and the police reports located were carefully reviewed.

Table 4-6 shows the crash counts by crash types and median openings at the study sites. In Table 4-6, four major types of crashes have been classified around opening 1 to opening 4, which are angle crash, sideswipe crash, opposing left-turn related crash and rear-end crash. And as shown in Figure 4-17, the angle crash has the highest crash rate along the test roadway segment. Sideswipe, opposing left-turn related and rear-end crash have relatively equal crash frequency. Moreover, as Figure 4-18 shows, opening 1 had the most accidents happen; 44 crashes were property damage and 19 of them had a personal injury.

Table 4-6. Crash Counts by Crash Type at Study Site 1.

Crash Type	Angle			Sideswipe			Opposing Left-Turn Related			Rear-end		Others	Total
	Code 10 Angle - Both Going Straight	Code 13 Angle - One Straight-One Right Turn	Code 14 Angle - One Straight-One left Turn	Code 21 Same Direction Both Going Straight-Sideswipe	Code 23 Same Direction One Straight-One Right Turn	Code 25 Same Direction Both Right Turn	Code 34 Opposing Direction One Straight-One left Turn	Code 36 Opposing Direction One Right Turn-One Left Turn	Code 38 Opposite Direction Both Left Turns	Code 20 Same Direction Both Going Straight-Rear End	Code 22 Same Direction One Straight-One Stopped	Code 1 OMV Vehicle Going Straight	
												-	
Opening 1	18	4	22	5	0	0	2	0	2	4	4	2	63
Opening 2	6	2	3	3	0	1	2	2	0	2	2	0	23
Opening 3	0	0	1	1	0	0	1	0	0	2	0	0	5
Opening 4	2	0	3	1	1	0	1	0	0	0	1	0	9
Subtotal	26	6	29	10	1	1	6	2	2	8	7	2	100
Total	61			12			10			15		2	

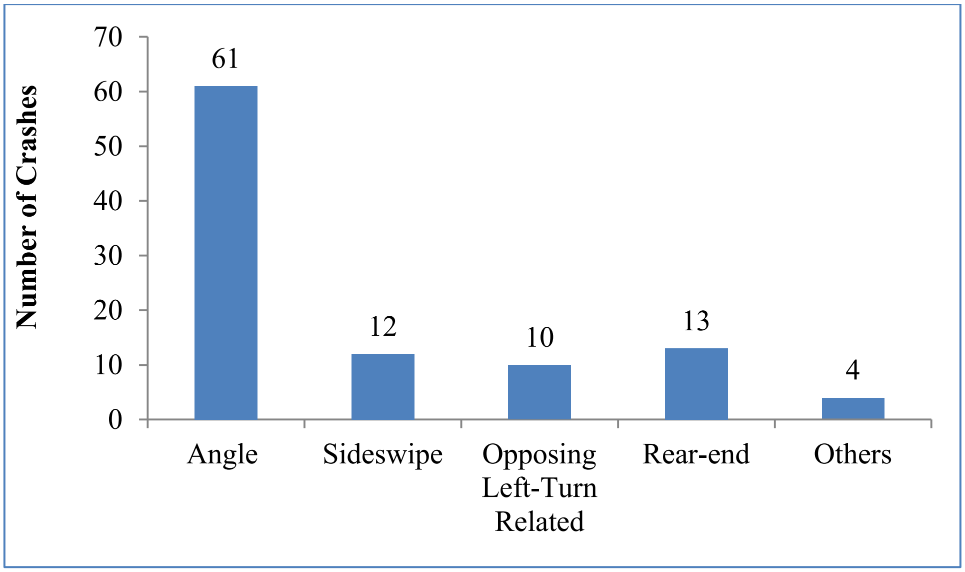


Figure 4-17. Crash Frequency by Type.

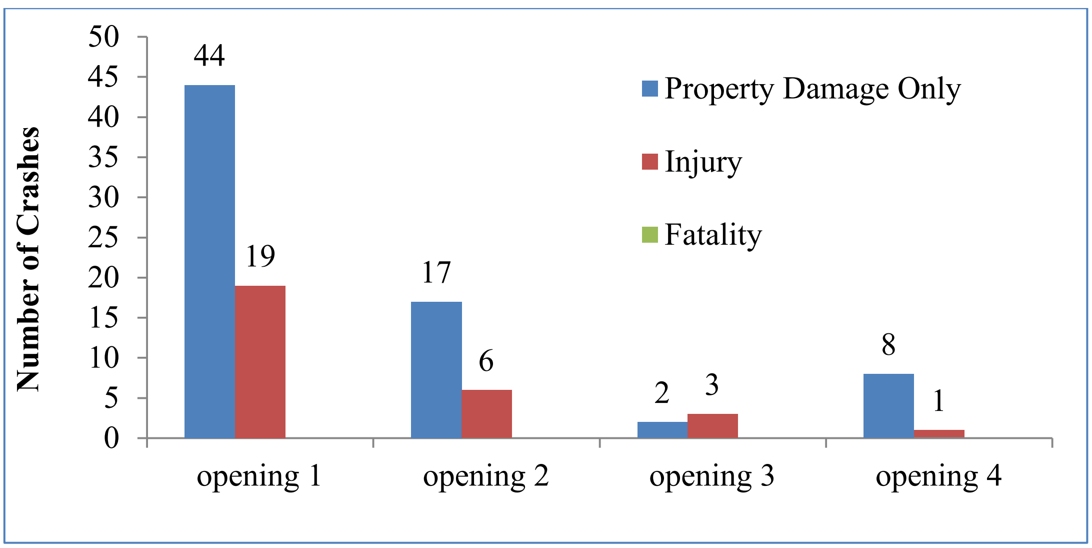


Figure 4-18. Crash Severity by Openings.

4.4.1.3 Safety Implications of the Data Collected at Jones Rd. in Houston

At this site, based on traffic conflicts observed in the field and the collected crash reports, three major safety issues associated with raised median design were identified and summarized as follows.

4.4.1.3.1 Narrow Median Opening Width

The insufficient median width is a major issue that caused conflicts and crashes in this segment. Seven of all the 29 observed traffic conflicts occurred due to the median being too narrow to accommodate a left-turning vehicle, and 15 of the 100 crashes were associated with the narrow medians. As illustrated in Figure 4-19, the blue left-turn vehicle from the driveway and the red left-turn vehicle from the mainline stopped in the opening and waited a gap to turn left. The insufficient median width, which blocked the mainline traffic and caused the conflicts with through vehicles, was unable to refuge the whole vehicle.

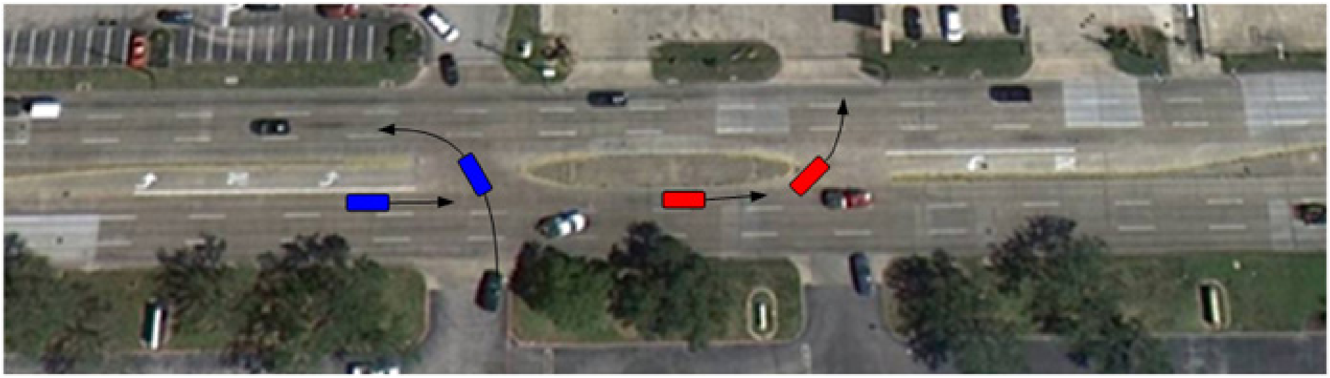


Figure 4-19. Two Types of Conflicts Caused by the Narrow Median Width.

4.4.1.3.2 High Driveway Density

There are 32 driveways or side streets on both sides along this 3,000-ft segment, and most of the driveways are not directly aligned to the median openings. This issue resulted in two other issues like weaving conflicts and right-turn queue spillback. Figure 4-20 indicates how weaving conflicts occurred. The red left-turn vehicle exited from the driveway that is very close to the downstream of the opening, which merged to the most inside lane leading to a possible weaving conflict with through traffic. There were two weaving traffic conflicts observed during the 3-day observation.

4.4.1.3.3 Median Opening within Functional Area of a Signalized Intersection

In this location, opening 1 is only 595 feet away from the major intersection of Jones Rd @ FM 1960. As shown in Figure 4-21, during peak hours, the right-turn queue will spillback to the driveway at this opening. As a result, the egress left turns from the driveway have to cross the queue to reach opening 1. Because their view is blocked by the vehicles in the queue, they may fail to detect the through vehicle approaching from the most left through lane, which will result in T bone crashes. According to the collected crash reports, during the most recent 5 years, 11 crashes that occurred at this opening were caused by this problem, and we also observed four traffic conflicts of this type during the 3-day field study. In addition, the gridlock events observed at this location were caused by this problem as we discussed before (see the Type 4 conflicts in Figure 4-16).

In addition, the main purpose for the field study at this location is to understand the benefits and shortcomings of closely spaced median openings with turn bays shorter than TxDOT standards. According to the observed traffic conflicts and the collected crash data, the following findings were obtained.

4.4.1.3.4 Short Left-Turn Bays Did Not Compromise the Safety along Studied Roadway Section at Jones Rd.

In this location, although the left-turn bays are all shorter than TxDOT standards, neither left-turn bay overflows nor rear-end conflicts inside the bays were observed during the 3-day field observation. In addition, fourteen rear-end crashes were identified along the studied segment. The crash experience showed that only one of the fourteen rear-end crashes was related to the short median left-turn lanes, i.e., at the southbound left-turn lane (260 ft in length) at median opening 2. According to the police report, the following vehicle failed to control speed and was unable to stop in time, while two vehicles stopped ahead of median opening 2. Overall, the eight median turn lanes with substandard lengths had an average rear-end crash rate of 0.025 crashes per turn lane per year, which is substantially low. The results partially indicated that the short lane lengths did not create significant safety issues. According to the field observation, it was found that given a short left-turn bay, left-turn vehicles usually gradually decelerated on the mainline travel lanes before entering the taper of the turning bay, which significantly reduced the risk of rear-end crashes. However, meanwhile, the short left-turn bays also caused traffic delays for the mainline through movements. The operational impacts of the short left-turn bay will be further evaluated in the following simulation studies.

Figure 4-20. Weaving Conflict.

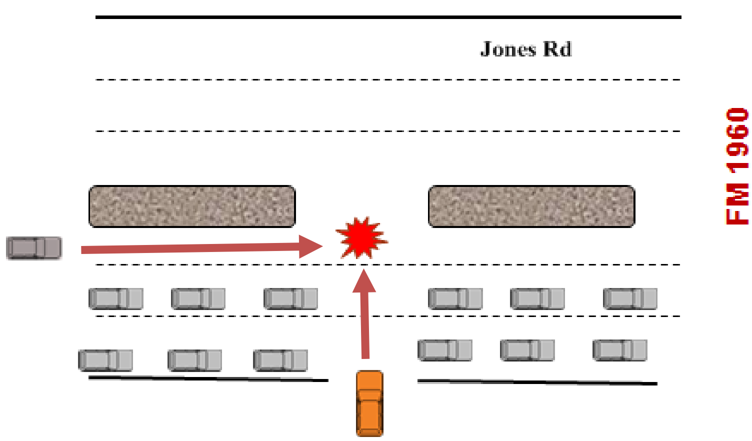


Figure 4-21. Right-Turn Queue Spillback.

4.4.2 U.S. 281 & Evans Rd. (Super Street)

4.4.2.1 Traffic Safety Data and Safety Implications at U.S. 281 & Evans Rd. (Super Street)

For the U.S. 281 Super Street location, no traffic conflicts were observed at the study intersection because it is a highly signalized location with most of the conflict movements controlled by the traffic signals. Therefore, only historical crash data and police reports were used to analyze the safety problems at this location. Historical data from January 2007 to December 2010 were collected to analyze the actual crashes along U.S. 281 near intersection U.S. 281 & Evans Rd. The Super Street in U.S. 281 was completed at the beginning of October 2010; therefore, the crash data were divided into two groups: before data and after data. Crashes that occurred before October 2010 were used as before data and crashes that occurred after October 2010 were used as after data. A total of 37 months' before data (from Jan. 2007 to Jan. 2010) with 387 crashes and 3 months' after data (from Oct. 2010 to Dec. 2010) with 34 crashes were studied. To analyze crash types, the research team has carefully reviewed 128 police reports, including 95 crashes that occurred before Super Street completion and 33 crashes that occurred after the Super Street completion.

4.4.2.2 Crash Frequency

On average, 126 crashes occurred each year before Super Street completion and 136 crashes on an annual basis after the completion, a slight increase by 7.9% in crash rate ("crash per years"), as shown in Figure 4-22.

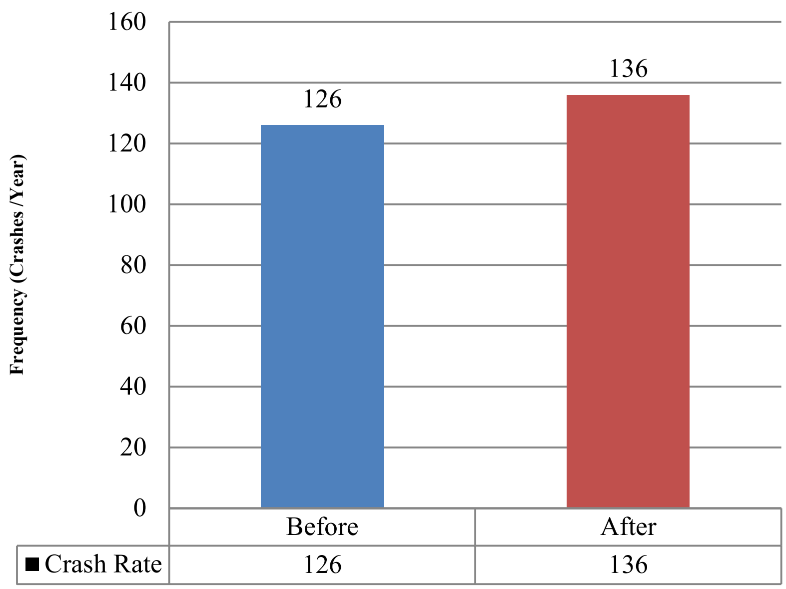


Figure 4-22. Crash Frequency around U.S. 281 & Evans Rd. (Jan. 2007–Dec. 2010).

Five major crash types were identified from the police reports: angle, sideswipe, opposing left-turn related, rear-end and others. Figure 4-23 shows the comparison of before and after crash frequencies.

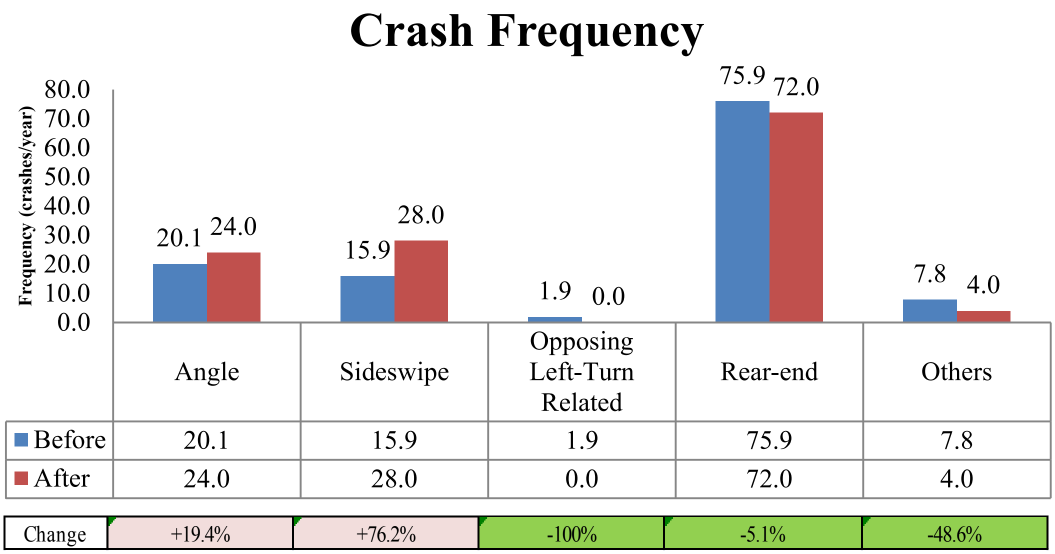


Figure 4-23. Crash Frequency by Types around U.S. 281 & Evans Rd. (Jan. 2007–Dec. 2010).

4.4.2.3 Angle Crash

Averagely, angle crashes increased 19.4% after the Super Street completion as shown in Figure 4-23. The increase is more significant in the eastbound approach from the minor road. As presented in Figure 4-25, compared with before crashes, the angle crash rate in the eastbound approach increased from 0.081 crash per year to 0.667 crash per year. In the Super Street design, through and left turn movements from minor roads are replaced by right turns followed by U-turn movements, causing more right turn traffic volume from the minor road. In the eastbound approach, right-turn-on-red is permitted, resulting in more angle conflicts.

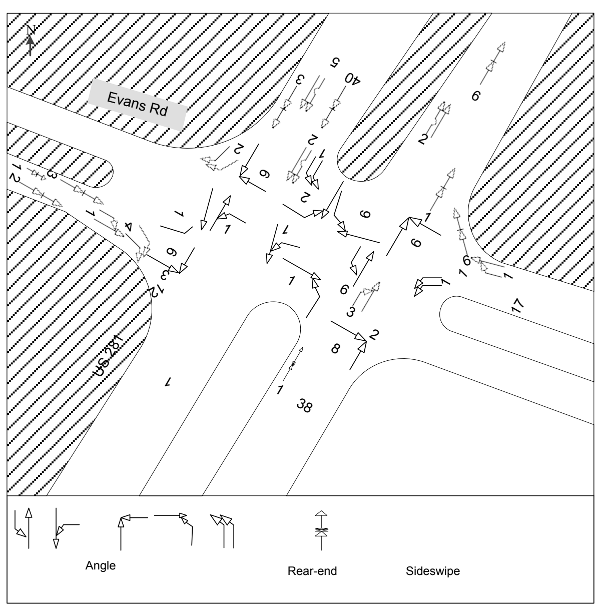


Figure 4-24. Collision Diagram before Super Street Completion.

	Before (crash/year)	After (crash/year)
RTOR (angle)	0.081	0.667

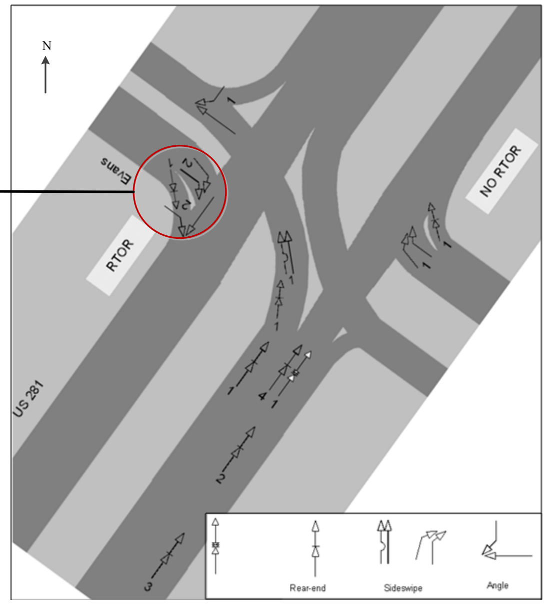
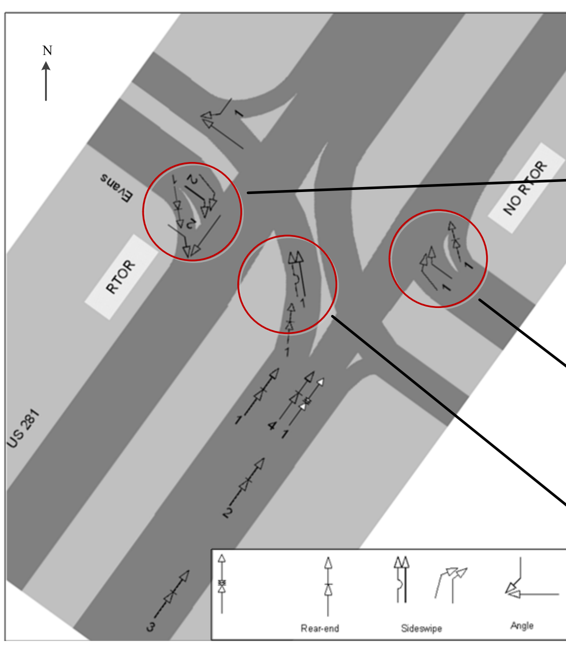


Figure 4-25. Angle Crash Diagram in Eastbound Approach after Super Street Completion.

4.4.2.4 Sideswipe Crash

According to Figure 4-23, sideswipe crashes increased 76.2%, from 15.9 crashes per year to 28.0 crashes per year. That may be because of the use of the triple right-turn lanes and double U-turn lanes. The Super Street design allows parallel right-turn or left-turn vehicles simultaneously, resulting in more sideswipe crashes. Figure 4-26 presents the comparison of before and after crash rates at different turning locations. Sideswipe crash rates increased at all the triple right-turn lane and dual left-turn lane approaches.



	Before (crash/year)	After (crash/year)
Sideswipe	0.148	0.667

	Before (crash/year)	After (crash/year)
Sideswipe	0.027	0.333

	Before (crash/year)	After (crash/year)
Sideswipe	0	0.333

Figure 4-26. Sideswipe Crash Diagram after Super Street Completion.

4.4.2.5 Opposing Left-Turn Related Crash

According to Figure 4-23, crashes between left turns and opposing through vehicles were reduced to zero because, in the Super Street design, left-turn movements from mainlines (U.S. 281) are channelized, which significantly shortened crossing distance for left turns and made it more protected, as shown in Figure 4-27.

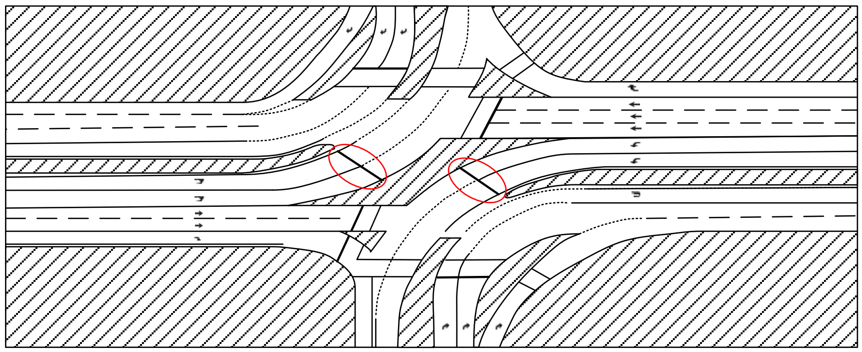


Figure 4-27. Shortened Cross Distance for Left Turns in Super Street Design.

4.4.2.6 Rear-End Crash

The rear-end crashes were also reduced from 75.9 crashes per year to 72.0 crashes per year because, in the Super Street design, traffic signal phases were reduced from five to two and traffic congestion was reduced especially on the mainline (U.S. 281). There is less stop-and-go traffic, and therefore, fewer rear-end crashes.

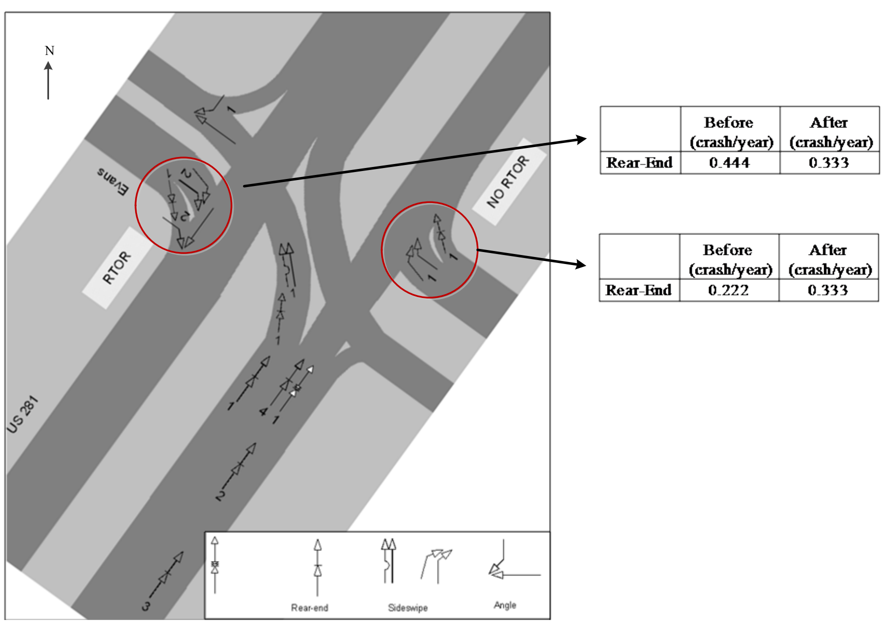


Figure 4-28. Rear-End Crash Diagram after Super Street Completion.

4.4.2.7 Overall Crash Severity

As to the overall crash severity, in the Super Street design, only injury crashes increased slightly (from 22.4% to 29.4%), while crashes of other severity level were all reduced, as shown in Figure 4-29. No fatality crash occurred after Super Street completion.

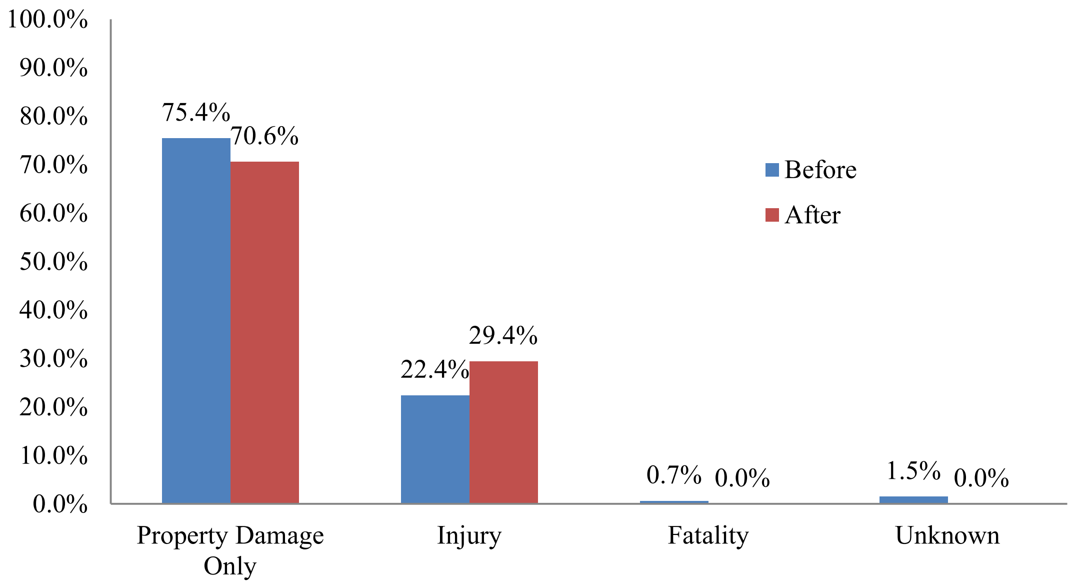


Figure 4-29. Comparison of Crash Severity around U.S. 281 & Evans Rd. (Jan. 2007–Dec. 2010).

4.5 SUMMARY

In this chapter, field studies were conducted in the two selected study sites as follows.

- Jones Road—between FM 1960 and Fallbrook for the purpose of understanding the benefits and shortcomings of closely spaced median openings with turn bays shorter than TxDOT standards.
- U.S. 281 at Evans Rd., San Antonio for the purpose of evaluating the effects of geometry design elements on the performance of a representative alternative movement, i.e., RCUT (or Super Street).

During the field study, traffic conflicts were observed; field geometric features, traffic condition information and historical crash data were collected. To collect the traffic data, including traffic volume and travel time, both traffic video counting and floating car methods were used. Base on the collected information especially the safety data (traffic conflicts and crash data), the safety issues at these two sites were identified and analyzed. Following are some key findings from these two sites.

4.5.1 Findings on Site 1 Jones Road—between FM 1960 and Fallbrook

- Narrow medians have significant, negative effects on traffic safety. Insufficient median width that is unable to refuge the whole vehicle will cause crashes/conflicts between through and turning vehicles at the median openings.
- High driveway density will increase the weaving traffic conflicts. Consolidating driveways can be a safety countermeasure for reducing weaving conflicts due to left turns at openings.

- It should be avoid placing a median opening within the influence area (queue length) of a signalized intersection, which will cause T-bone crashes between egress vehicles from the driveway and the through vehicles on the mainline and will cause gridlock problems.
- Short left-turn bays did not compromise the safety along the studied roadway section. Given a short left-turn bay, left-turn vehicles were observed to decelerate on the mainline travel lanes before entering the taper, which reduced the risk of rear-end crashes.

4.5.2 Findings on Site 2 U.S. 281 at Evans Rd., San Antonio

- Super Street/RCUT design significantly improved traffic operation for mainline traffic, but compromised traffic operation for traffic from side streets.
- Super Street/RCUT design significantly reduced crashes between left turns from mainlines & opposing traffic (shortened cross distance).
- Super Street/RCUT design increased RTOR and sideswipe crash rates from the side street approaches.
- Super Street/RCUT design reduced rear-end crash rates.

4.6 REFERENCES

1. Texas Department of Transportation, Roadway Design Manual, 2009.
2. Gaston, G. *U.S. Highway 281 Superstreet—Project Summary Report*. By Pape-Dawson Engineers, Inc., for Alamo RMA, April 2011.

CHAPTER 5: SIMULATION-BASED STUDIES FOR EVALUATING THE OPERATIONAL AND SAFETY IMPACTS OF RAISED MEDIAN TREATMENTS

In this chapter, simulation-based studies were conducted to evaluate the operational impacts of various geometric design and treatments relating to raised medians: 1) length of left-turn lanes, 2) directional vs. full median openings, and 3) median widths on four-lane highways for accommodating U-turn movements. The results of this chapter will provide a basis for developing the proposed guidelines for raised median design.

5.1 DEVELOPING SIMULATION MODELS BASED ON FIELD STUDIES AT JONES RD. IN HOUSTON

The traffic, geometric, and environmental conditions at Jones Rd (between FM 1960 and Fallbrook) in Houston, Texas, were used in the simulation experiments. Simulation scenarios were developed to replicate the observed conditions.

5.1.1 Description of the Base-Case Corridor

The study segment is located on Jones Rd. in the northwest section of Houston, Texas, and Jones Rd. is a six-lane arterial connecting U.S. Highway 290 and State Highway 249, designed and operated by Harris County, TX. Bounded by FM 1960 and Fallbrook Rd., the study segment has a total length of 3,000 ft and four full median openings along the segment. A mixture of land use for residential and small business purposes is abutting Jones Rd., and the study segment has high driveway density with a total of 32 driveways (or side streets) along this 3,000-ft segment. The posted speed limit is 45 mph (72 kph) and the peak hour traffic is heavy, approximately 1,200 to 1,600 vph in peak direction. The median openings are closely spaced, ranging from 285 to 820 ft, and the current left-turn lane lengths range from 130 ft to 260 ft.

Figure 5-1. Jones Road between FM 1960 and Fallbrook.

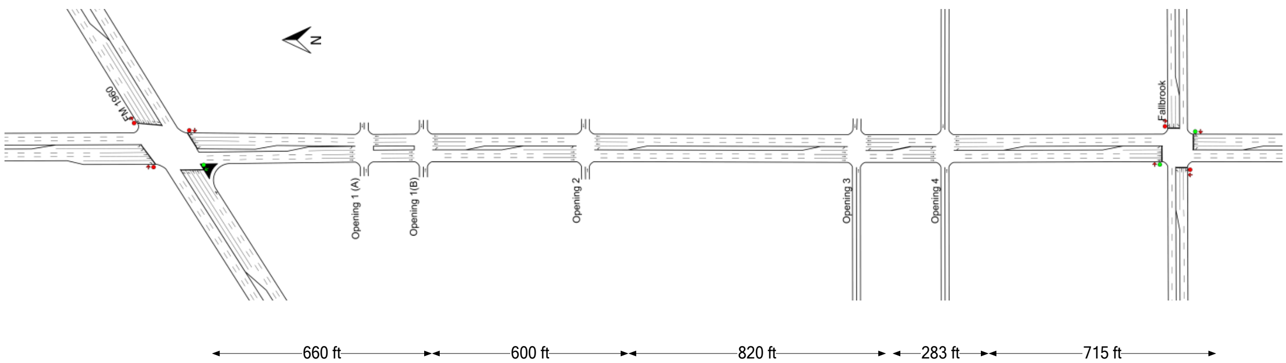


Figure 5-2. Lane Configurations of the Study Segment.

The study location has the following characteristics:

- Closely spaced median openings.
- Compromised length of left-turn lanes relative to TxDOT or AASHTO Greenbook standards.

According to the TxDOT Roadway Design Manual, the minimum turn-lane length is typically 445 ft given a design speed of 45 mph, i.e., a deceleration of 345 ft and a storage of 100 ft. According to the AASHTO Greenbook, the minimum turn-lane length should be 395 ft, including a deceleration of 345 ft and a storage of 50 ft. There are eight dedicated median left-turn lanes installed, the lengths of which range from 130 ft to 260 ft. Note that the turn-lane lengths were restricted by the frequent presence of median openings.

Table 5-1. Deceleration Lengths Suggested by the TxDOT Roadway Design Manual (2009).

Design Speed (mph)	Full length (the same as AASHTO Greenbook)	15-mph speed differential	20-mph speed differential	Minimum Storage Length (TxDOT)	Minimum Storage Length (AASHTO Greenbook)
30	160 ft	110 ft	75 ft	100 ft	50 ft
35	215 ft	160 ft	110 ft	100 ft	50 ft
40	275 ft	215 ft	160 ft	100 ft	50 ft
45	345 ft	275 ft	215 ft	100 ft	50 ft
50	425 ft	345 ft	275 ft	100 ft	50 ft
55	510 ft	425 ft	345 ft	100 ft	50 ft

Table 5-2. Lane Lengths of the Study Segment.

Lane Length	Direction	Opening 1	Opening 2	Opening 3	Opening 4
Actual length	Southbound	250 ft (76 m)	260 ft (80 m)	200 ft (61 m)	150 ft (46 m)
	Northbound	200 ft (61 m)	260 ft (80 m)	130 ft (40 m)	230 ft (70 m)

5.1.2 Calibration of the Base-Case Model

Calibration is a process of adjusting model parameters so that simulated response agrees with the measured field conditions. For our study, the objective of model calibration was to obtain the best possible match between model performance estimates and the field measurements at the study location. In this research, travel time was selected as the parameter for calibrating the base-case model.

A floating-car survey was conducted for the data collecting procedure. The floating-car method, which involved a driver and a passenger, was used to measure the travel time on the selected routes. The driver drove the route at the speed of the surrounding traffic, while the passenger recorded the travel time over the route. For the study location, the average northbound and southbound travel times along the entire studied segment were observed. The red lines in Figure 5-3 were the reference lines for measuring the times. For further calibrating the simulation models, the left-turn travel times observed at two selected openings were collected, as shown in Figure 5-3. The left-turn travel times were collected from the time when the vehicle arrived at the stop line to the time when the vehicle finished the left-turn maneuvers, entering the target driveway from the median left-turn lanes.

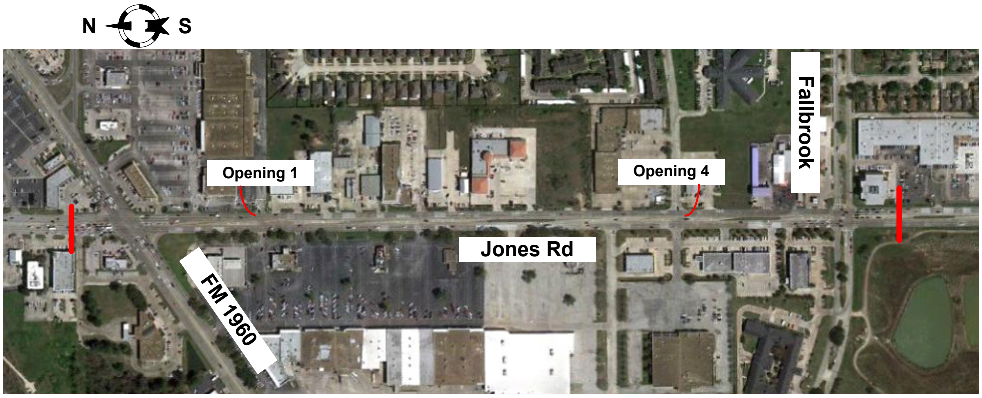


Figure 5-3. Travel Times along the Study Segment.

The calibrated models were validated by comparing simulated travel times against field observations. The results of the calibration are summarized in Table 5-3. Overall, the calibrated models were in good agreement with the observed data sets. The simulated travel times along the corridor had very low error rates of around 10%. The model also yielded reasonable estimates of travel times for the left-turn movements from the mainline.

Table 5-3. Effectiveness of Calibrated Micro-Simulation Models.

Unit: second	Travel Time Across Entire Segment		Travel Time at Median Opening 1		Travel Time at Median Opening 4	
Movements	NB	SB	SB Left Turn	NB Left Turn	SB Left Turn	NB Left Turn
Observed	181.0	134.0	40.4	15.9	22.0	11.7
Simulated	165.7	148.8	40.9	12.5	23.9	12.9
Absolute Error	-15.3	14.8	0.5	-3.4	1.9	1.2
Relative Error	-8%	11%	1%	-21%	9%	10%

5.2 OPERATIONAL AND SAFETY IMPACTS OF SHORT LEFT-TURN LANES AT UNSIGNALIZED MEDIAN OPENINGS

The purpose of this part of the simulation study is to help the researchers understand the operational and safety impacts of closely spaced median openings with left-turn lanes shorter than AASHTO/TxDOT standards.

5.2.1 Operational Impacts of Short Left-Turn Lanes at Unsignalized Median Openings

Table 5-4 lists hypothesized extensions of four of the median turn lanes, which were used in designing simulation scenarios to estimate the impacts of substandard turn-lane lengths. Assuming no changes were made to the spacing of median openings, additional lengths along the centerline were available for only four of them. Note that three of the four lanes were extended to a full length of 395 ft (including a deceleration of 345 ft, plus a taper of 50 ft in length in light of the AASHTO Greenbook).

With other settings of the median openings unchanged, the original turn lanes and the turn lanes hypothetically extended would have similar traffic conditions. This enabled straightforward comparisons to identify the impacts of short turn lanes in the simulation studies.

Table 5-4. Hypothetically Extended Lengths of Left-Turn Lanes at the Study Segment.

Lane Length	Direction	Opening 1	Opening 2	Opening 3	Opening 4
Extended length	Southbound	Unchanged	Unchanged	395 ft (120 m)	Unchanged
	Northbound	250 ft (73 m)	395 ft (120 m)	Unchanged	395 ft (120 m)

To investigate the impacts of substandard median turn lanes, four simulation scenarios were created from the base-case model, with various combinations of median left-turn lane lengths (actual/extended) and traffic volumes (100% and 120% of actual volumes). To exclude the impacts of signal timing, the software Synchro, in conjunction with SimTraffic, was used to optimize the signal timing in terms of cycle, split, and offset for the signalized intersections in each of the scenarios.

The simulation results for all the scenarios are summarized in Figure 5-4 in terms of average delay, average speed, and total travel time over the studied road segment. The results indicated that the use of short left-turn lanes did not result in significant downgrade in network operational performance.

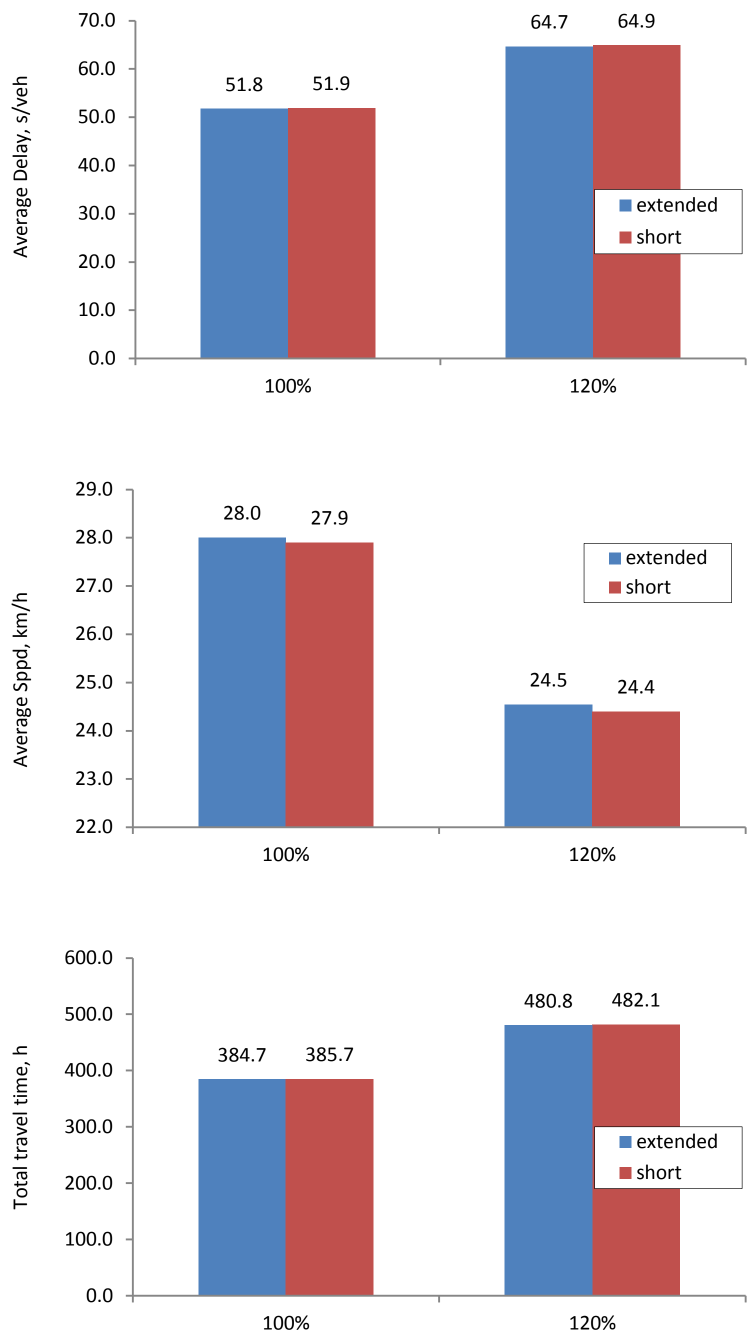


Figure 5-4. Impacts of Short Median Turn-Lane Length on Corridor-Level Operational Performance.

5.2.2 Safety Impacts of Short Left-Turn Lanes at Unsignalized Median Openings

Associated with substandard median lane lengths, major safety concerns center on excessive deceleration in the inner through traffic lane, which may create high potential for rear-end collisions. Therefore, the frequencies of rear-end crashes and rear-end conflicts were used as indicators of the safety impacts of median turn lanes of substandard lengths. A rear-end crash refers to a crash in which the front of one vehicle collides with the rear of another vehicle, while a rear-end traffic conflict means a near-collision situation when the following driver has to brake sharply to avoid a rear-end collision.

5.2.2.1 Crash Experiences

Actual crash data were collected during a 60-month period from January 2006 to December 2010 at the studied segment on Jones Rd., between FM 1960 and Fallbrook Rd. A total of 100 crashes occurred during the study period. Each crash record includes 171 fields of information entries, saved in Excel databases. The data specify exact location (e.g., geographic information system [GIS] coordinates), severity (e.g., fatalities, injuries, and property damages), crash type (e.g., the relative position, angle of involved vehicles), and other descriptions (e.g., time, weather, lighting conditions, road surface, and traffic control). In conjunction with the crash data, researchers also located police accident reports for 75 available out of the 100 crashes at the studied road segment. Researchers carefully reviewed them because such reports typically include more description and drawings, which describe how the accident happened.

As we discussed in Chapter 4, the crash experience showed that only one of the fourteen rear-end crashes was related to the short median left-turn lanes, i.e., at the southbound left-turn lane (260 ft in length) at median opening 2 (please see Table 5-5). Therefore, there are no evidence of adverse impacts of substandard turn lane length on the occurrence of rear-end crashes.

Table 5-5. Actual Rear-End Crashes along the Study Road Segment (2006-2010).

Median turn lanes studied		LT Volume, vph (PM peak)	TH Volume, vph (PM peak, 3 lanes)	Length of median turn lane, ft	Crash Count (5 years)
Opening 1	Southbound	9	1158	250	0
	Northbound	13	1514	200	0
Opening 2	Southbound	11	1163	260	1
	Northbound	53	1551	260	0
Opening 3	Southbound	16	1138	200	0
	Northbound	61	1596	130	0
Opening 4	Southbound	34	1097	150	0
	Northbound	59	1576	230	0

5.2.2.2 Simulated Traffic Conflicts

To supplement the crash analysis, a simulation-based surrogate safety study was also conducted. A computational tool known as the Surrogate Safety Assessment Model (SSAM) was used for facilitating the analysis. From the VISSIM simulation models, one vehicle trajectory file was generated from each simulation run, which was then input into SSAM for further processing. The SSAM model automatically processed the trajectories to identify traffic conflicts. Two surrogate measures of safety are used to delineate which vehicle-to-vehicle interactions should be classified as conflicts. These surrogate measures include time-to-collision (TTC) and post-encroachment time (PET), the thresholds for which need to be predetermined. The TTC concept considers two vehicles with eventually crossing trajectories and computes the time at which the two vehicles would collide if they maintained their current vectors at each time step of the micro-simulation. PET is normally defined as the time between the departure of the encroaching vehicle from the conflict point and the arrival of the vehicle with the right-of-way at the conflict point. In this study, a TTC threshold of 1.5 s and a PET threshold of 5.0 s were used. If the TTC and PET of two simulated vehicles during a micro-simulation were less than the predetermined thresholds, the interaction between them was identified as a traffic conflict. After that, according the conflict angle, the identified traffic conflicts were further categorized into lane-change, crossing, and rear-end conflicts.

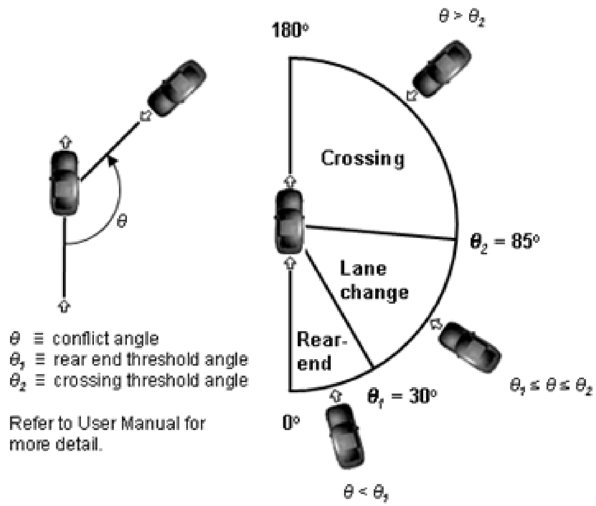


Figure 5-5. Conflict Angle Thresholds for Delineate Type of Traffic Conflicts.

Note that the actual crashes and field-observed traffic conflicts have a significant correlation at the study road segment, as shown in Figure 5-6, which verified the reasonableness of the traffic conflict study as a supplemental study approach.

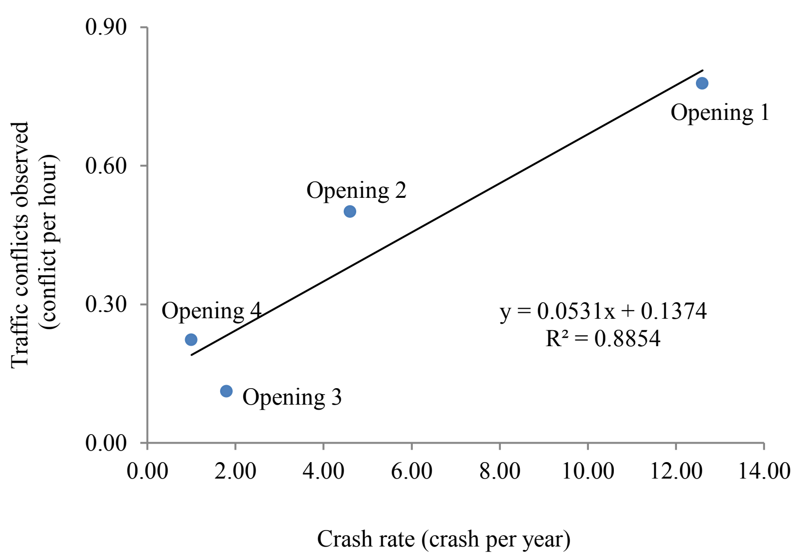


Figure 5-6. Correlation between Actual Crashes and Field-Observed Traffic Conflicts.

Using SSAM, rates of simulated traffic conflicts were acquired for each of the eight median turn lanes, given different traffic conditions and different turn-lane lengths. For a specific median turn lane, the rates of rear-end conflicts between exiting left-turn and following through vehicles demonstrated a weak correlation with the lane lengths (Figure 5-7).

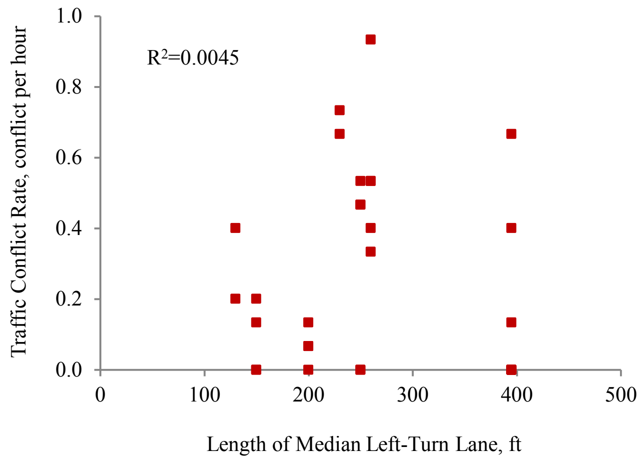


Figure 5-7. Rear-End Conflict Rate vs. Turn Lane Length.

In summary, the crash experience at the studied road segment did not demonstrate evidence of adverse impacts of substandard turn lane length on the occurrence of rear-end crashes. Statistically, rear-end conflict rates showed a weak association with the length of the median turn lanes. Generally, the results of this study indicated that the median left-turn lane with a substandard length did not result in significantly compromised safety performance.

5.2.3 Summary

Based on the studies, the operational and safety impacts of short left-turn lanes at median openings can be summarized as follows:

- Generally, a median left-turn lane shorter than full lengths suggested by the TxDOT Roadway Design Manual did not result in significantly compromised safety performance.
- Even though the delay caused by using substandard median turn lanes is relatively small, the resulting delays can add up, causing significant delays, if such lanes are used consistently along a corridor. Therefore, the desirable lengths recommended by the TxDOT Roadway Design Manual should be used whenever it is practical to do so.

5.3 OPERATIONAL AND SAFETY IMPACTS OF DIRECTIONAL MEDIAN OPENINGS

The purpose of this part of the simulation study is to help the researchers understand the operational and safety impacts of using directional median openings.

5.3.1 Design of Experimental Scenarios

A major safety concern at the study segment was associated with narrow median width, which was insufficient to accommodate an egress vehicle from driveways waiting at the median openings. As a result, significant crossing and angle crashes occurred at opening 1 and opening 2, which are located near the influence area of the signalized intersection of FM 1960 & Jones Rd. In response to this issue, a setting of a directional median opening was considered to restrict egress left turns from driveways at opening 1, in hopes of helping mitigate the safety and operational issues at this location.

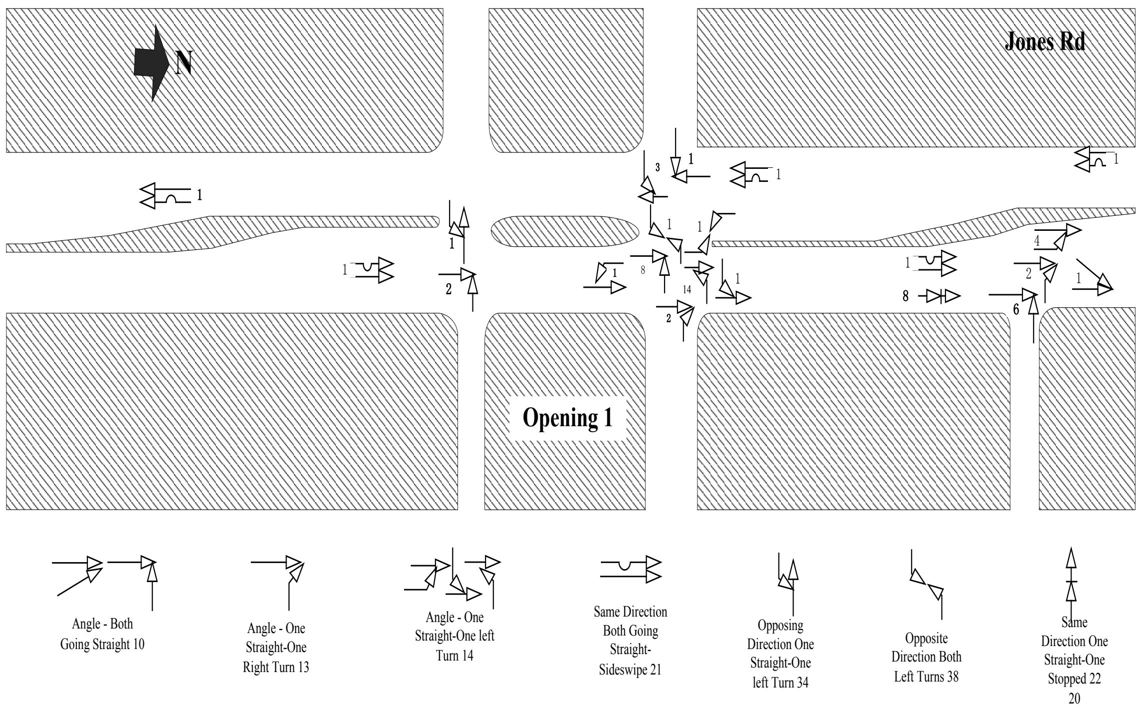
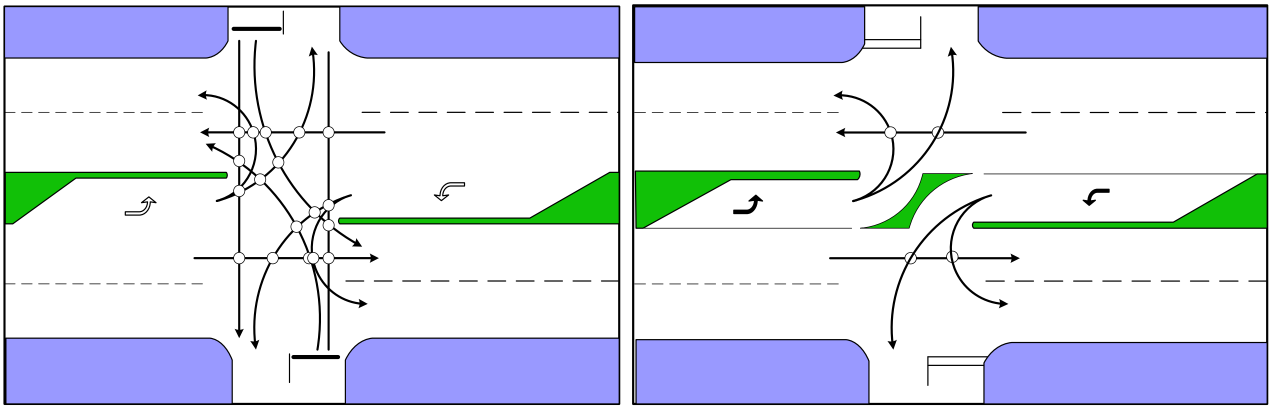


Figure 5-8. Safety Issues Relating to Left Turns from Driveways at Opening 1.

As shown in Figure 5-10, three scenarios were designed for testing and understanding the effects of directional median openings on traffic operations and safety along the corridor. Scenario I was the base case, which represented the existing geometry design. Scenarios II and III represented the situation when opening 1 was changed from a full median opening to a directional median opening, which meant that left turns from the driveways at opening 1 were not allowed.



(a) Full Median Opening, 18 Major Conflicts

(b) Directional Median Opening, 4 Major Conflicts

Figure 5-9. Full Median Opening vs. Directional Median Opening.

In Scenario II, U-turns were allowed at FM 1960, so the westbound left-turn vehicles from the driveways were rerouted to make U-turns at the intersection of Jones Rd. & FM 1960. In Scenario III, U-turns were assumed to be prohibited at FM 1960, and left-turn vehicles were rerouted to a nearest median opening downstream of the intersection of Jones Rd & FM 1960. A U-turn prohibited sign (as shown in Figure 5-11) can be installed for implementing the operation. Table 5-6 shows the characteristics of the three experimental scenarios. Figure 5-10 shows the rerouted left turns from driveways of opening 1. The signal timings were optimized by Synchro for these three simulation scenarios, which eliminated the effects of signal timing and focus on the effects of the opening settings.

Table 5-6. Experimental Scenarios Designed.

Scenarios	Opening Type	Location where left turns make maneuver	Signal setting	Driveways where egress traffic has to make indirect LT
I	Full	Left turn at Opening 1	Optimized	None
II	Directional	U-turn at Intersection of Jones Rd at FM 1960	Optimized	Driveways 1, 2, 3, and 4
III	Directional	U-turn at downstream opening	Optimized	Driveways 1, 2, 3, and 4

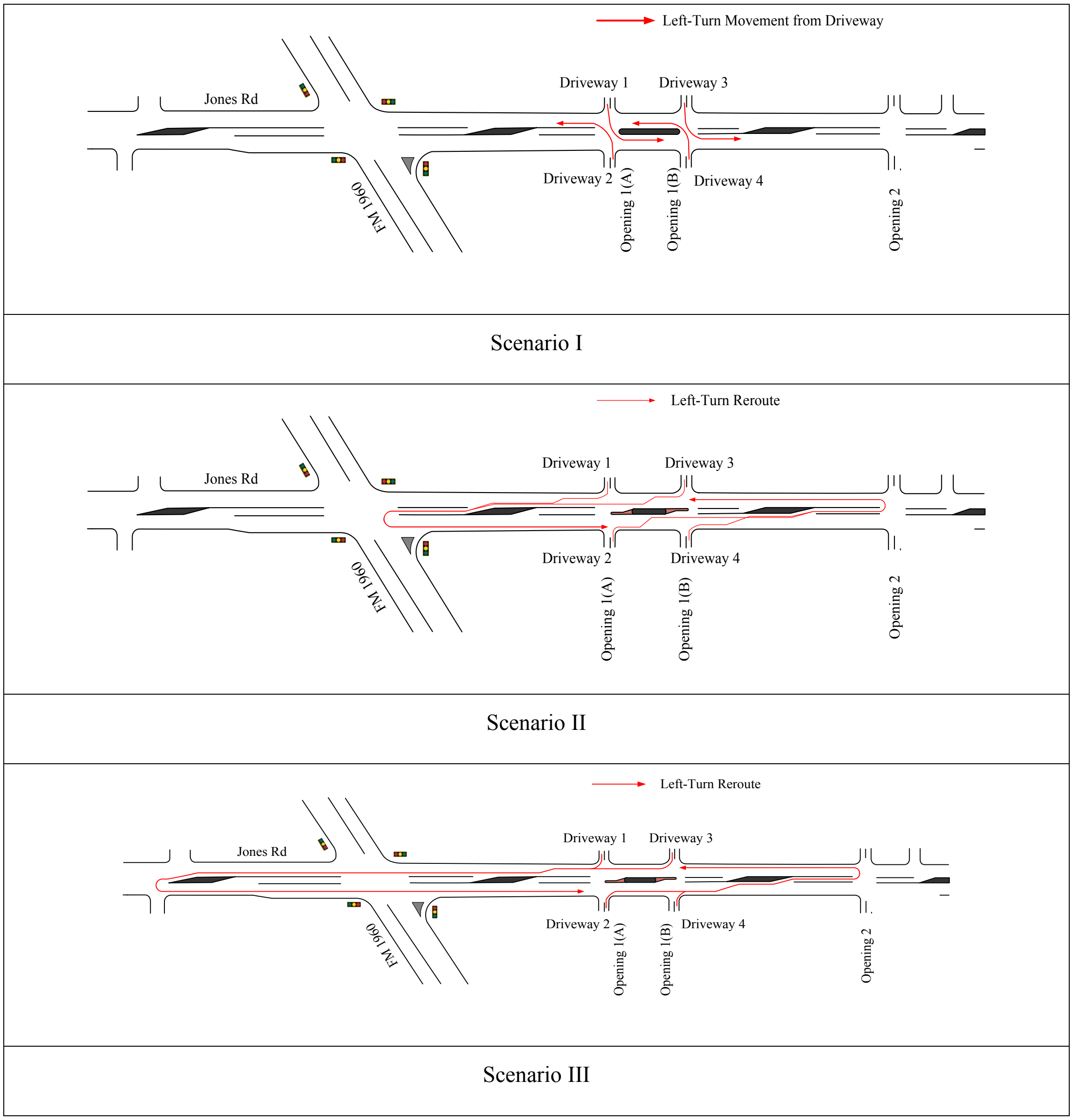


Figure 5-10. Experimental Scenarios.

Source: TxDOT MUTCD R3-4

Figure 5-11. U-Turn Prohibited Sign.

5.3.2 Operational Impacts of Directional Median Openings

VISSIM Version 5.30 was used to model and analyze the three experimental scenarios. Measures of performance, e.g., travel time, delay, and level of service (LOS), were collected from the VISSIM models for evaluating various scenarios given different geometric settings.

5.3.2.1 Impacts on the Focused Movements

Table 5-7 presents the simulation results of travel time for focused movements of this study. These movements included 1) through movements along the studied segment, 2) the left-turn movements from the mainline at opening 1, and 3) the left-turn movements from driveways at opening 1. The results show that the rerouted traffic as a result of opening 1 changed to a directional opening to increase the travel time of the through traffic along the corridor. For left turns from the mainline at opening 1, travel time in Scenarios II and III (when the direct left turns were forbidden for the driveways) was similar to that in Scenario I (when the direct left turns were allowed from the driveways). The rerouting increased the travel time dramatically for the egress left turns from the driveways.

Table 5-7. Simulated Travel Times (in Seconds).

Scenario	Through movements along the corridor		Left turns from the mainline		Left turns from the driveways	
	Northbound	Southbound	Opening 1 Northbound	Opening 1 Southbound	Driveway 1	Driveway 2
I: Base Case (full opening)	116.3	136.7	9.4	31.2	17.6	15.4
II: U-Turn allowed at FM 1960 (directional opening)	117.1	138.5	9.0	29.2	74.9	52.6
III: U-Turn at downstream FM 1960 (directional opening)	116.5	140.0	9.9	31.5	235.7	53.3

5.3.2.2 Impacts on the Network-Wide Performance

The network-wide impacts of using the directional median opening were also analyzed for the experimental scenarios. In Table 5-8, the results of the network average-wide delay and speed are summarized.

Table 5-8. Simulated Delay and Speed.

Scenario	Average Delay (s/veh)	Average Speed (mph)
I: Base Case (full opening)	55.2	27.1
II: U-Turn allowed at FM 1960 (directional opening)	56.0	27.6
III: U-Turn at downstream FM 1960 (directional opening)	70.5	24.6

The results showed that, at network levels, Scenarios I and II yielded similar results, while Scenario III has the worst operational performance over the network.

5.3.2.3 Impacts on the Signalized Intersection

The effects upon the neighboring signalized intersection were also analyzed. Table 5-9 presents the delay and LOS of the intersection for the three experimental scenarios.

Table 5-9. Signalized Intersection Delay and LOS.

Scenario	Delay (seconds)	LOS
I: Base Case	41.5	D
II: U-Turn allowed at FM 1960 & Jones	42.5	D
III: U-Turn at downstream of FM 1960 & Jones	55.4	E

The results indicated that rerouting left turns from driveways at opening 1 (by using the directional opening in Scenarios II and III) increased the delay at the signalized intersection especially for the scenario III because at the signalized intersection (FM 1960 & Jones Rd.), the v/c ratio for the northbound through movement was already quite high (i.e., =1.08). In Scenario III, by adding all the rerouted left-turn traffic to this critical movement, more congestion resulted at this intersection and the overall intersection delay increased significantly.

5.3.3 Safety Impacts of Directional Median Openings

Using SSAM, researchers investigated whether the use of the directional opening can mitigate the safety issues caused by the full median opening at median opening 1. Researchers acquired the simulated traffic conflicts, including crossing, lane-change, and rear-end conflicts for the safety analysis.

5.3.3.1 Traffic Conflicts in Each Impacted Area

As shown in Figure 5-9, after converting the full median opening into a directional opening, crossing conflicts might be mitigated because after direct, egress left-turn movements are eliminated from the driveways, all left-turn vehicles egressed from the driveways will make a right turn followed by a U-turn. However, these changes could cause additional crossing, rear-end and lane-change conflicts. In this study, areas whose safety performance could be affected by converting median openings into directional settings are termed as "impacted area." As shown in Figure 5-12, four impacted areas were bounded by red boxes as marked. They are Area 1 (the northbound approach to intersection FM 1960 & Jones Rd.), Area 2 (opening 1), Area 3 (the southbound approach to Opening 2) and Area 4 (opening 2). In order to conduct the traffic conflict analysis, all conflict data were collected from impacted areas 1 to 4 individually and analyzed type by type.

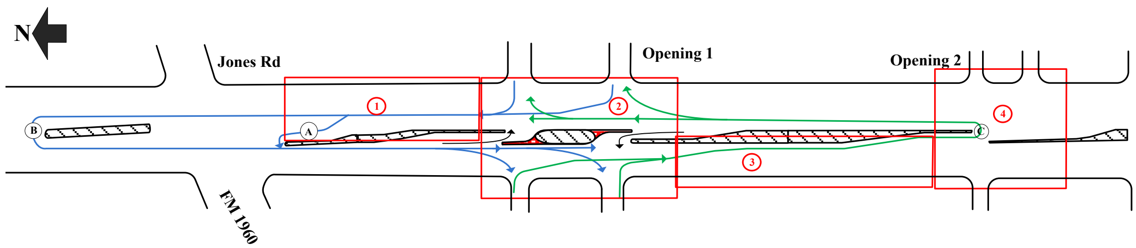


Figure 5-12. Impacted Areas in which the Safety Performance Can Be Affected by the Directional Opening.

Figure 5-13 shows the number of simulated traffic conflicts (lane change and crossing) at each impacted area. As we can see, changing opening 1 to a directional setting led to a significant decrease in the crossing traffic conflict at opening 1 (Impacted Area 2); however, the change also resulted in an increase in lane-change conflict rates, as the egress vehicles had to merge to the left after they turned right from the driveway.

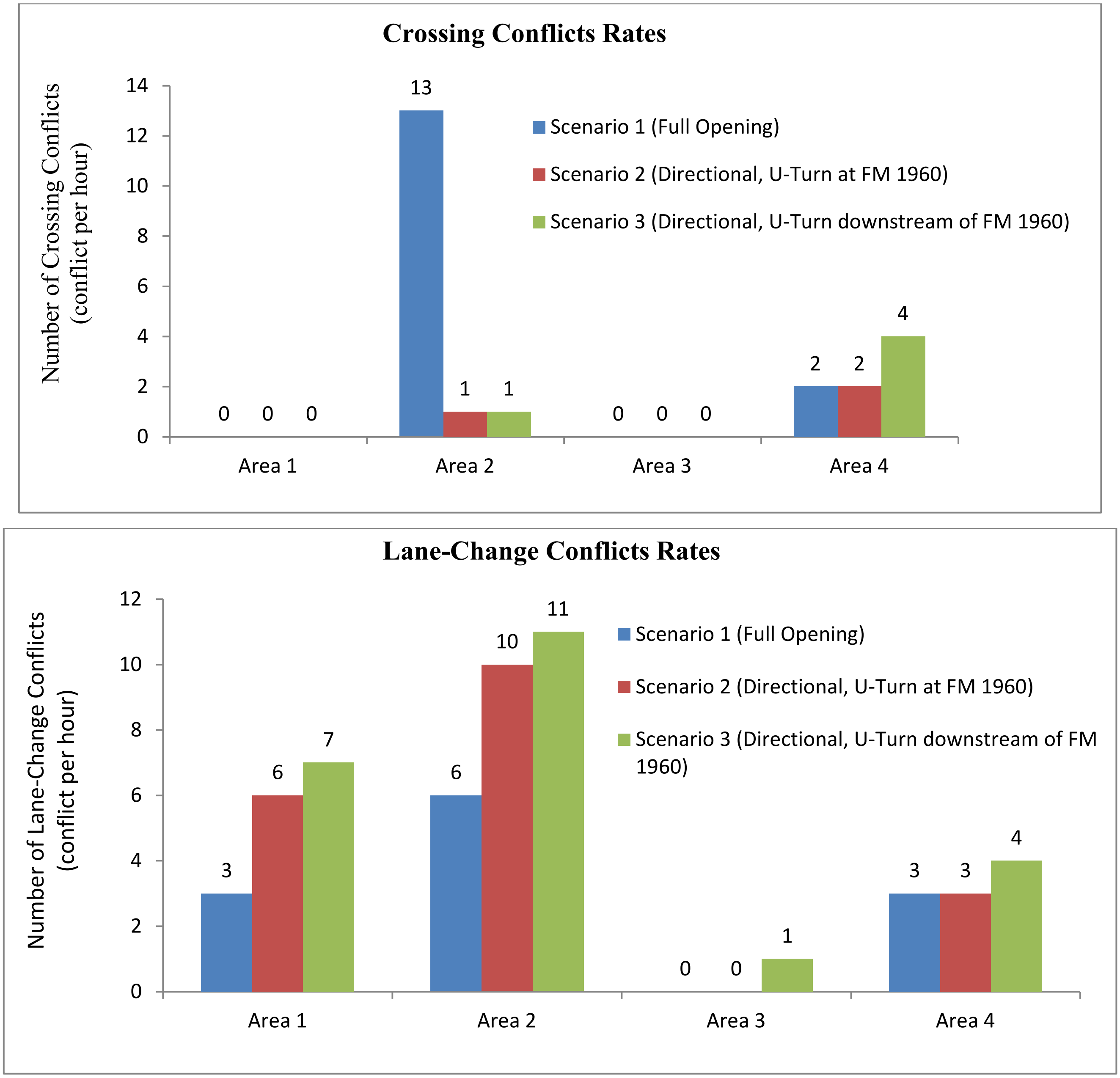


Figure 5-13. Number of Simulated Traffic Conflicts (Crossing and Lane Change) at Each Impacted Area.

5.3.3.2 Total Number of Traffic Conflicts (Lane Change and Crossing)

Figure 5-14 indicates that among the four simulated scenarios, the case with a full median opening at opening 1 had a significantly higher crossing conflict rate than when a directional opening was used. On the other hand, after converting the full median opening into a directional opening, lane-change conflict increased. While the total number of related traffic conflicts (crossing and lane change) was similar among various scenarios, the safety performance of the directional opening was generally better considering the severity of a crossing conflict is usually greater than a lane-change conflict.

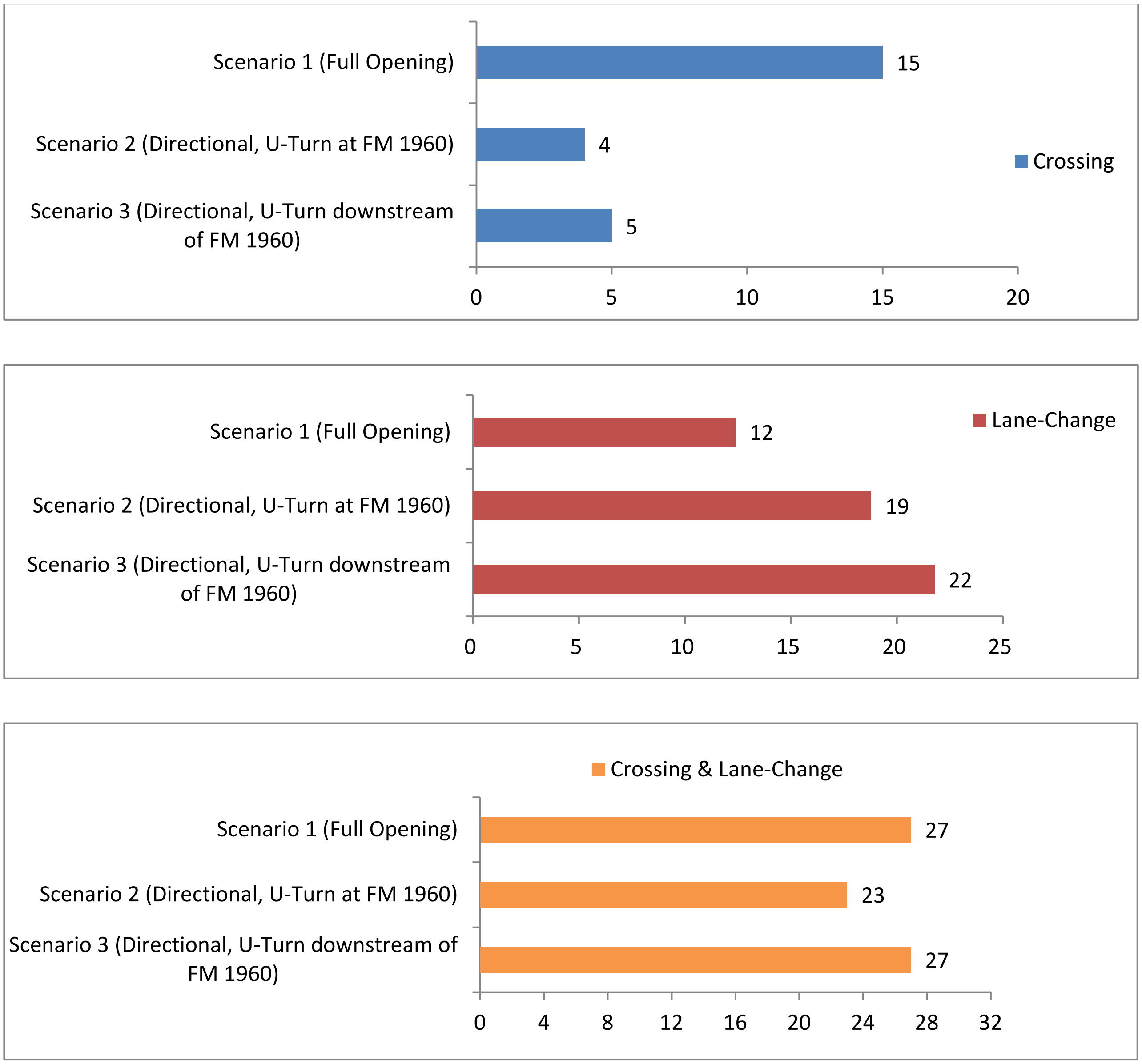


Figure 5-14. Total Number of Simulated Traffic Conflicts (Crossing and Lane Change, Conflict per Hour).

5.3.4 Summary

- In terms of traffic operations, directional median openings within the intersection influence area are generally less favorable than full median openings. Use of the directional median openings will increase the congestion level at the intersection and increase the delay for the rerouted traffic from the driveways.
- The selection of rerouting paths largely depends on the available capacity along the path to accommodate the rerouted traffic volumes. The path with bottlenecks (high V/C ratios) should be avoided as the rerouting path.

- From traffic safety standpoints, after converting the full median opening into a directional opening, crossing conflicts reduced significantly and the overall safety performance was generally improved.

5.4 FOUR-LANE HIGHWAYS IN ACCOMMODATING U-TURN MANEUVERS—SWEPT PATH ANALYSIS

A concern related to the development of urban raised median facilities is the conversion of four-lane undivided roadways to four-lane divided facilities in areas of restricted rights-of-way. The Roadway Design Manual suggests a minimum median width of 16 feet (17 feet if a pedestrian refuge is needed). The use of this minimum median width on a four-lane curbed roadway does not provide adequate space for mid-block U-turn movements by large size vehicles, such as pick-up trucks, SUVs or vans. To make this type of movement, larger vehicles have to conduct a 3-point turn into the on-coming lanes or detour through private parking lots, resulting in operational and safety issues.

The objective of this part of the study is to investigate the types of vehicles that can be accommodated by restricted ROW (i.e., 80, 90, 100, and 120 ft) through a swept path analysis. The study led to recommendations for minimum median and ROW widths to provide operationally effective urban roadways.

The swept path analysis was conducted according to AASHTO Green Book (A Policy on Geometric Design of Highways and Street, 2011, 6th Edition). The guidebook provides minimum turning path requirements for different types of design vehicles in Chapter 2—"Design Controls and Criteria." Minimum median widths for accommodating U-turn movements were calculated for typical four-lane divided highways on urban arterials. In addition, typical dimensions (e.g., lane width, borders, and offsets) were assumed for the cross-section, as shown in Figure 5-15.

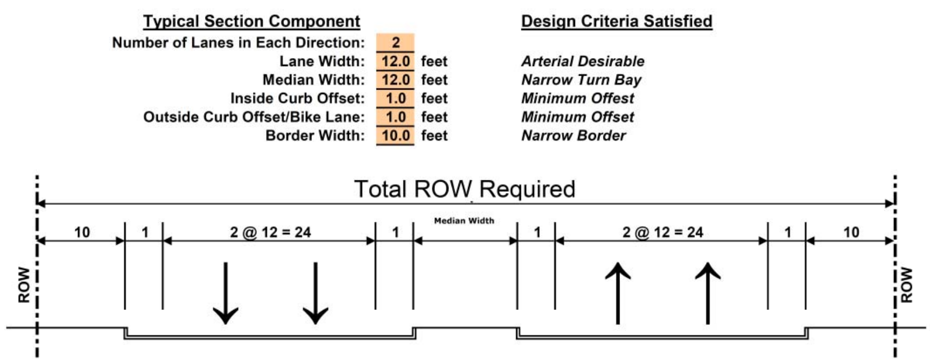


Figure courtesy of Mr. Jim Heacock, P.E., TxDOT

Figure 5-15. Urban Arterial Typical Section Design.

The minimum widths of medians to accommodate U-turns were calculated for different types of design vehicles based on the assumption that U-turn vehicles turn from the lane adjacent to the median to the outer lane on a typical four-lane divided highway.

Four types of opening designs are considered. These designs are 1) openings without dedicated left-turn bay, without loon; 2) openings without dedicated left-turn bay, with loon; 3) openings with dedicated left-turn bay, without loon; and 4) openings with dedicated left-turn bay, with loon. The equations for calculating the minimum median widths for these four types of roadway designs are shown as follows.

5.4.1 No Dedicated Left-Turn Bay, No Loon

The minimum median width can be estimated as

$$W_1 = D - 2 * 6 - 12 \quad (5)$$

where *D* is the centerline turning diameter, 12 ft is the typical width of a lane assumed in the calculation, as shown in Figure 5-16.

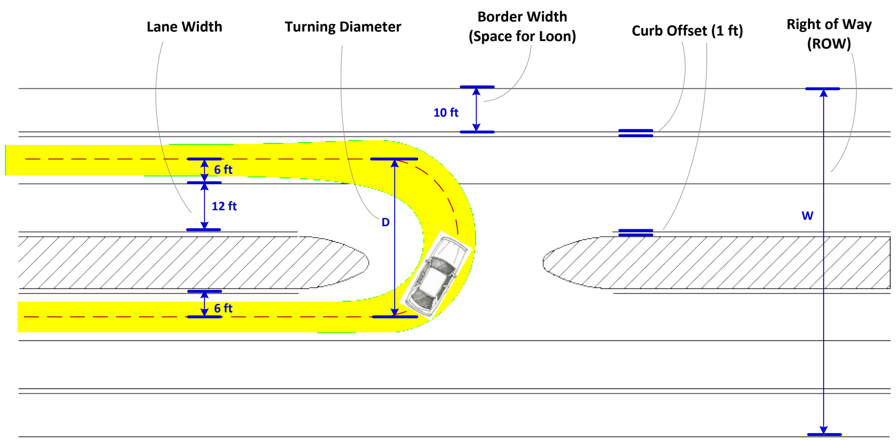


Figure 5-16. Right-of-Way to Accommodate U-Turns with No Dedicated Left-Turn Bay, No Loon.

5.4.2 No Dedicated Left-Turn Bay, with Loon

The minimum median width can be estimated as:

$$W_2 = W_1 - 10 \quad (6)$$

where 10 ft is the width of a border on the roadside. In the calculation, it is assumed that the loon should be constructed within the border area, as shown in Figure 5-17.

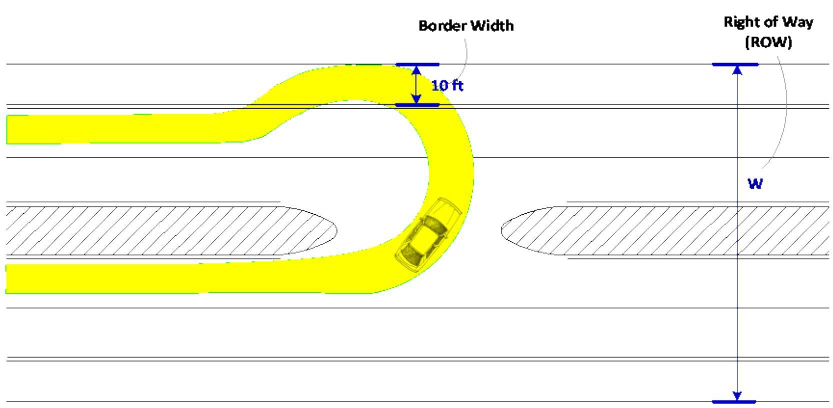


Figure 5-17. Right-of-Way to Accommodate U-Turns with Loon but No Dedicated Left-Turn Bay.

5.4.3 Roadway with Left-Turn Bay, without Loon

The minimum median width can be estimated as:

$$W_3 = D - 2 * 6 - 12 + 12 \qquad (7)$$

Figure 5-18 illustrates the calculation for the openings with dedicated left-turn bays installed, but no loon installed.

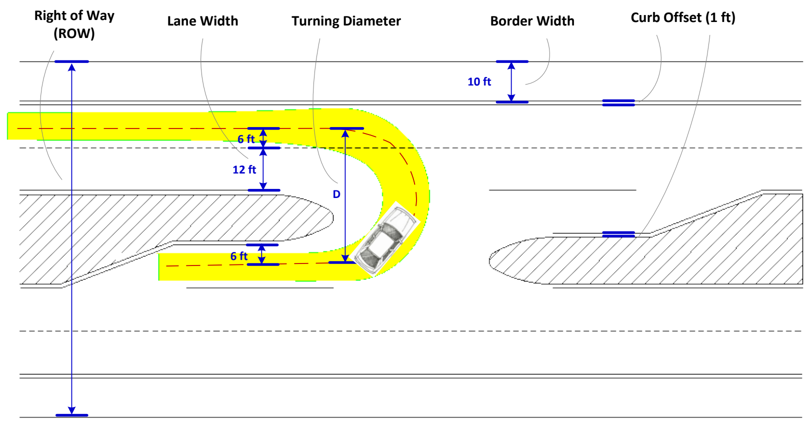


Figure 5-18. Right-of-Way to Accommodate U-Turns with Dedicated Left-Turn Bays but No Loon.

5.4.4 Roadway with Left-Turn Bay, with Loon

The minimum median width can be estimated as:

$$W_4 = W_3 - 10 \qquad (8)$$

Figure 5-19 illustrates the calculation for the openings with dedicated left-turn bays and loon installed.

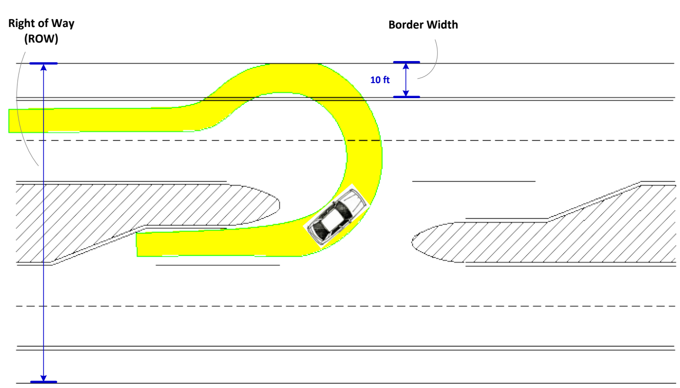


Figure 5-19. Right-of-Way to Accommodate U-Turns with Dedicated Left-Turn Bays and Loon.

5.4.5 Results of Swept Path Analysis

Based on the minimum swept paths, minimum median width is shown for different design vehicles (as shown in Figure 5-20).

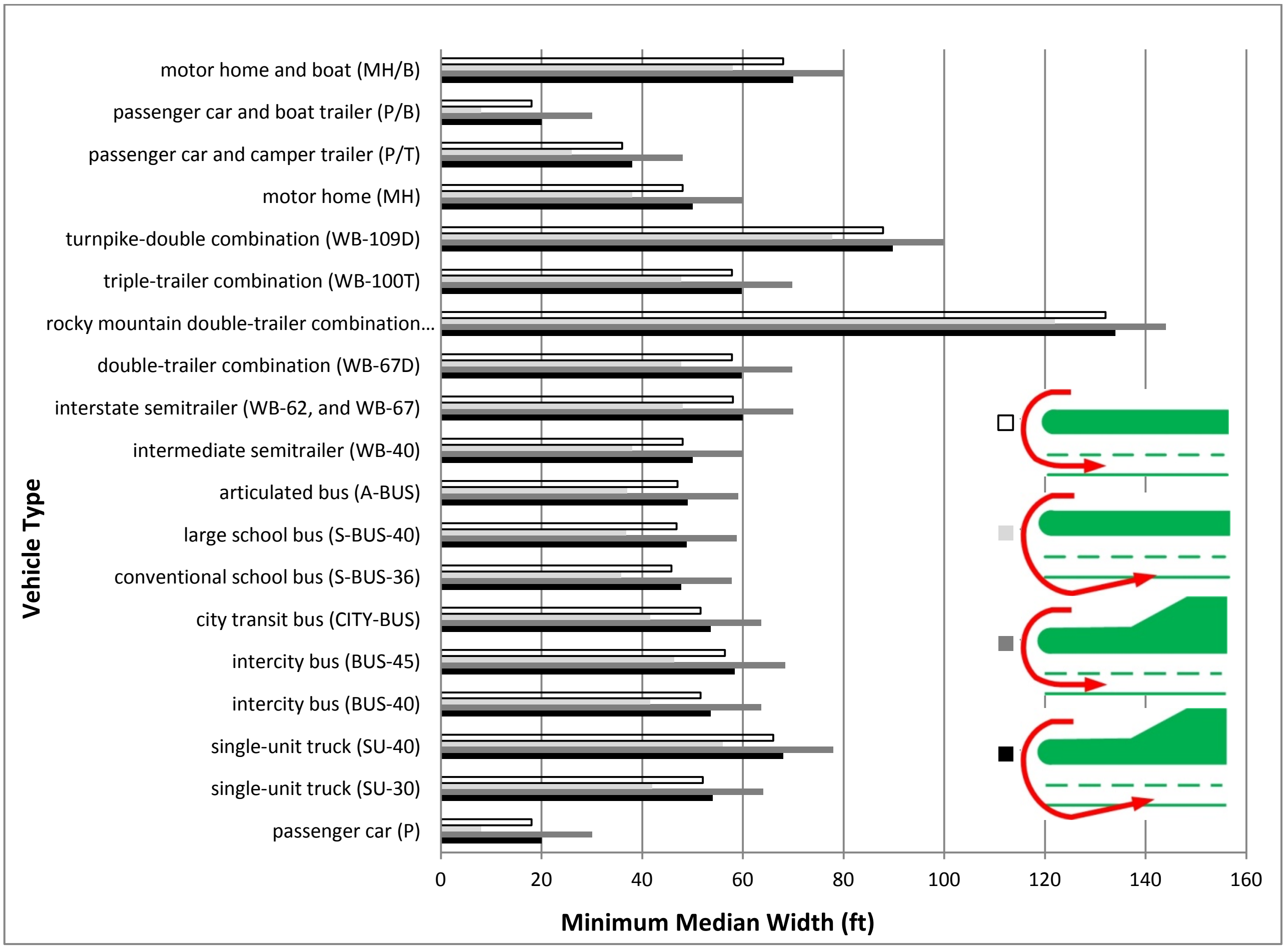


Figure 5-20. Minimum Median Width Requirements.

ROW was calculated according to the minimum median width requirements. The ROW can be calculated as follows:

$$ROW = W + 20 + 4 + 12 * 4 \qquad (9)$$

where 20 ft represents the total width of borders on both sides.

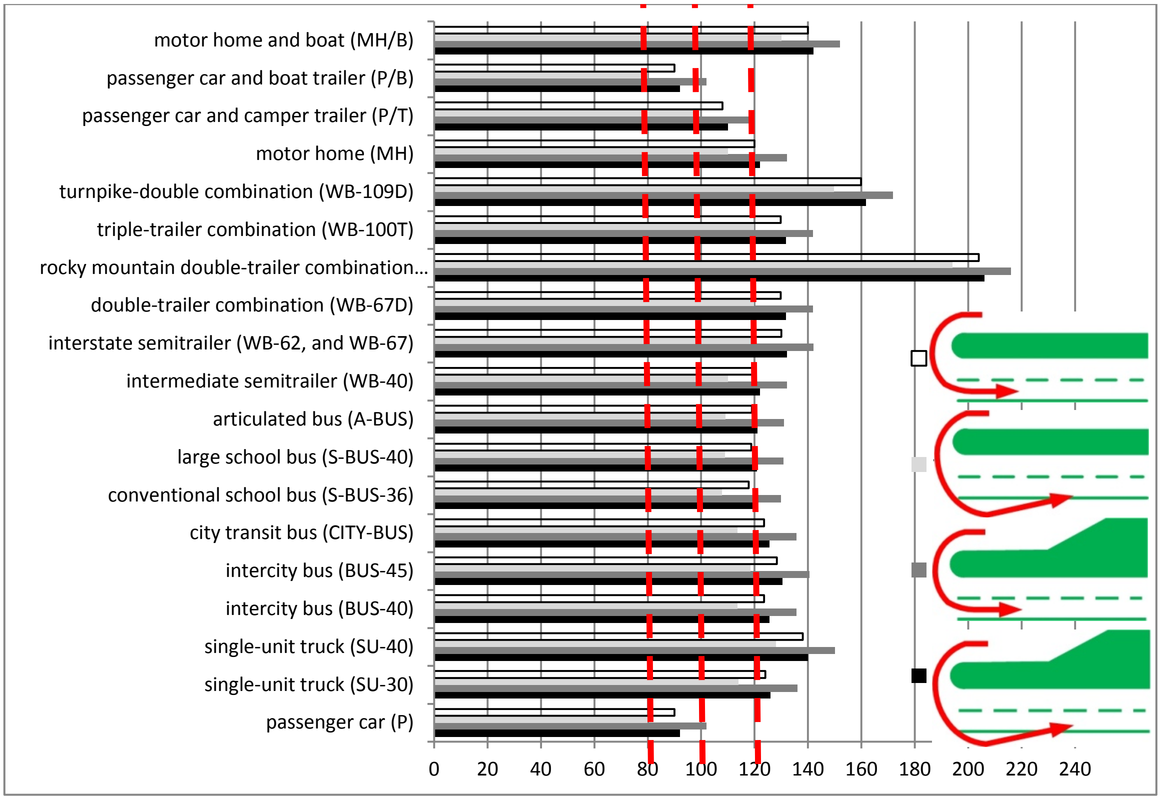


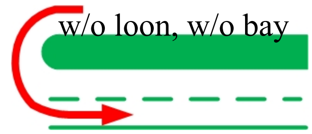
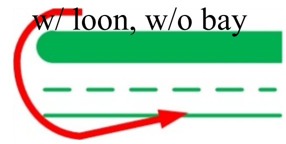
Figure 5-21. ROW for Accommodating U-Turns for Different Design Vehicles.

Figure 5-21 can be used to check whether the existing/planned ROW can accommodate U-turn movement for a particular type of design vehicle. While a left-turn lane at an opening can eliminate left-turn vehicles from stopping on the through lane, a wider median and the resulting ROW will be required (wider by approximately 12 ft). Loon is an effective way for narrow roads with restricted ROW to accommodate U-turn movements; however, business owners tend to dislike loons in front of their properties. From the results presented in this section, we can also tell what would fit in a narrow cross-section where the acquisition of additional ROW is not an option.

5.4.6 Results Validation

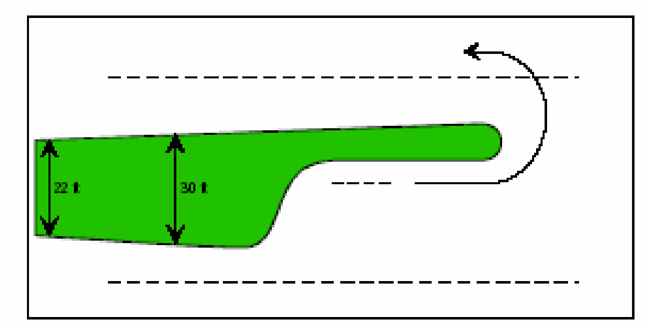
The recommended median-width values were compared with the provisions in the AASHTO Greenbook. Note that the AASHTO Greenbook only suggested the median widths for a limited number of design vehicles, and only dealt with the geometrics without median left-turn lanes. As shown in Table 5-10, the recommended median-width values are consistent with the AASHTO Greenbook suggested values, which indicate the reasonableness of the method used in this study. Actually, these results complemented the provisions in the AASHTO Greenbook.

Table 5-10. Comparison between Recommended Median-Width Values and AASHTO Values.

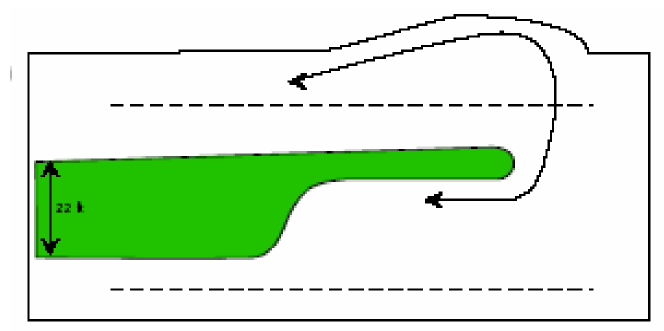
Vehicle Type	 w/o loon, w/o bay		 w/ loon, w/o bay	
	Recommended	AASHTO	Recommended	AASHTO
Passenger car (P)	18	18	8	8
Intermediate semitrailer (WB-40)	48	49	38	39
Single-unit truck (SU-30)	52	51	42	41
Single-unit truck (SU-40)	66	64	56	54
City transit bus (CITY-BUS)	52	51	42	41
interstate semitrailer (WB-62, and WB-67)	58	57	48	47

5.4.7 Designs That Help Accommodate Mid-Block U-Turns

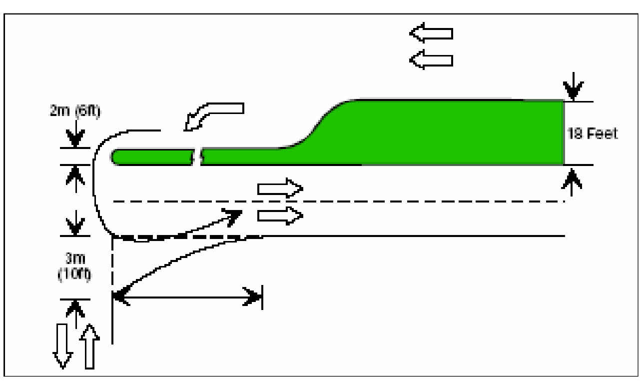
According to literature, several methods can be used for reducing the amount of needed right-of-way to accommodate mid-block U-turns, as shown in the figure below.



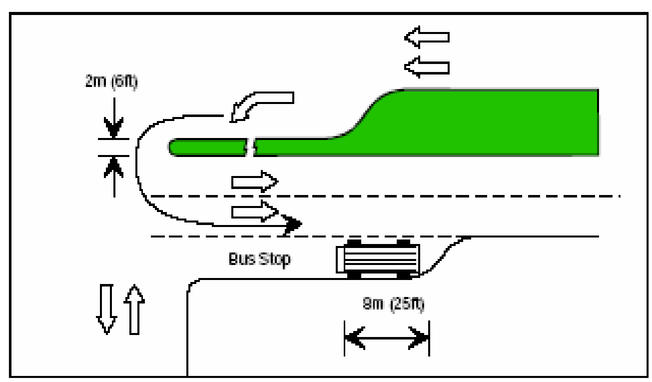
(a) Median "bulb-out"



(b) Loon or "flare-out" (Type 1)



(c) Loon or "flare-out" (Type 2)



(d) Loon or "flare-out" (Type 3)

Figure 5-22. Methods for Reducing the Right-of-Way Needed to Accommodate Mid-Block U-Turns.

5.4.8 Summary

In this section, researchers suggested a set of minimum median widths for four-lane divided roadways in areas of restricted ROW. The proposed median-width values are validated using AASHTO Greenbook recommended values. Importantly, the results complemented the recommendations in the AASHTO Greenbook, providing suggested ROW/median width for more types of design vehicles and more types of opening geometrics than the Greenbook. The results can be used to meet the need for planning and designing urban raised median roadways, particularly in the conversion of four-lane undivided roadways for future projects.

5.5 REFERENCES

1. *A Policy on Geometric Design of Highways and Streets*. American Association of State Highway Transportation Officials (AASHTO). Washington, D.C., 2011.
2. *Surrogate Safety Assessment Model and Validation: Final Report*, FHWA-HRT-08-051, May 2008.
3. *Synchro 6 User Guide*. Trafficware Ltd, 2005.
4. Texas Department of Transportation, Roadway Design Manual, 2009.
5. *VISSIM 5.30-04 User Manual*. PTV, 2011

CHAPTER 6: GUIDELINES FOR OPERATIONALLY EFFECTIVE RAISED MEDIANS

The purpose of this chapter is to develop guidelines for operationally effective raised medians based on the results from the previous chapters.

In proposing the guidelines, both operational and safety performances were considered. In this chapter, the recommended guidelines were highlighted in shaded text boxes for easy reference.

Guideline 1 – Conditions under which installation of a raised median needs to be considered

An average daily traffic (ADT) exceeds 20,000 vehicles per day or new development is occurring.

Other factors, including high midblock left-turn volumes, excessive number of driveways, and high accident rates, should also be taken into the consideration when determining whether a raised median should be used.

This guideline is based on the TxDOT Roadway Design Manual, the results of the literature review in Chapter 2 and the survey of traffic engineers conducted in Chapter 3. According to the survey results, 64.7% of Texas respondents and 44.0% elsewhere have guidelines for considering median installation based upon the ADT volume. The threshold varies greatly between 10,000 and 30,000 vehicles per day (out-of-state responses often were at the higher end of that range, at least 20,000 vehicles per day). Therefore, the current provision (20,000 vpd) in the TxDOT Roadway Design Manual represents a reasonable threshold to trigger the consideration for TxDOT engineers.

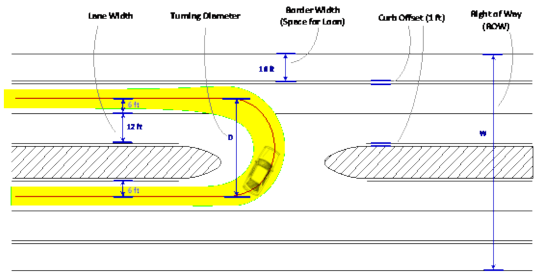
In addition, 41.2% of Texas respondents and 36.0% elsewhere have guidelines for considering median installation based upon high mid-block turning volume, 23.5% of Texas respondents and 36.0% elsewhere have guidelines for considering median installation based upon an excessive number of driveways, and 23.5% of Texas respondents and 56.0% elsewhere have guidelines for considering median installation based upon a high accident rate. There were very few responses to high design speed as a factor to spur discussion of raised median installation. This guideline is also consistent with the existing guidelines used by other states and the results of existing studies.

<u>Guideline 2 – Median width:</u>

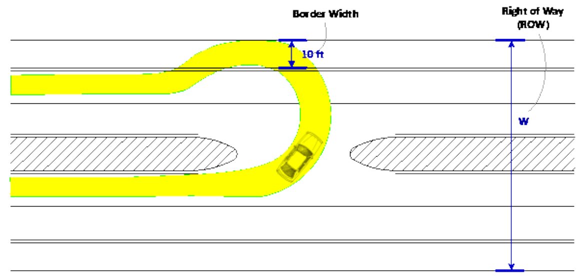
Minimum urban median widths: Typical median width should be at least 16 ft, including a 12-foot lane plus a 4-foot separator. However, for four-lane urban roadways, if mid-block U-turn is allowed, the minimum median width needs to be determined according to the swept path analysis of a design vehicle (Figure 6-1).

Desirable urban median widths: Where the right-of-way is available, a median width of 25 ft is recommended that can provide sufficient refuge for at least one left-turn vehicle.

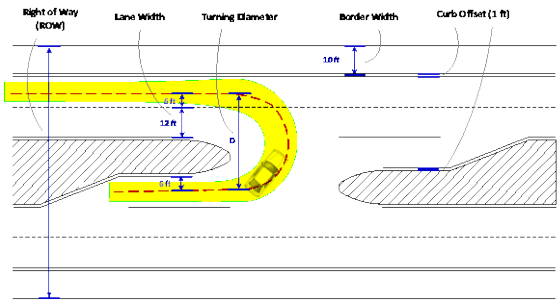
This guideline is based on the TxDOT Roadway Design Manual, the results of the traffic conflicts study (Chapter 4), and the vehicle swept path analysis (Chapter 5). The current TxDOT Roadway Design Manual suggests a width of 16 ft for urban median widths. However, typically, the minimum median width of 16 ft on a four-lane roadway does not provide adequate turning radius for mid-block U-turn movements by trucks. In Chapter 5, a vehicle swept path analysis was conducted to derive the minimum median widths for accommodating U-turn movements on four-lane roadways for four different types of median opening designs: 1) openings without a dedicated left-turn lane or loon; 2) openings without a dedicated left-turn lane, but with loon; 3) openings with a dedicated left-turn lane, but without loon; and 4) openings with a dedicated left-turn lane and a loon. Please see Figure 6-1 for these four designs and Figure 6-2 for the derived minimum median widths. Note that the results in Figure 6-2 also can be used for determining the types of vehicles that should be prohibited for making U-turns at a median opening with a given width.



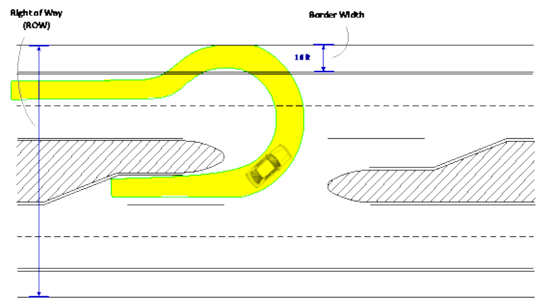
(a) w/o dedicated left-turn bay, w/o loon



(b) w/o dedicated left-turn bay, w/ loon



(c) w/ dedicated left-turn bay, w/ loon



(d) w/dedicated left-turn bay, w/ loon

Figure 6-1. Four Different Types of Median Opening Designs.

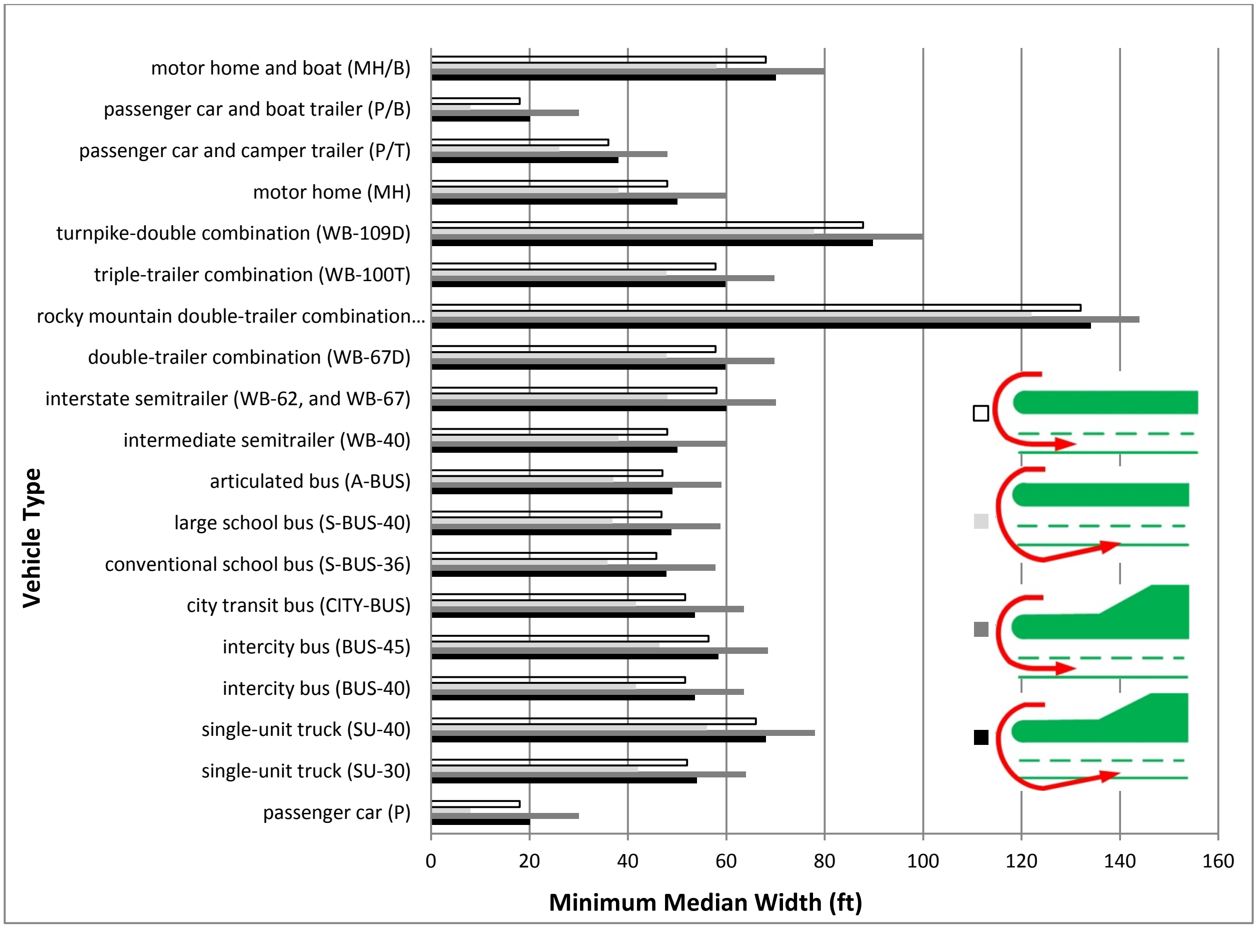


Figure 6-2. Minimum Median Width Requirements.

In addition, based on the traffic conflict study conducted in Chapter 4, a median width narrower than the length of a regular full-size passenger car was associated with a significant number of traffic conflicts and crashes involving a left-turn vehicle egress from driveways. Therefore, where the right-of-way allows, a median width of 25 ft is recommended that can provide sufficient refuge for at least one left-turn vehicle from side streets/driveways.

<u>Guideline 3 – Placement of median openings:</u>

<u>When and where to place a median opening:</u>

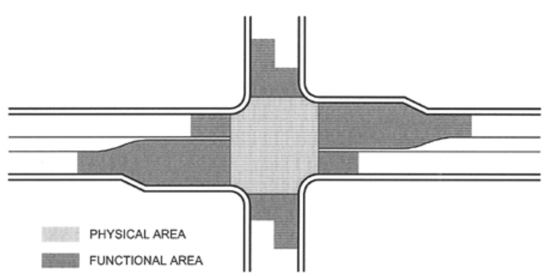
- Spacing of the median opening should be selected to provide openings at all public roads and at major traffic generators such as industrial sites or shopping centers.
- Additional openings should be provided so as not to surpass a maximum of one-half mile (about 2,640 ft) spacing (in particular, at the areas that have to provide access to U-turn movements on long sections of a continuous raised median).

<u>When and where not to place a median opening:</u>

- Openings should be avoided in the functional areas of intersections, especially when traffic conditions (e.g., heavy left-turn egress from driveways) pose operational or safety problems.
- Openings should not be provided at locations where the stopping sight distance is inadequate.
- Median openings that allow the movements across exclusive right turn lanes should be avoided.

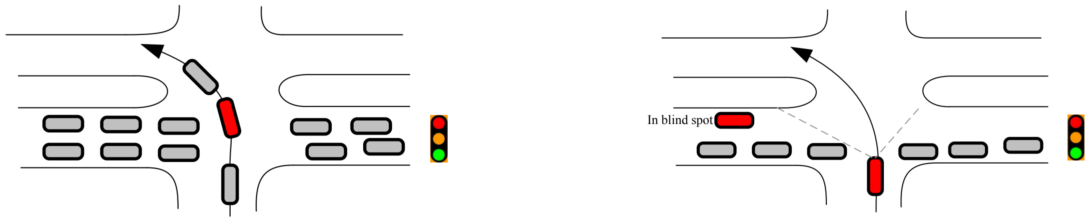
The recommended guidelines were mainly based on the TxDOT Roadway Design Manual, the literature review in Chapter 2, and the safety-impact analysis in Chapters 4 and 5.

The guidelines for when and where to place a median opening were directly from the TxDOT Roadway Design Manual. The basic concept used in median opening placement and design is to avoid unnecessary conflicts that result in crashes. The crash analysis and the field traffic conflict study conducted in Chapter 4 indicated that median openings placed within the functional areas (shown in Figure 6-3, which consists of distance traveled during perception/reaction time, plus deceleration distance, plus queue storage) of intersections resulted in gridlock problems as shown in Figure 6-4 (a) or resulted in impaired sight distance for drivers exiting from the driveways as shown in Figure 6-4 (b). As an example, in the studied location, a roadway segment at Jones Rd between FM 1960 and Fallbrook, the median opening placed in the intersection functional areas of Jones Rd. & FM 1960 had a significant higher crash rate than the other openings that were not in functional areas. Please see the crash diagram presented in Figure 6-5.



Source: Signalized Intersections: Informational Guide, 2004.

Figure 6-3. Illustration of Intersection Functional Area.



(a) Gridlock due to aggressive egress left turns from driveway (operational issue)

(b) Impaired sight distance for drivers exiting from the driveways (safety issue)

Figure 6-4. Adverse Impacts of Median Openings in the Functional Areas of Intersections.

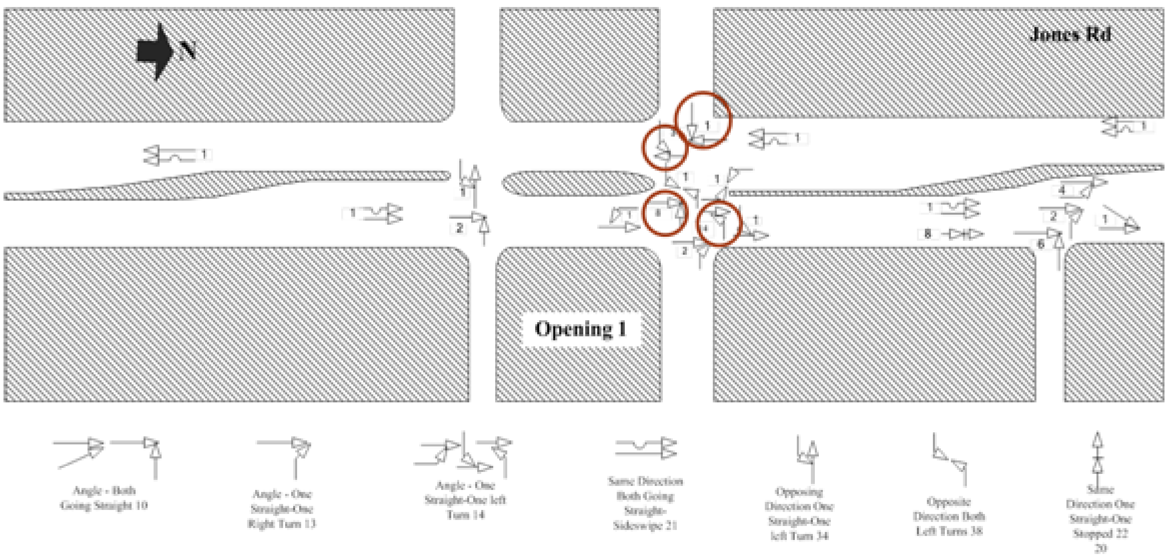
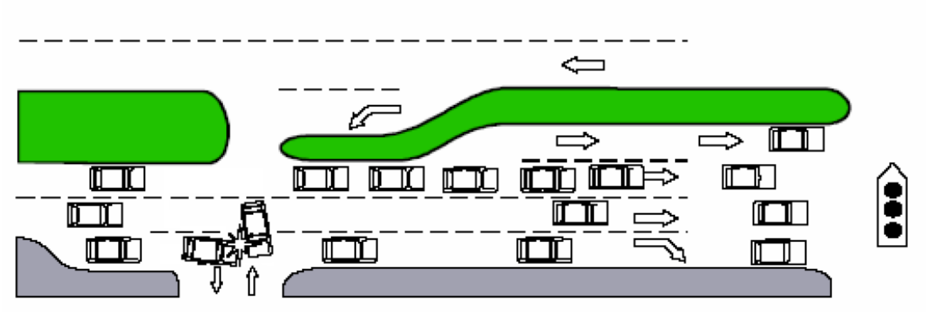


Figure 6-5. Adverse Safety Impacts of Median Openings in the Functional Area of Intersections.

In addition, according to the TxDOT Roadway Design Manual and the design manuals of Missouri and Montana, openings should not be provided at locations where the stopping sight distance is inadequate. Furthermore, according to the Median Handbook of the Florida Department of Transportation, median openings that allow the movements across exclusive right turn lanes should be avoided because, as shown in Figure 6-6, when queues build up across the opening area, some "nice drivers" might allow the left turner through, only to crash with a vehicle moving freely in the separate right-turn lane.



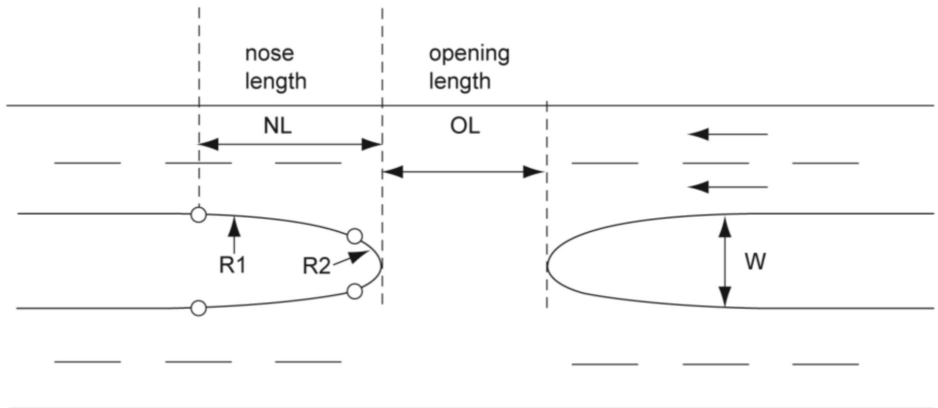
Source: Median Handbook. Florida Department of Transportation, 2006.

Figure 6-6. An Unfavorable Median Opening That Allows the Movements across an Exclusive Right-Turn Lane.

<u>Guideline 4 – Length of median openings</u>

- Median opening lengths should not be less than 40 ft.
- The required median opening lengths can be determined based on the types of design vehicles, median width, and median nose design. Please see Figure 6-7.

These guidelines were developed based on the TxDOT Roadway Design Manual and the AASHTO Greenbook, 2011.



Length of Median Opening (OL, feet)		
Width of median (W, feet)	**Passenger Car (P)**	
	Semicircular	Bullet nose
4	76	76
6	74	60
8	72	56
10	70	56
12	68	56
14	66	56
16	64	56
20	60	56
24	56	56

Length of Median Opening (OL, feet)				
Width of median (W, feet)	**Single Unit Truck (SU-9)**		**Semitrailer Truck (WB-40)**	
	Semicircular	Bullet nose	Semicircular	Bullet nose
4	96	96	146	122
6	94	76	144	121
8	92	68	142	112
10	90	62	140	104
12	88	58	138	98
14	86	56	136	92
16	84	56	134	88
20	80	56	130	78
24	76	56	126	72
28	72	56	122	65
32	68	56	118	60
36	64	56	114	54
40	60	56	100	49

Figure 6-7. Length of Median Openings.

Source: AASHTO 2011

Guideline 5 – Length of dedicated left-turn lanes at median openings

Where an adequate length is available between adjacent openings

- Generally, the provisions in the TxDOT Roadway Design Manual (2010) should be complied with in determining the deceleration and storage lengths.

Where inadequate lengths are available between adjacent openings

- Case-by-case engineering studies are desirable for the decision on using the turn-lane lengths shorter than the TxDOT Roadway Design Manual standards.
- The following equation can be used for estimating the minimum necessary left-turn lane length when providing the desirable lane length is impractical at an unsignalized opening:

  $$L = D + \max\left(50,\ (V \cdot S / 30)\right)$$

  where D = the deceleration length (ft), according to the TxDOT standards under the 20-mph speed differential in Table 1; V = the left-turn volume (vph); 50 = the minimum storage length (ft) required by the AASHTO Greenbook; 30 = the number of two-minute intervals in each hour; S = the storage length for a waiting vehicle, and 25 ft/veh can be used when the percentage of trucks is under 5%.
- Signalization can be considered to control the queue lengths with proper signal timing where a short turn-lane length is proven inappropriate by engineering studies.

Table 6-1. TxDOT Standards for Deceleration Lengths in a Left-Turn Lane (ft).

Design speed (mph) \ Assumed speed differential	AASHTO	TxDOT	TxDOT	TxDOT
	10 mph	10 mph	15 mph	20 mph
30	160	160	110	75
35	(215)	215	160	110
40	275	275	215	160
45	(345)	345	275	215
50	425	425	345	275
55	(510)	510	425	345

In urban areas, the requirements for the deceleration and storage of turning vehicles may exceed the available length between two adjacent openings, especially for the arterials with high design speeds and high demand for left-turn movements. On the other hand, if the frequency of median openings is reduced, the demand for mid-block U-turns will increase and will result in longer storage length requirements. Research efforts were made in Chapter 3 (the survey), Chapter 4 (crash analysis, traffic conflict study, and field data collection), and Chapter 5 (the simulation studies).

In the Greenbook standards, it was implicitly assumed that left-turn vehicles travel at the design speed when entering the taper of a left-turn lane (i.e., entry speed=design speed), and that they will decelerate about 10 mph when they have cleared the through-traffic lane. However, our field observations (Chapter 4) indicated that in advance of a substandard left-turn lane, the entry speed was normally 10 mph less than the design speed. When they have cleared the through-traffic lane, the speed can be 20 mph less than the design speed. Therefore, the TxDOT standards in Table 6-1 (assuming 20-mph speed differential and suggesting 85 ft to 160 ft shorter than the Greenbook provisions) generally pose no problems with having left-turn vehicles coming to a full stop.

In the study performed for Jones Rd. between FM 1960 and Fallbrook, most of the eight left-turn lanes are about 260 ft in length, which accommodated the deceleration length of 215 ft suggested by the TxDOT standards (for a design speed of 45 mph), plus a storage of 50 ft required by the Greenbook standards. The case study showed that the lanes that adhered to these standards presented appropriate operational and safety performance in cases in which providing the desirable full-deceleration lengths is impractical due to restricted conditions.

Guideline 6 – Conditions under which a median left-turn lane should be considered for four-lane highways

- The thresholds suggested by Harmelink (1967) can be used to determine the need for a dedicated median left-turn lane on four-lane highways (Figure 6-8).

The thresholds suggested by Harmelink (1967) are one of the most widely accepted warrants for a median left-turn lane. They are also the basis for the current version of the AASHTO Green Book, which mainly deals with warrants for left-turn lanes on two-lane highways.

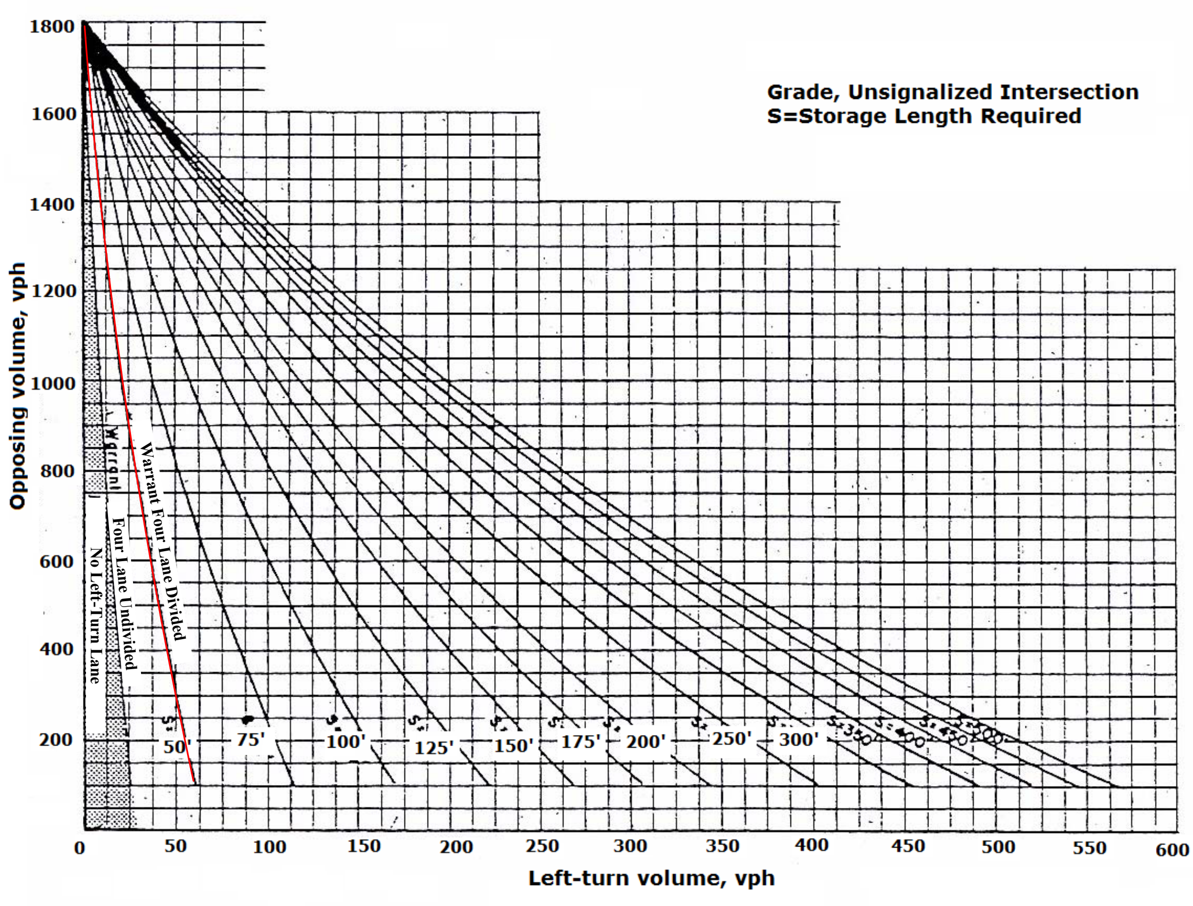


Figure 6-8. Warrants for a Left-Turn Lane at Unsignalized Intersections.

Source: Harmelink 1967

<u>Guideline 7 – Full median openings versus directional median openings:</u>

- Under most circumstances, full median openings are recommended unless a traffic engineering study justifies that the operation and safety can be significantly improved by restricting the direct left-turn/through movements from driveways.
- A directional opening can be considered in replacement of a full opening that is located in the functional areas of intersections when operational or safety problems are caused by the heavy crossing or left-turning traffic exiting from the driveways at the opening. Before the conversion, traffic engineers should carefully examine whether the capacity of the rerouted paths, especially the U-turn location downstream of the driveway, can accommodate the additional demands of the egress vehicles performing a RTUT (right turn followed by a U-turn) maneuver.

Most transportation agencies participating in the survey (Chapter 3) expressed their preference of full median openings over directional openings, unless there exist specific circumstances for which directional openings may be helpful. In addition, according to the operational and safety impacts analysis conducted in Chapter 5, the rerouting path for the egress traffic needed to be carefully examined to avoid shifting congestion and crash risk to another location.

REFERENCES

1. *A Policy on Geometric Design of Highways and Streets*. American Association of State Highway Transportation Officials (AASHTO). Washington, D.C., 2011.
2. Florida Department of Transportation, Median Handbook, 2006.
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6. Texas Department of Transportation, Roadway Design Manual, 2009.

CHAPTER 7: ANALYZE OPERATIONAL AND SAFETY IMPACTS OF THE USE OF ALTERNATIVE MOVEMENTS

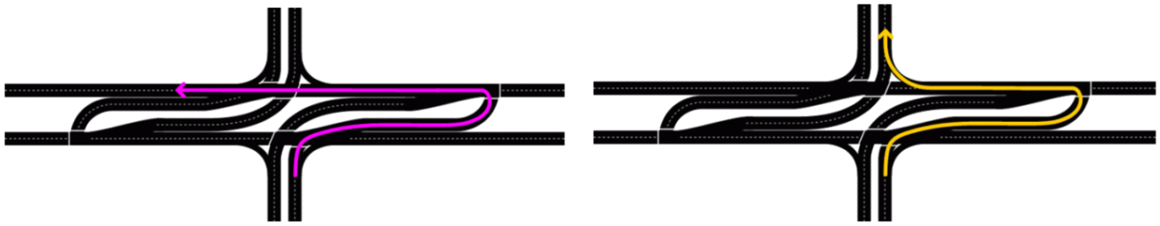
The purpose of this chapter is to (1) evaluate the operational and safety impacts of the design elements (e.g., crossover distances/placement, side-street lane configuration) on the Super Street performance through simulation studies, and (2) summarize the operational and safety impacts of other representative alternative-movement designs through a review of best practices. The research team has conducted simulation studies for evaluating the operational and safety impacts of crossover placement on the performance of the Super Street in Texas—a representative alternative movement known as restricted crossing U-turn intersection. The results can be used for designing appropriate turn lanes and determining placement of crossovers for RCUT design in future similar projects. In addition, the team has studied the effects of side-street lane configurations on Super Street intersections. The prior experience on implementing "Michigan U" at Plano, Texas, was summarized and presented. Literature was synthesized for "Super Street," "Michigan U," and CFI in terms of operational and safety performance and the issues regarding accommodating pedestrians. This chapter provides necessary understanding for the development of the guidelines for alternative movements.

7.1 ANALYSIS OF IMPACTS OF CROSSOVER PLACEMENT ON PERFORMANCE OF SUPER STREET

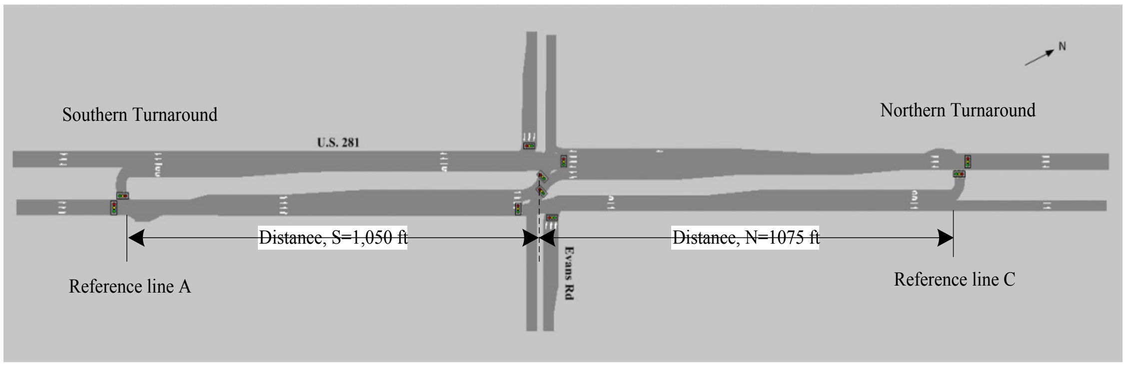
The purpose of this section is to help the researchers understand the operational and safety impacts of crossover locations on superstreet performance, and thereby suggest methods for determining the appropriate distance for placing crossovers for future RCUT projects. For this purpose, the team observed the traffic, geometric, signal control, and environmental conditions at the U.S. 281 & Evans Rd. intersection in San Antonio, Texas, for three weekdays in November 2011. After that, simulation models were developed to replicate the observed conditions and then project the performance given different distances of the U-turn crossovers. VISSIM (Version 5.30) was used to conduct the simulation experiments, and SSAM developed by Siemens was used for safety analysis.

7.1.1 Description of the Study Location

The intersection studied is operated and maintained by TxDOT. The intersection is on U.S. Highway 281, a signalized six-lane highway with a posted speed limit of 65 mph (some parts of U.S. Highway 281 have a posted speed limit of 60 mph). As shown in Figure 7-1, at this intersection, crossovers for U-turn movements are used to reroute through and left-turn movements departing from the side streets (Evans Rd.). The U-turns are controlled by signals at the crossovers, considering the high speeds and the resulting difficulty for drivers to judge the gaps. The crossovers have dual U-turn lanes with loons installed.



(a) Rerouted left turns from minor roads (b) Rerouted through movements from minor roads



(c) Current distances between the crossovers and the main intersection

Figure 7-1. U.S. 281 & Evans Rd. in San Antonio, Texas.

The crossover in the north of the main intersection is 1,075 ft away from the main intersection, and the crossover in the south is 1,050 ft away from the main intersection.

7.1.2 Development of the Base-Case Model

A base-case model was developed to replicate the traffic, geometric, control, and environmental conditions at the studied intersection. At first, the model was developed by inputting the roadway geometric designs, observed traffic volumes and signal timing during the afternoon peak hour. To validate the model, the field-observed travel time was used as benchmarks. Overall, the calibrated models were in good agreement with the observed data, showing very low relative errors of about 10%. This means the simulation model developed can perform reliably in predicting the traffic conditions at the studied locations.

Table 7-1. Effectiveness of the Calibrated Micro-Simulation Model.

	Simulated	Observed	Relative error
Travel time from A to C	73.4 s	79.6 s	-7.8%
Travel time from C to A	60.8 s	59.9 s	1.5%
Delay at the southern crossover	88.1 s	98.6 s	-10.7%
Delay at the northern crossover	44.9 s	49.6 s	-9.4%

Note: A and C are reference lines shown in Figure 7-1

7.1.3 Design of Scenarios

7.1.3.1 Determining Minimum Required Distance for Placing the Crossovers

The distance between the crossovers and the main intersection should meet the following conditions:

1. It should be enough to accommodate the pocket lanes with sufficient storage and deceleration lengths for the U-turn lanes at the crossover (Q_U).
2. It should be enough to accommodate the pocket lanes with sufficient storage and deceleration lengths for the left-turn lanes at the main intersection (Q_{LT}).
3. It should be enough to accommodate the through queue length at the main intersection (Q_{TH}), as shown in Figure 7-2.

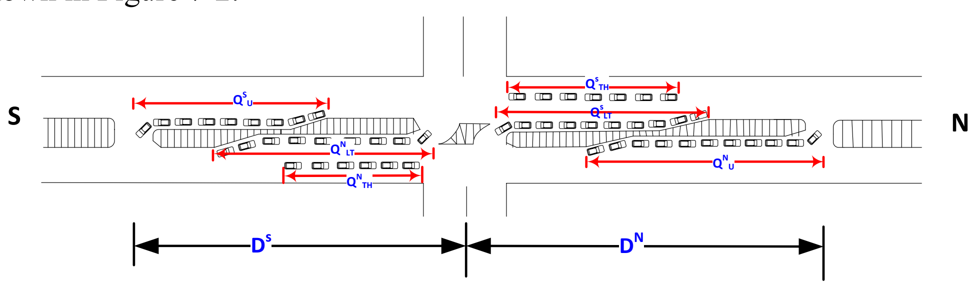


Figure 7-2. The Minimum Required Lengths for the Distances between Crossovers and Main Intersection.

The minimum distances should be the maximum values of these lengths, i.e., max[Q_U, Q_{LT}, Q_{TH}]. The rule-of-thumb method suggested by the TxDOT Roadway Design Manual was used to calculate the necessary pocket lane lengths. The progression adjustment factor recommended in the Highway Capacity Manual 2000 was used to estimate the through queue length. Given the field-observed conditions and optimized signal timing, the minimum required distance for the northern opening is 600 ft, and the minimum required distance for the southern opening is 550 ft. Please see the calculation in Appendix C.

7.1.3.2 Different Scenarios with Various Distances

To analyze the impacts of crossover placement, various distances between the crossovers and the main intersection were tested in the traffic simulation experiments. As shown in Figure 7-1, we denote the distance between the northern opening and the main intersection as N, and the distance between the southern opening and the main intersection as S. The minimum required distance for the crossovers is N=600 ft, S=550 ft; the current distance is N=1,075 ft, S=1,050 ft. Accordingly, nine experimental scenarios with various distances were designed.

1. 450 ft & 400 ft (N=450; S=400)—insufficient distance (less than the minimum requirements)
2. 600 ft & 550 ft (N=600; S=550)—minimum required distances
3. 660 ft & 590 ft (N=660; S=590)
4. 760 ft & 690 ft (N=760; S=690)
5. 775 ft & 750 ft (N=775; S=750)
6. 925 ft & 900 ft (N=925; S=900)
7. 1,075 ft & 1,050 ft (N=1,075; S=1,050)—current distances
8. 1,375 ft & 1,350 ft (N=1,375; S=1,350)
9. 1,575 ft & 1,550 ft (N=1,575; S=1,550)

In these scenarios, only the values of the crossover distances varied. All the other conditions remained the same. The signal timing in all the scenarios was optimized through Synchro/SimTraffic software. In this way, the impacts of different distances of the crossovers on the corridor performance are able to be isolated.

7.1.4 Experimental Results on Operational Performance

For each scenario, a two-hour simulation analysis was conducted, and the performance measures (travel times and speeds) in the second simulation hour were recorded. The first hour was intended as the "warm-up" period for the empty network to reach the equilibrium situation. After the first hour, the simulation results were averaged among ten simulation runs based on the same set of random number seeds. The results of travel time, average speed, and the network-level performance are summarized as follows.

7.1.4.1 Travel Time along U.S. 281

The travel time along U.S. 281 was measured between the reference lines as shown in Figure 7-3. The total distance between the lines is 3,330 ft, covering both of the crossovers in all the scenarios. The background map in Figure 7-3 represents the scenario with the largest assumed crossover distances (N=1,575; S=1,550).

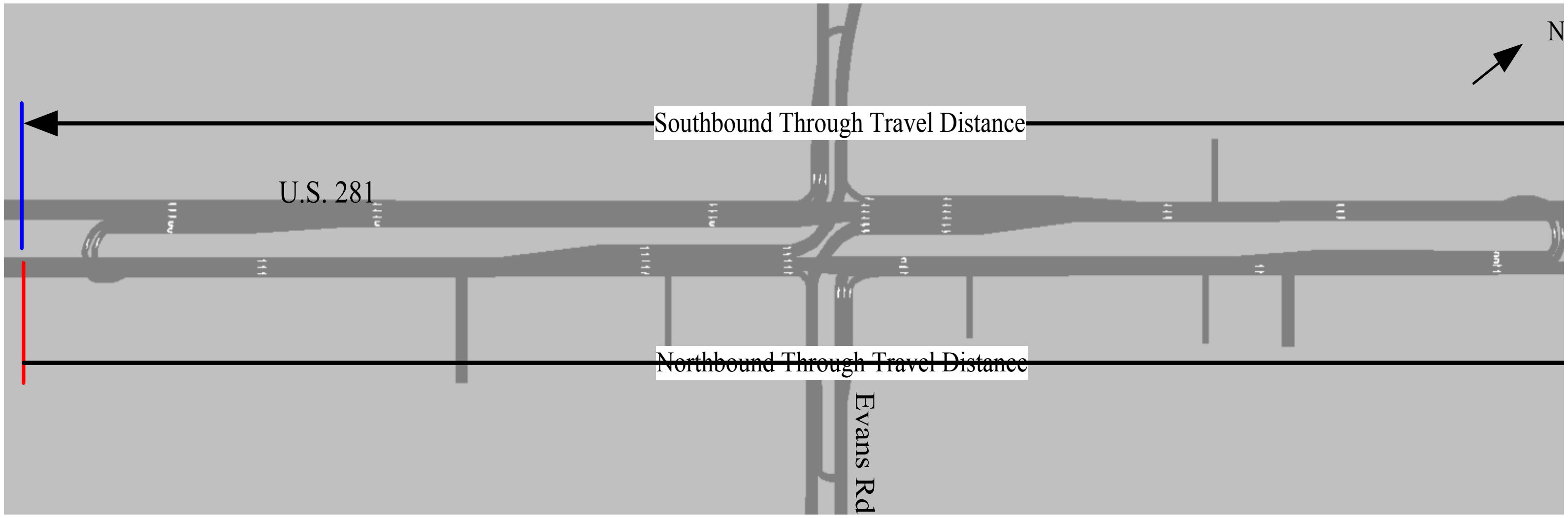


Figure 7-3. Reference Lines for Measuring Travel Time along U.S. 281.

Table 7-2. Simulated Travel Time along U.S. 281 (Unit: seconds).

	N=450; S=400	N=600; S=550	N=660; S=590	N=760; S=690	N=775; S=750	N=925; S=900	N=1075; S=1050	N=1375; S=1350	N=1575; S=1550
NB TH	114.4	100.3	100.9	101.2	101.5	101.0	101.4	101.2	99.5
SB TH	97.2	79.4	79.6	80.5	77.8	79.5	79.6	80.1	78.4

Note: N=1,075 and S=1,050 are the existing distances, NB=northbound, SB=southbound, TH=through

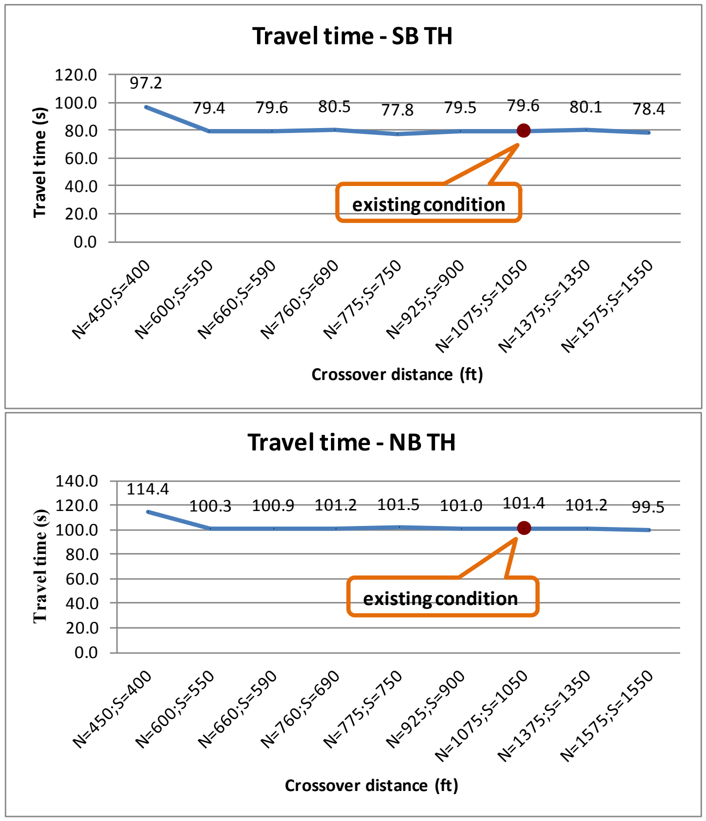


Figure 7-4. Relationship between Distances of Crossovers and Travel Time along U.S. 281.

Figure 7-4 shows when the distance is shorter than the minimum required values (i.e., N=600 ft; S=550 ft), the travel time along U.S. 281 was increased dramatically because traffic congestion caused by the vehicle overflows at NB left-turn lane and at the southern crossover (please see Figure 7-5 for the scenario N=450 ft; S=400 ft). When the distance is longer than the minimum required values, the congestion did not occur. Therefore, location of crossovers has little impact on the travel time through traffic on the main corridor.

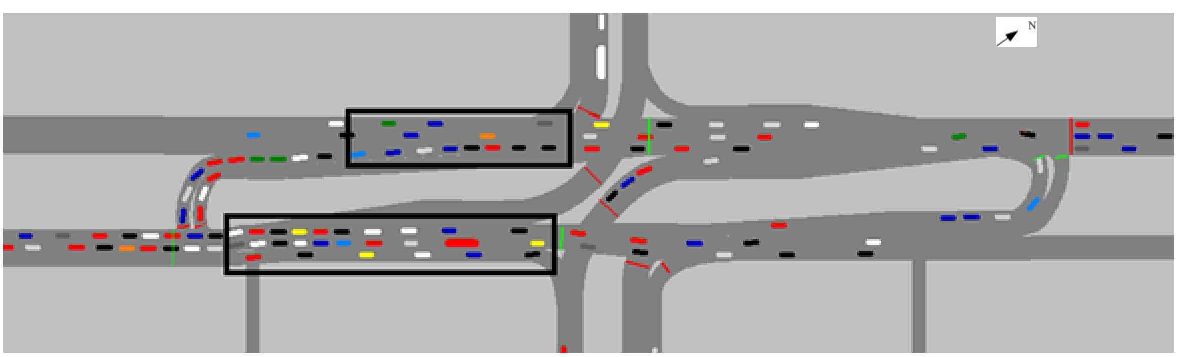


Figure 7-5. Congestion in Scenario N=450 and S=400.

7.1.4.2 Travel Time for the Westbound Side-Street Approach

The travel distances for the westbound through and left-turn vehicles were measured as shown in Figure 7-6, starting from the red reference line and ending at the blue reference line.

Figure 7-6. Measurements for Indirect Left-Turn and Through Maneuvers from the Westbound Approach.

Given different crossover distances, the resulting travel distances are different. The farther the crossover is relative to the main intersection, the longer distance the vehicles from the side street need to travel. Table 7-3 shows the travel distances for through and left-turn maneuvers in different scenarios with crossovers placed at different locations.

Table 7-3. Distance Traveled for the Westbound Approaches (Unit: ft).

	N=450; S=400	N=600; S=550	N=660; S=590	N=760; S=690	N=775; S=750	N=925; S=900	N=1075; S=1050	N=1375; S=1350	N=1575; S=1550
WB TH	896.4	1192.6	1306.9	1515.3	1522.6	1824.7	2153.2	2748.2	3123.0
WB LT	945.5	1241.9	1356.3	1564.8	1572.1	1874.2	2202.7	2797.7	3172.5

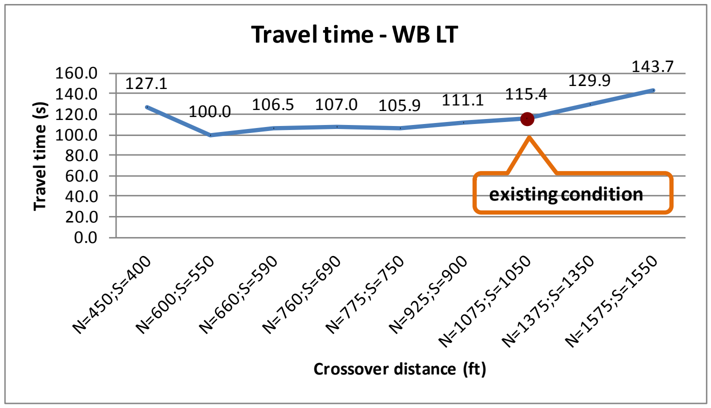
Note: N=1,075 and S=1,050 are the existing distances, WB=westbound, TH=through, and LT=left turn

Table 7-4 shows the corresponding travel times for the through and left-turn maneuvers in different scenarios.

Table 7-4. Travel Time for the Westbound Approaches (Unit: seconds).

	N=450; S=400	N=600; S=550	N=660; S=590	N=760; S=690	N=775; S=750	N=925; S=900	N=1075; S=1050	N=1375; S=1350	N=1575; S=1550
WB TH	82.1	86.6	89.8	96.3	95.8	101.4	107.1	121.8	138.4
WB LT	127.1	100.0	106.5	107.0	105.9	111.1	115.4	129.9	143.7

Note: N=1,075 and S=1,050 are the existing distances, EB=eastbound, TH=through, and LT=left turn



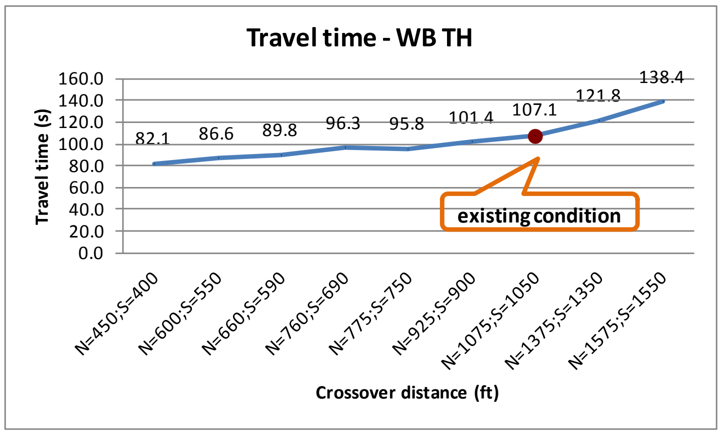


Figure 7-7. Through and Left-Turn Travel Times from the Westbound Approach.

The westbound through movement does not have to travel through the congestion areas shown in Figure 7-5. Thus, the travel time is only related to the distance traveled. As the distance increases, the travel time increases gradually. For westbound left-turn movements, in the scenario with insufficient crossover distances (e.g., N=450 ft; S=400 ft), vehicles had to travel through the congestion areas as shown in Figure 7-5. Thus, the corresponding left-turn travel time (i.e., 127.1 s) is higher than other scenarios with sufficient crossover distances (e.g., N=600 ft; S=550 ft or longer).

7.1.4.3 Travel Time for the Eastbound Side-Street Approach

Similar to the westbound movements, the travel times for the eastbound through and left-turn movements from Evans Rd. were measured as shown in Figure 7-8. Table 7-5 and Table 7-6 show the results of travel distance and travel time for the eastbound movements.

Figure 7-8. Measurements for Indirect Left-Turn and Through Maneuvers from the Eastbound Approach.

In the scenario with crossover distances of N=450 ft and S=400 ft, both eastbound through and left-turn movements need to travel through the two congestion areas (Figure 7-5). Therefore, the travel time in this scenario was higher than those in other scenarios. For the scenario with crossover distances of N=925 ft and S=900 ft or longer, the congestion was mitigated and the travel time was solely a function of the distance traveled.

Table 7-5. Distance Traveled for the Eastbound Approaches (Unit: ft).

	N=450; S=400	N=600; S=550	N=660; S=590	N=760; S=690	N=775; S=750	N=925; S=900	**N=1075; S=1050**	N=1375; S=1350	N=1575; S=1550
EB TH	845	1133.8	1209.4	1421.6	1552.9	1822.5	**2119.9**	2719.2	3142.5
EB LT	926.8	1215.4	1291	1503.3	1634.6	1904.2	**2201.6**	2800.9	3224.3

Table 7-6. Travel Time for the Eastbound Approaches (Unit: seconds).

	N=450; S=400	N=600; S=550	N=660; S=590	N=760; S=690	N=775; S=750	N=925; S=900	N=1075; S=1050	N=1375; S=1350	N=1575; S=1550
EB TH	475.41	243.49	239.33	230.57	164.48	120.22	126.09	141.33	155.58
EB LT	340.2	244.49	248.86	238.19	227.94	146.10	148.50	170.30	174.29

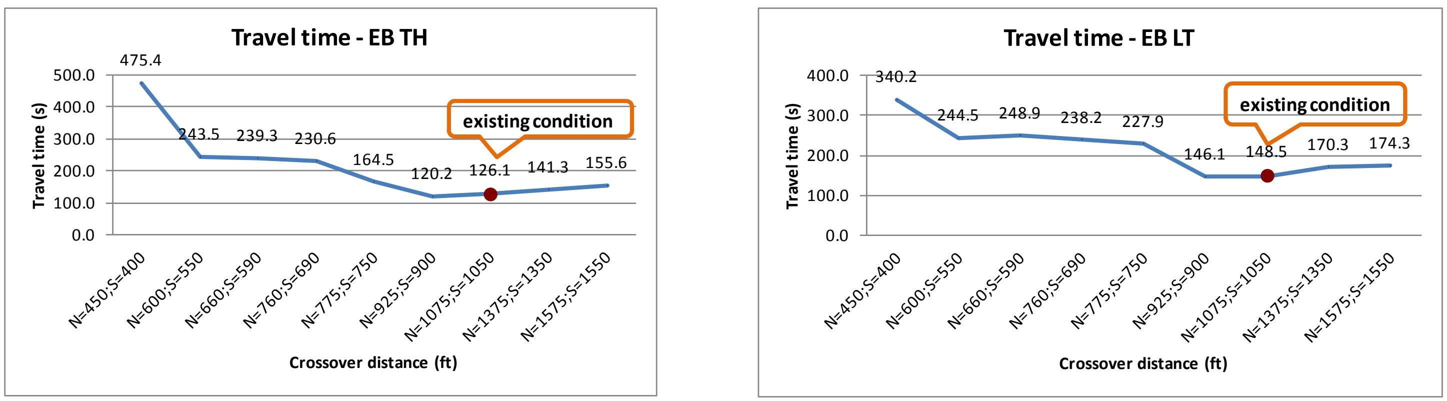


Figure 7-9. Travel Time for Eastbound Through and Left-Turn Movements from Evans Rd.

7.1.4.4 Simulated Speed

The average speed for each movement can be calculated as the distance traveled divided by the simulated travel time (the travel time included control delays at the main intersection and the crossovers). The following figures illustrate the relationship between crossover distance and the resulting average speed for various movements at the studied intersection. As we can see, the speeds of the through movements along U.S. 281 were basically the same except for the case when the crossover distance is shorter than the minimum required distances N=600 and S=550. The average speed of the movements from the side street increased as the crossover distances increased because with the increase of crossover distances, drivers had to travel longer distances on the major road U.S. 281, which had a relatively high speed.

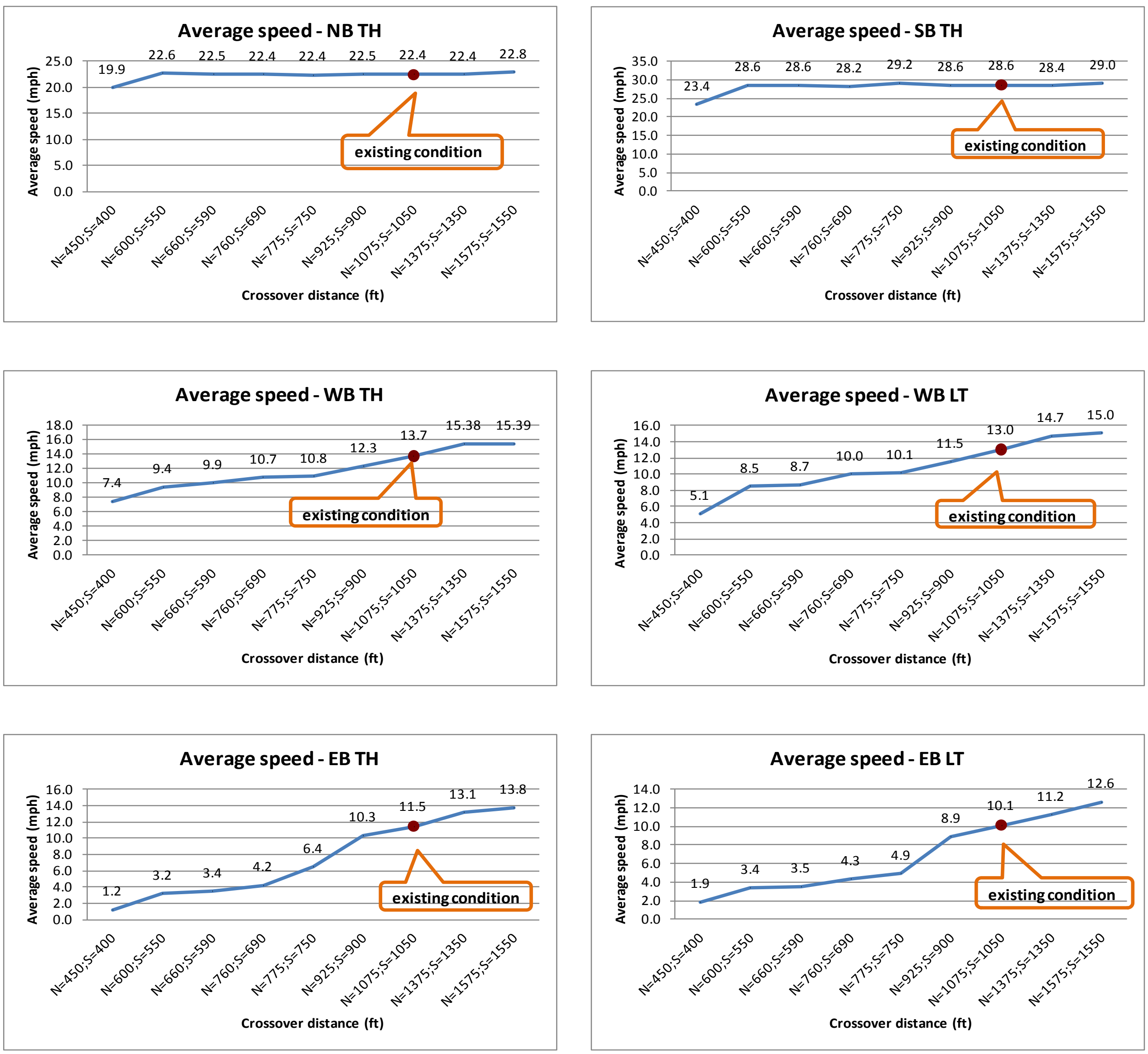


Figure 7-10. Average Speed for Various Movements at the Studied Intersection.

7.1.4.5 Network Performance

To analyze the network wide performance, average delay, average speed, and total travel time were derived and compared based on the simulation results.

Table 7-7. Network-Level Performance Measures.

Scenarios	Average delay (s)	Average speed (mph)	Total travel time (h)
N=450; S=400	67.9	25.2	424.7
N=600; S=550	40.0	27.8	375.3
N=660; S=590	38.9	27.7	379.0
N=760; S=690	39.4	27.9	376.7
N=775; S=750	38.0	28.1	372.0
N=925; S=900	34.2	28.7	367.3
N=1075; S=1050	34.2	28.6	370.5
N=1375; S=1350	36.1	28.5	374.6
N=1575; S=1550	35.3	28.6	374.5

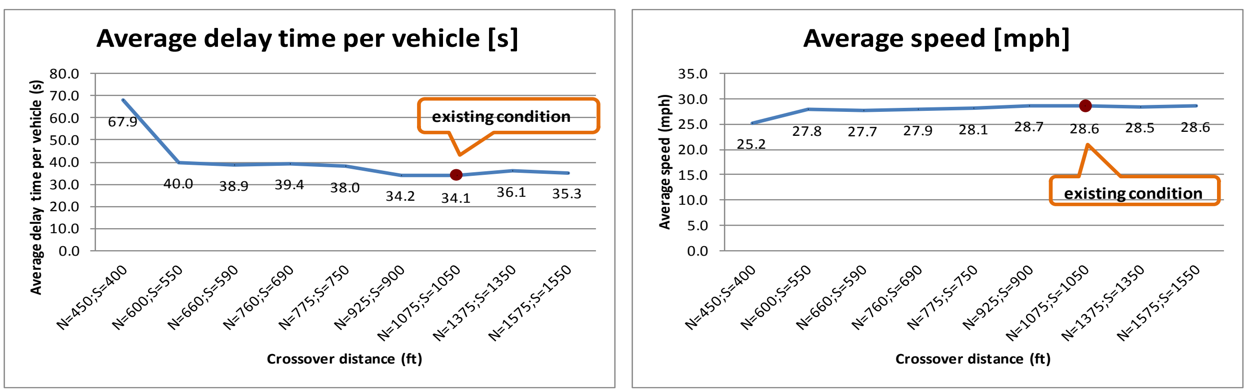


Figure 7-11. Network-Level Delay and Speed Given Various Distances of Crossovers.

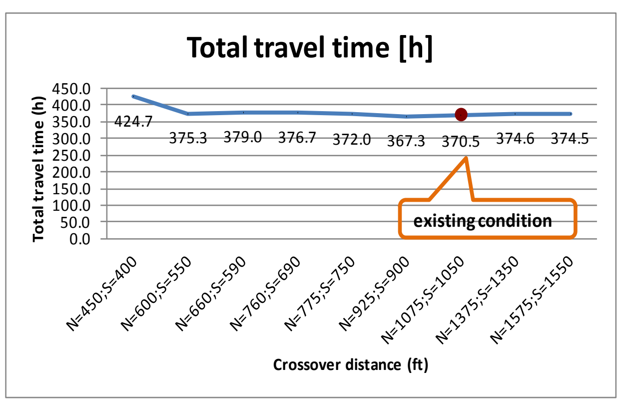


Figure 7-12. Network-Level Travel Time Given Various Distances of Crossovers.

These results all indicated that the scenario with insufficient crossover distances (N=450 ft and S=400 ft less than the minimum required values) represented the worst case, while the other scenarios showed little difference.

7.1.4.6 Summary of Operational Impacts

The results presented in Figures 7-4, 7-7, 7- 9, 7-10, 7-11, and 7-12 indicate the following major findings:

- When the crossover distance is shorter than the minimum required values (N=600 ft and S=550 ft for the studied location), the RCUT intersection cannot perform well (i.e., the travel times of all the movements increased significantly as a result of turn lane overflows).
- When the crossover distance is longer than the minimum required values (N=600 ft and S=550 ft for the studied location), the location of crossover does not have significant impacts on the traffic operation on major roads. However, there are some operation costs for the side-street traffic because vehicles have to travel longer distances for making alternative U-turns.
- According to the simulation results, the current crossover distances for the studied intersection (i.e., U.S. 281 Super Street & Evans Rd.) are well designed, which led to good and stable system operational performance.

7.1.5 Experimental Results on Safety Performance

Similar to the safety analysis conducted in Chapter 5, the simulation-based approach was used to derive the different types of traffic conflicts, including lane-change, crossing, and rear-end conflicts, for each of the scenarios. The results are summarized as follows.

7.1.5.1 Impacts of Crossover Distance on Total Number of Traffic Conflicts

Given the scenarios with different crossover distances, the simulated traffic conflicts were counted for the same area as defined in Figure 7-13. The results are presented in Figures 7-14 and 7-15. As we can see, rear-end conflict rates decreased as the crossover distance increased. The rates of crossing and lane-change conflicts decreased exponentially with the increase of the distance. As the distance was changed from N=450 ft and S=400 ft to N=600 ft and S=550 ft, the conflict rates decreased sharply. When the distance was greater than N=600 ft and S=590 ft, which are the minimum distances required, the differences among various scenarios were generally insignificant.

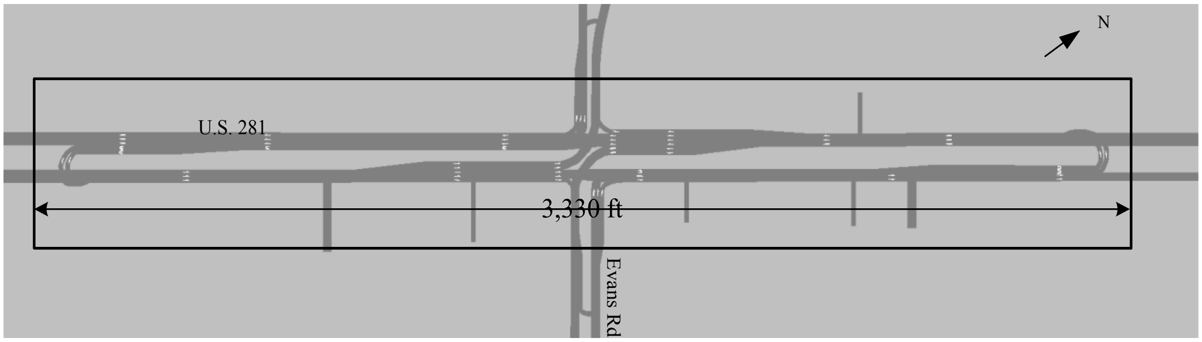


Figure 7-13. Area for Measuring the Total Number of Traffic Conflicts

Note that the numbers of the traffic conflicts can only be used to compare the relative rankings of safety performance of various scenarios, rather than being interpreted as predicted numbers of actual traffic conflicts.

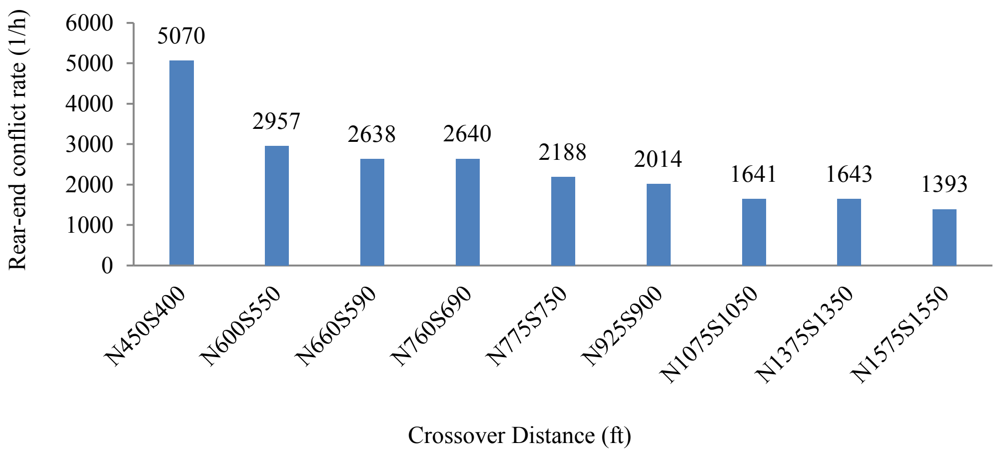


Figure 7-14. Rear-End Conflict Rate with Different Scenarios of Placement of Crossovers.

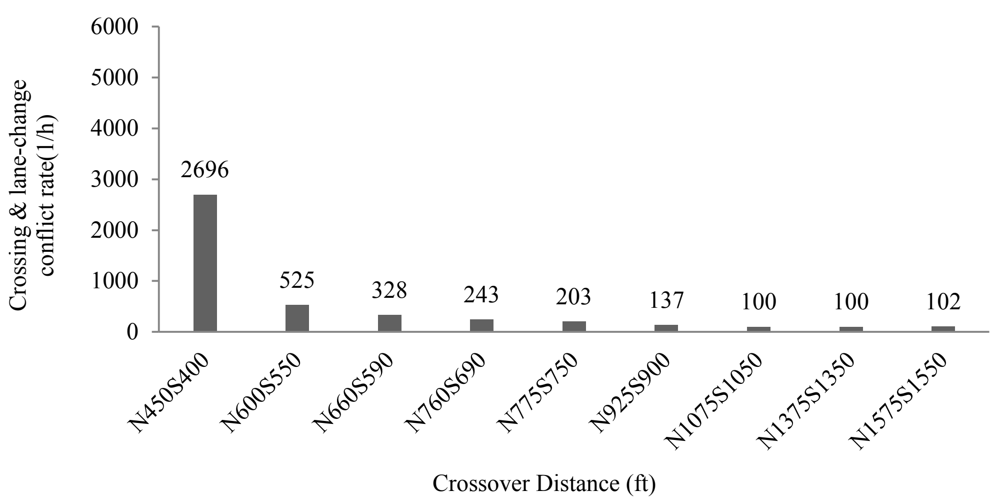


Figure 7-15. Crossing and Lane-Change Conflict Rate with Different Scenarios of Placement of Crossovers.

7.1.5.2 Impacts of Crossover Distance on Weaving Conflict Rate

For the through movements from the side streets, after making a U-turn at crossovers, drivers need to weave to the curb lane to make right turns. Thus, the distance between the main intersection and the crossover determines the available weaving distance. In this study, based on the SSAM analysis results, the rate of lane-change conflicts was used as an indicator of the safety performance associated with the weaving segments.

In the studied intersection, as shown in Figure 7-16, between the main interaction and the southern side crossover, weaving conflict rate decreased as the crossover distance increased. Given a distance of greater than 490 ft (the minimum required distance), the downtrend of the weaving traffic conflicts was less significant.

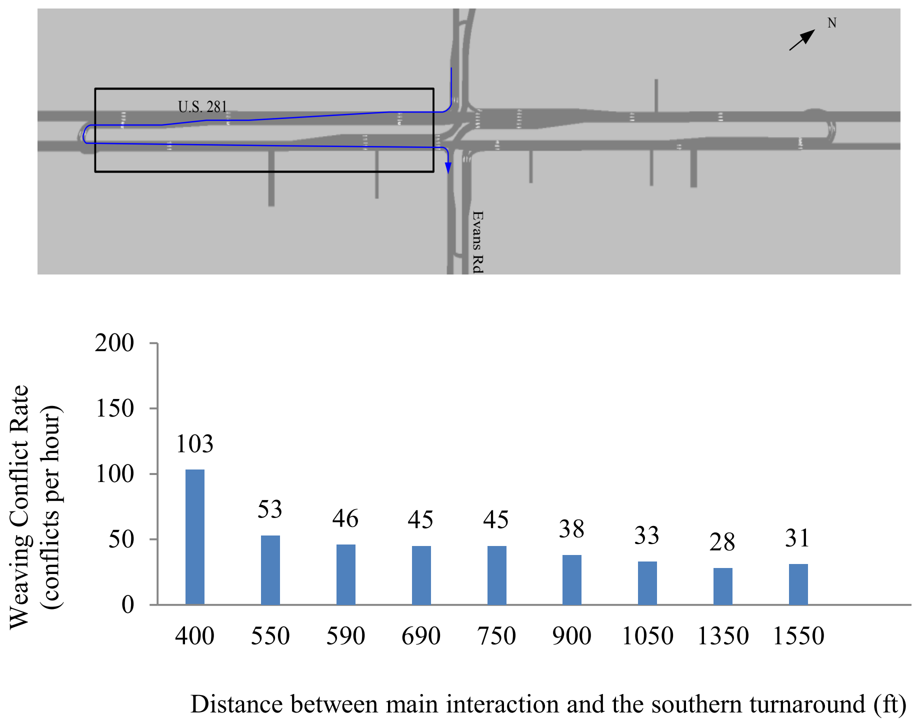


Figure 7-16. Weaving Conflict Rates vs. Distance of Crossover (Southern Crossover).

Likewise, as shown in Figure 7-17, between the main interaction and the northern side crossover, weaving conflict rate decreased as the distance increased. Given a distance of 450 ft, the downtrend of the weaving traffic conflicts was considerably less sharp.

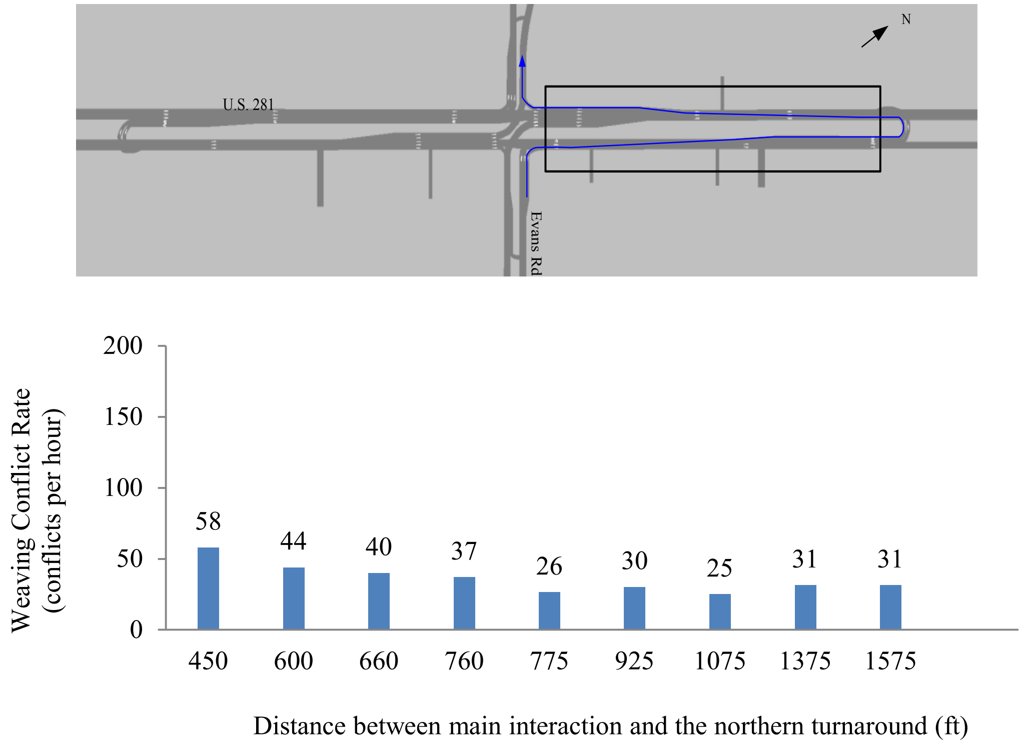


Figure 7-17. Weaving Conflict Rates vs. Distance of Crossover (Northern Crossover).

7.1.6 Summary

7.1.6.1 Operational Impacts

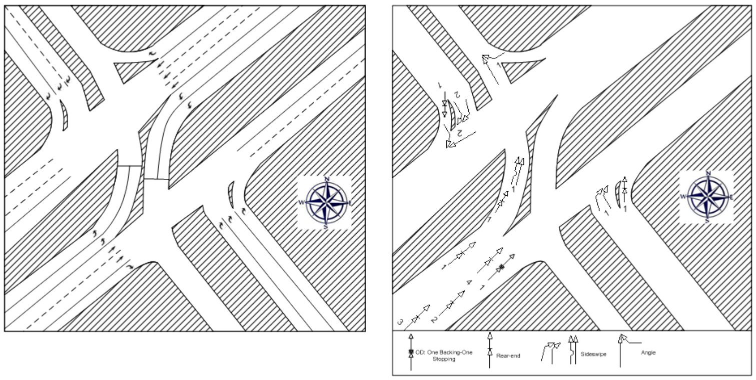
- The distances between the crossovers and the main intersection should be enough to provide sufficient storage and deceleration lengths for both left-turn and U-turn vehicles. The distances should also be enough to accommodate the queue of the through and right-turn movements at the main intersection.
- The experiments showed that failure to provide the minimum required crossover distances or adequate turning lane length resulted in overflow from the turning lanes and serious congestions.
- On the other hand, when the crossover distance is longer than the minimum required values, the placement of the crossovers has little impact on the performance of the intersection.

7.1.6.2 Safety Impacts

- The simulation studies indicated that the farther the crossovers from the main intersection, the better the whole intersection safety performance because the routed traffic from the side street will have longer weaving distance and fewer interactions with the through and left-turn traffics on the major street.
- Once the minimum required distances between the crossovers and the main intersection were met, the placement of the crossovers has little impact on the safety performance of the whole RCUT intersections.

7.2 IMPACTS OF USE OF DUAL RIGHT-TURN LANES ON SIDE STREETS COMPARED WITH TRIPLE RIGHT-TURN LANES

As shown in Figure 7-18, in the current geometric settings for the U.S. 281 Super Street, triple right-turn lanes are installed on both side-street approaches on Evans Rd. According to the prior crash analysis, sideswipe crash rates increased after the implementation of the Super Street, which may be associated with the use of the triple right-turn lanes. To address this safety concern, this research investigated whether the safety performance can be improved by replacing the triple right-turn lanes with dual right-turn lanes. In addition, the operational impacts of this change were analyzed.



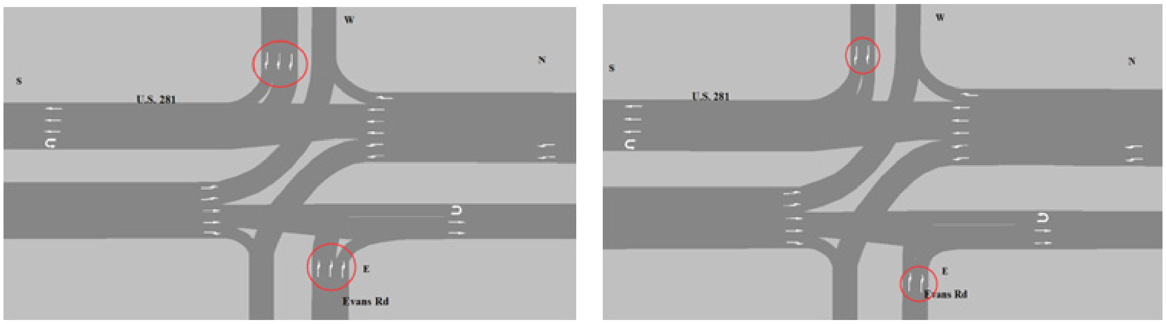
Crash rate: crash per year	Eastbound approach		Westbound approach	
	Before (conventional design)	After (Super Street)	Before (Conventional design)	After (Super Street)
Rear-End	0.444	0.333	0.222	0.333
Sideswipe	0.148	0.667	0.027	0.333

Figure 7-18. Comparison of Crash Rates—a Safety Concern Associated with the Triple Right-Turn Lanes.

(a) Triple right-turn lanes on the eastbound approach (RTOR allowed)

(b) Triple right-turn lanes on the westbound approach (RTOR prohibited)

Figure 7-19. Triple Right-Turn Lanes on the Side-Street Approaches on Evans Rd.



(a) Triple right-turn lanes (existing condition)

(b) Dual right-turn lanes (hypothesized scenario)

Figure 7-20. Two Scenarios of Different Right-Turn Lanes for Comparison.

Figure 7-20 shows the lane configurations of the side-street approaches in two comparison scenarios. In the hypothesized dual right-turn lanes, it is assumed that the two right-turn lanes were separated by the existing channelization. In conjunction with VISSIM simulation, SSAM was used for assessing the safety performance of these two scenarios. Simulated vehicle trajectories exported from VISSIM were inputted to SSAM to derive the traffic conflict frequencies at the turn lane areas.

7.2.1 Experimental Results on Safety Performance

At a 95% confidence level, paired t-tests were conducted for the traffic conflicts outputted from SSAM, and the results are summarized in Tables 7-8 and 7-9.

Table 7-8. T-Test for Traffic Conflicts on the Westbound Approach (RTOR Prohibited).

Conflict Type	Triple right-turn lanes (conflicts per hour)	Dual right-turn lanes (conflicts per hour)	t-statistics	Significance (α=0.05)
Rear-end	9.92	12.92	1.771	NO
Sideswipe (lane-change)	1.52	4.16	4.217	YES
Total	11.44	17.08	2.672	YES

For the westbound approach (No RTOR):

- Total conflicts in the dual right-turn lane design are significantly more than those in the existing triple right-turn lanes case.
- The frequency of sideswipe conflicts given the dual right-turn lanes design was significantly higher than that in the triple right-turn lanes.
- There was no significant difference in rear-end conflicts between the triple right-turn lanes and the dual right-turn lanes designs.

Note that after converting the triple left-turn lanes to dual right-turn lanes, the sideswipe conflicts also increased. This may be due to the increase of congestion at the turning lanes, which results in the increased chance of vehicles turning abreast.

Table 7-9. T-Test for Traffic Conflicts on the Eastbound Approach (RTOR Allowed).

Conflict Type	Triple right-turn lanes (conflicts per hour)	Dual right-turn lanes (conflicts per hour)	t-statistics	Significance (α=0.05)
Rear-end	4.36	8.84	5.586	YES
Sideswipe (lane-change)	4.24	10.08	9.376	YES
Total	8.60	18.92	9.475	YES

For the eastbound approach (RTOR allowed):

- Similarly, the total conflicts in the dual right-turn lane design significantly increased compared with the existing triple right-turn lanes design.
- The frequency of rear-end conflicts in the dual right-turn lane design is significantly lower than that in the existing design.
- Compared with the westbound approach where RTOR is prohibited, the increase of rear-end conflicts in the eastbound approach is more significant because RTOR is allowed for the curb side turning lane at this approach and rear-end conflicts were highly associated with the RTOR maneuvers. When the approach is converted into dual right-turn lanes, congestion will increase and a considerably higher proportion of turning traffic will make a right turn on red. During RTOR, a rear-end crash commonly occurs when the attention of a turning driver is placed on the cross-street traffic and the driver fails to stop when the car in front of him or her makes a sudden stop.
- The sideswipe conflicts in the dual right-turn lanes design also increased compared with the existing design.

Therefore, overall, the safety performance will become worse if the existing triple right-turn lanes on the side-street approaches are replaced with the dual right-turn lanes.

7.2.2 Experimental Results on Operational Performance

7.2.2.1 Throughput

For the westbound approach, since the traffic is unsaturated (351 vph), there was no difference in the throughputs, as all the arriving vehicles could be fully discharged. For the eastbound approach, the traffic volume (671 vph) was near the capacity. In this case, the triple turn lanes enabled a higher discharge rate from the approach and provided more storage space. The capacity of the dual right-turn lanes was considerably lower than the triple turn lane option.

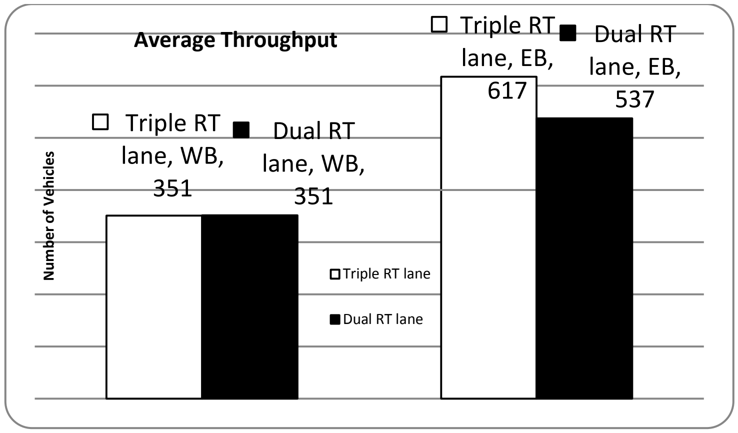


Figure 7-21. Comparison of Average Throughputs of the Side-Street Approaches.

7.2.2.2 Delay

To compare the operational impacts, delay and travel time were also measured for the side-street approaches, from the red reference line to the blue line as shown in the figure blow.

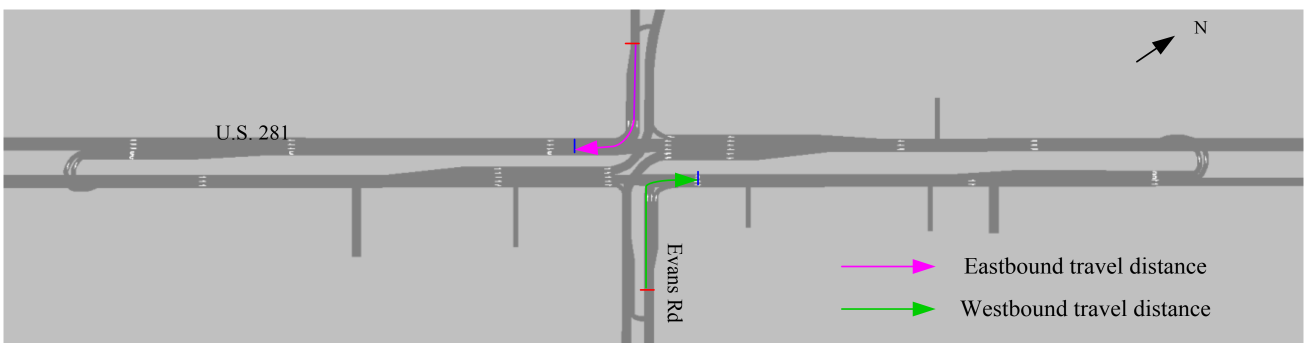


Figure 7-22. Travel Time Measurements in the Analysis of Delays.

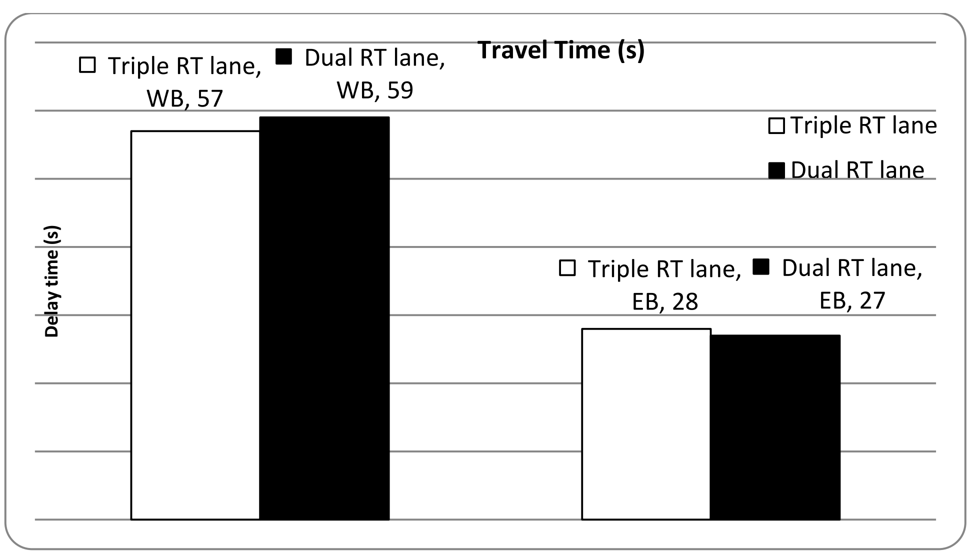


Figure 7-23. Comparison of Travel Times on the Approaches on Evans Rd.

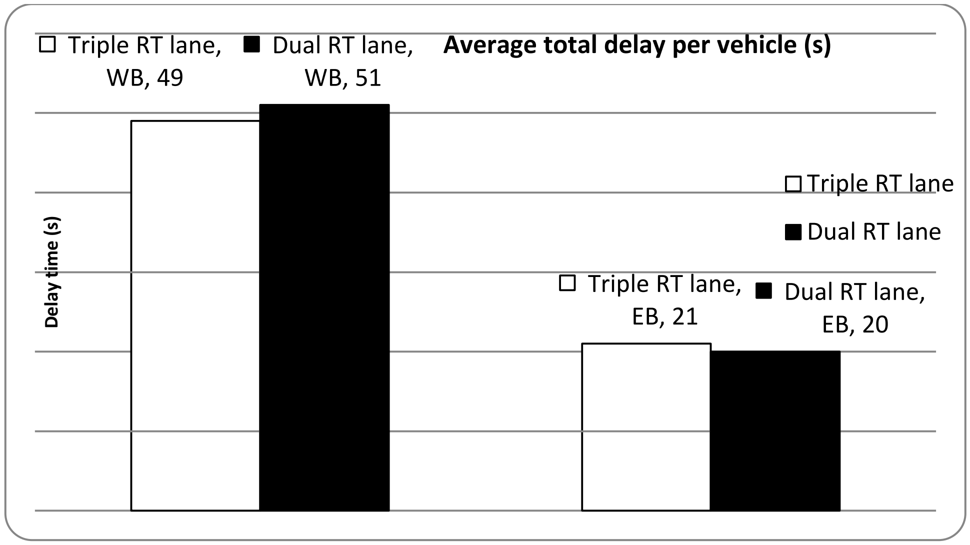


Figure 7-24. Comparison of Delays on the Approaches on Evans Rd.

For the westbound approach, the average travel time and delay per vehicle were increased when the turn lanes were reduced to dual right-turn lanes. Since the volumes from the eastbound approach were generally low, the number of right-turn lanes had little effect on the travel time.

7.2.2.3 Queue Length

When the dual right-turn lanes were in use, both the average queue lengths and maximum queue lengths were significantly longer than in the triple right-turn lane scenario.

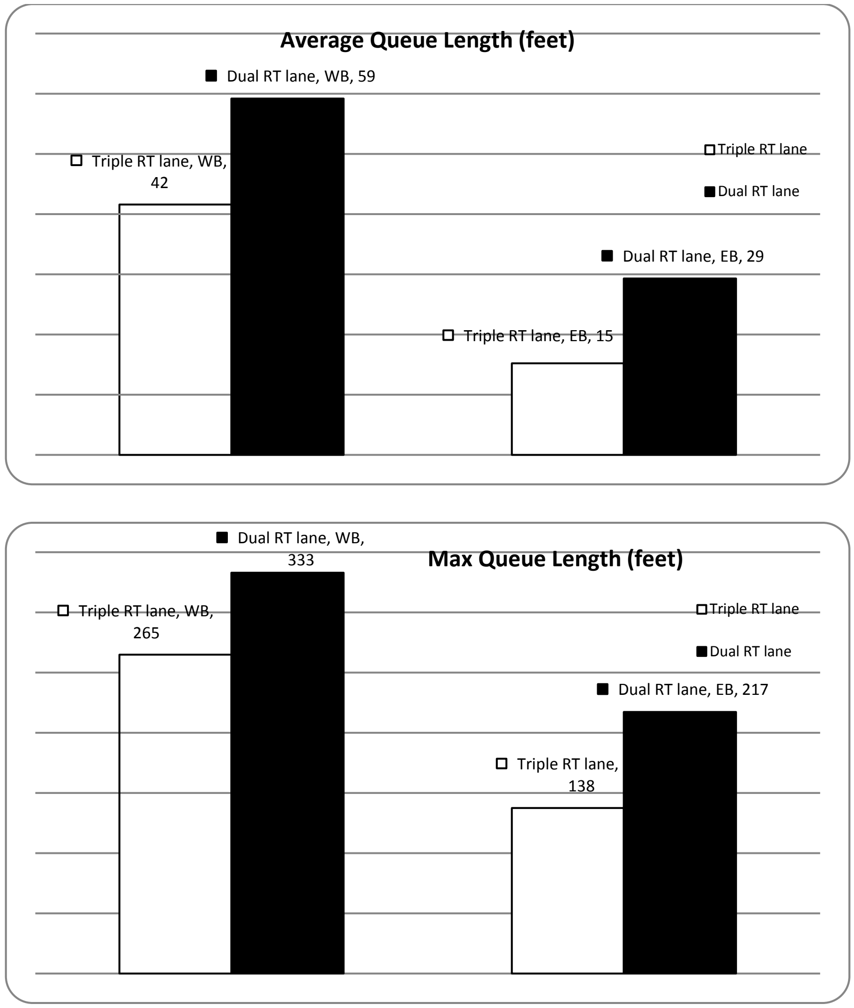
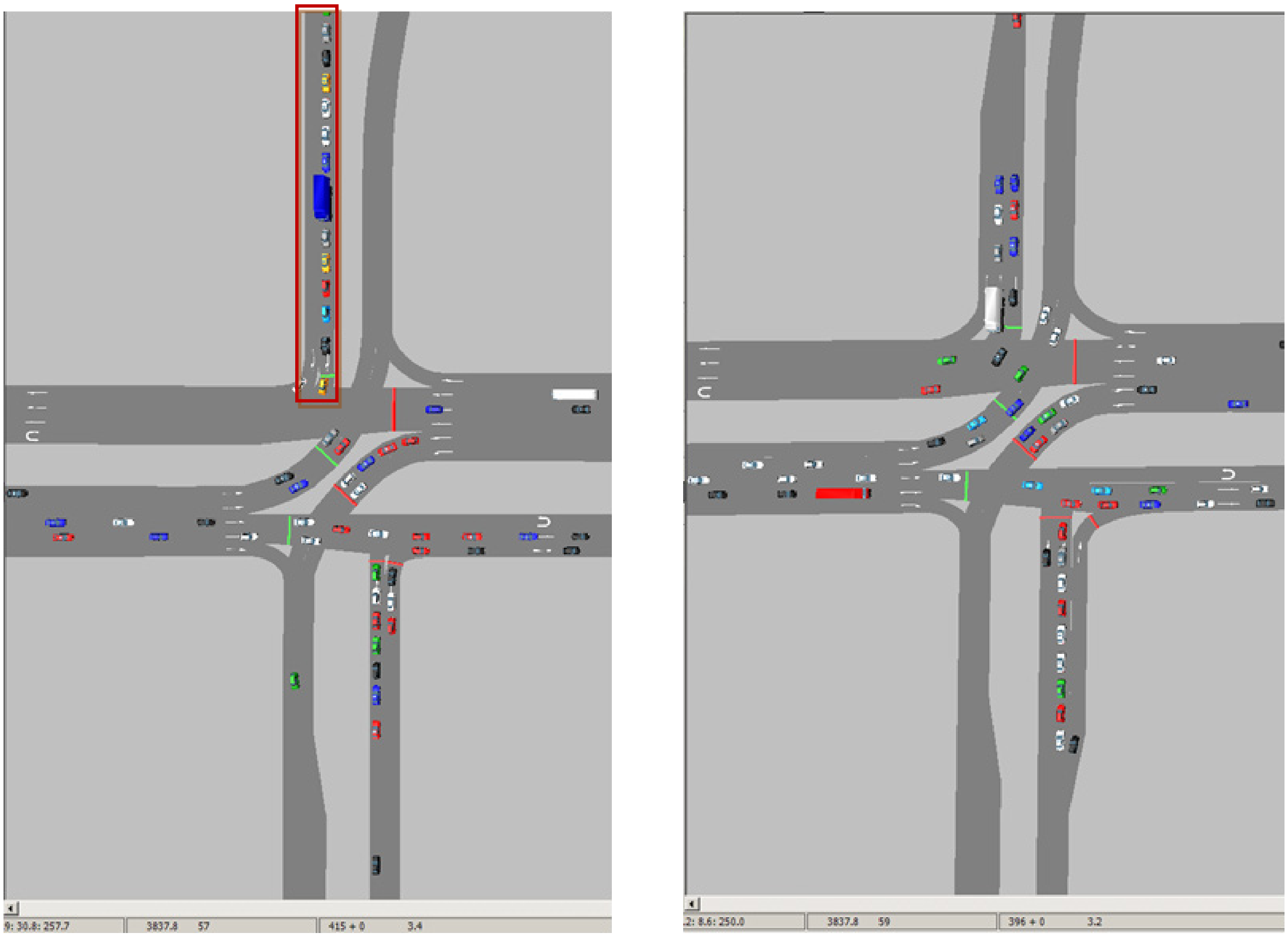


Figure 7-25. Comparison of Queue Lengths.



(a) Queue length in dual right-turn lane design (b) Queue length in triple right-turn lane design

Figure 7-26. Comparison of Queue Lengths through VISSIM Visualization.

7.2.3 Summary

Based on the results described above, the current triple right-turn lanes design resulted in a significantly higher capacity and shorter queue lengths for the side-street approaches compared with the dual right-turn lanes design. From a safety standpoint, the triple right-turn lanes design had a lower potential for sideswipe and rear-end conflicts. Therefore, the triple right-turn lane design represents a better option in terms of operational and traffic safety performances as opposed to the dual right-turn lanes design.

7.3 APPLICATION OF "MICHIGAN U" IN PLANO, TEXAS

In the previous studies, we have investigated the operational and safety performance of two representative alternative movements, i.e., indirect left turns from driveways (Chapter 5) and the RCUT Super Street designs (Chapter 7). A broader definition of an alternative movement is any at-grade design concept that is able to reroute critical movements and reduce the number of traffic signal phases at the main intersection, thereby increasing the efficiency and capacity of the intersection and improving progression at the corridors.

The objective of this section is to summarize the performance of another common alternative movement, i.e., Michigan left-turns (Michigan U). Currently, these designs have been implemented in Texas. As we will see more and more such designs in Texas, it is important for traffic engineers to understand how these designs perform in terms of traffic operations and safety.

7.3.1 Median U-Turn (MUT)/"Michigan U"

A MUT intersection, which is also known as "Michigan U" or "Michigan left-turn" intersection, is an at-grade intersection design that replaces each left turn with a permutation of a U-turn and a right turn. The design was given the name due to its frequent use along Michigan's roads and highways since the late 1960s. In 2010, the first MUT intersection was implemented at SH 289/Preston Road & Legacy Drive in the city of Plano, Texas. In this design, direct left turns are removed from signalized intersections as shown in Figure 7-27.

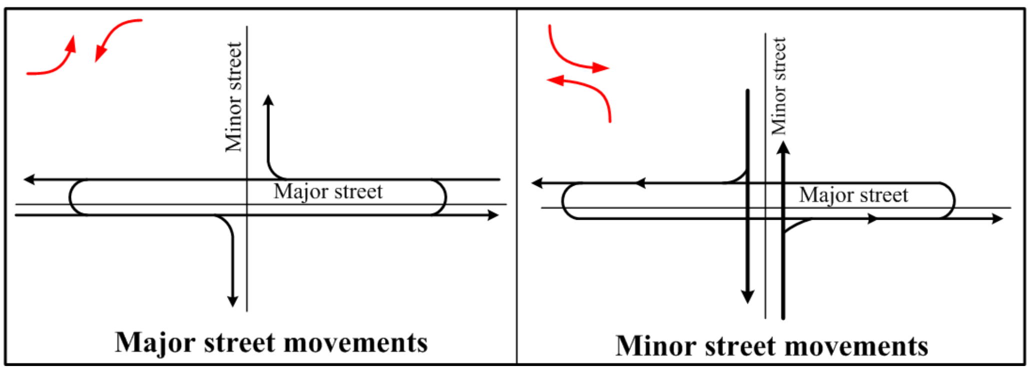


Figure 7-27. Median U-Turn at Signalized Intersections.

Source: Signalized Intersections: Informational Guide (1)

Left-turn vehicles from the major street need to make a U-turn downstream of the intersection and then turn right at the intersection to complete this alternative maneuver. The movement of left-turn vehicles from the minor streets would have to turn right first and then make a U-turn downstream of the intersection. The MUT concept eliminates all left turns at the main intersection, and allows two-phase signal controls. The removal, or reduction in numbers of left turns and U-turns from the signalized intersection, also allows for shorter signal cycles, improved progression, and increased capacity along the arterial. The U-turn openings can be controlled using traffic signals when it is hard for drivers to correctly estimate the gaps in the through traffic flow because of high speed or high through volume.

7.3.2 Application of Michigan U in Plano, Texas

For the recently implemented MUT intersection at Plano in Texas, as shown in Figure 7-28, it was found that the traffic operation at this intersection has been significantly improved according to the following factors:

- Back-up reduced 60%.
- Delay reduced 35 sec/veh.
- Fewer calls complaining about congestion and unfamiliarity with design.

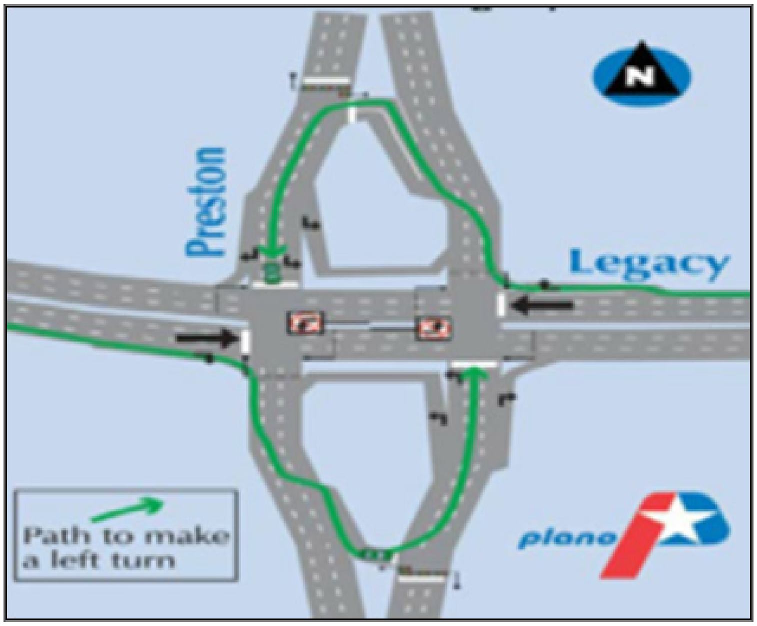


Figure 7-28. Median U-Turn Intersection in Plano, Texas.

In terms of safety, there was no significant accident rate increase after the implementation of a "Michigan U" intersection, but the crash severity level was increased especially for injury caused by running a red light. Tables 7-10 and 7-11 show the crash statistics during the before (July 2009 to July 2010) and after time periods (July 2010 to June 2011).

Table 7-10. Crash Rates Comparisons.

Causes	Before MUT (7/2009- 7/2010)	After MUT (7/2010- 6/2011)
Disregard Stop & Go Signal	8	10
Fail to Control Speed	5	7
Disregard Stop Sign/Light	4	1
Fail to Yield Right of Way	4	1
Disregard Turn Marks	3	0
Driver Inattention	3	3
Following Too Closely	2	3
Turned Improperly	2	0
Changed Lane When Unsafe	1	1
Turned When Unsafe	0	1
Other	0	3
Total	**32**	**30**

Table 7-11. Severity Level Comparisons for the Injury Crashes.

Injury Crashes	Before MUT (7/2009- 7/2010)	After MUT (7/2010- 6/2011)
Running Red Light	2	7
Following Too Close—Fail to control speed	3	5
Disregard Traffic Control Device—no left turn	0	2
Other	3	1
Total	**8**	**15**

It was also found that this new type of intersection deign did cause some drivers confusion, especially during the first three months after the installation. During the first month, the 30-day grace time period, 405 warning citations were issued for drivers making illegal left turns. After that, totally, 238 citations were issued for making illegal left turns. Figure 7-29 shows the total amount of citations at this location by month.

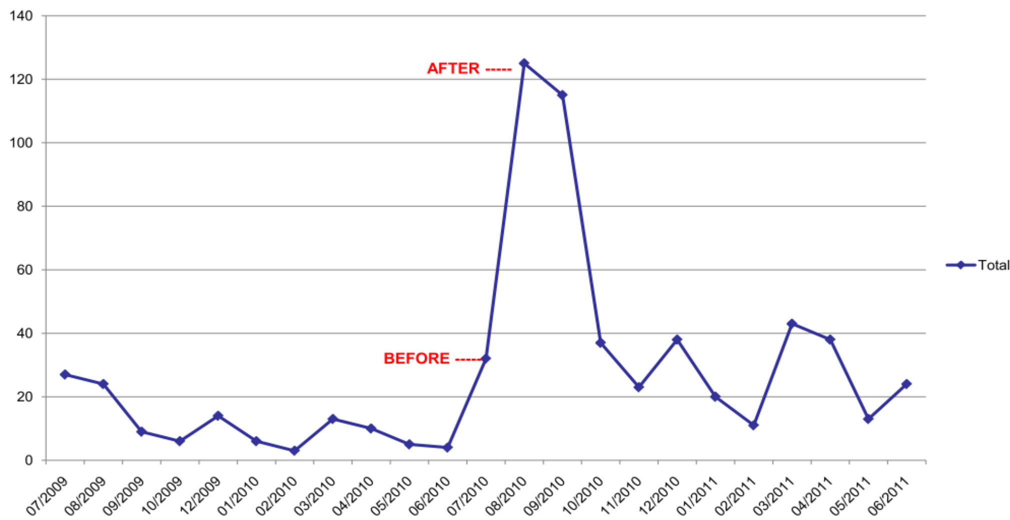


Figure 7-29. Citations by Months.

Source: pdf.**plano**.gov/engineering/tran/Pub.../MLTPrestonLegacy8-7-11.pdf

From Figure 7-29, it can be seen that after three months of a learning period, drivers adapted to this new intersection configuration, and the amount of violation citations has been significantly reduced.

7.4 SYNTHESIS OF OPERATIONAL AND SAFETY IMPACTS AND PEDESTRIAN ACCOMMODATIONS FOR THREE TYPES OF ALTERNATIVE DESIGNS

In this section, existing literature was synthesized for "Super Street," "Michigan U," and continuous flow intersections in terms of operational and safety performance and the issues regarding accommodating pedestrians.

7.4.1 Median U-Turn/"Michigan U"

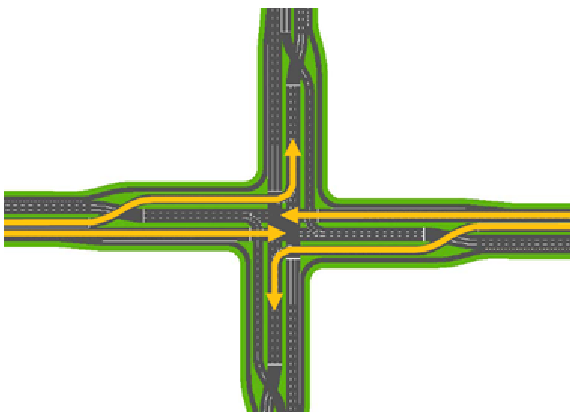
According to the existing literature, the operational and safety performances of restricted MUT intersection are summarized in Table 7-12. Overall, MUT can increase the intersection capacity, reduce critical lane volumes, travel time and delay, increase speed, and reduce crash rate and conflict points at the intersections.

Table 7-12. Operational and Safety Performances of Median U-Turn Intersection.

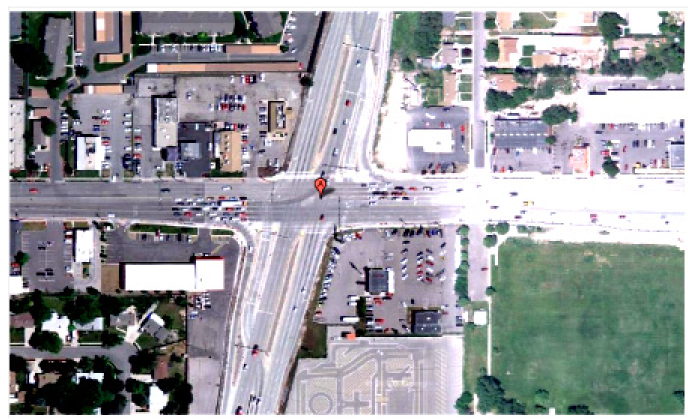
Performance			Reference
Operational Performance	Capacity	• Corridor capacity: increase 20% to 50%	Savage, W.F. (1974)
		• Throughput capacity: increase 20% to 50%	Maki, R.E. (1992)
		• Capacity: increase 14% to 18% (compare with the conventional dual left-turn lane design)	Koepke and Levinson (1993).
	Critical Lane Volumes (CLVs)	• CLVs: reduce 7% to 17%	Koepke and Levinson (1993)
		• CLVs: reduce 17%	Stover, V. (1990)
	Travel Time	• Left-turn total travel times: lower	Dorothy et al. (1997)
		• Network travel times: lower (compared to the five-lane TWLTL design)	Dorothy et al. (1997)
		• Total travel time: 17% decrease	Reid and Hummer (1999)
		• Total travel times: significantly lower	Reid and Hummer (2001)
		• Travel time: lower for the U-turn design at higher entering flows (greater than 6,000 veh/h) with 10% and 20% left-turning volumes.	Bared and Kaisar (2002)
		• Total travel time: reduce	Topp and Hummer (2005)
		• The average intersection travel times: significantly lower	Hughes et al. (2010)
	Delay	• Delay: reduce	Topp and Hummer (2005)
	Speed	• Average speeds: increased 25%	Reid and Hummer (1999)
Safety Performance	Conflict points	• Conflict points: eliminates all related to left turns • Merge/diverge conflict points: reduce from 32 to 16	FHWA report.
	Crash rate	• Rear-end crashes: reduce 17% • Angle crashes: reduce 96% • Sideswipe crashes: reduce 61%	Jagannathan, R. (2007)
		• Crash rates: lower	Kach, B. (1992)
		• Crash rates: increasingly lower	Castronovo et al. (1998)
		• Accident rates: 48% lower for three-legged intersections • Accident rates: 15% lower for four-legged intersections	NCHRP Report 524

7.4.2 Continuous Flow Intersections

CFI, also known as displaced left-turn intersection, was first seen in Mexico in the mid-1980s, and there are approximately 50 in operation in the United States today. Several states are currently using CFIs, including Maryland, Louisiana, Utah, Missouri, Ohio, New York, Colorado, and Mississippi. The CFI is characterized by relocating left-turn movements to approximately 400 to 500 ft upstream of the main signalized intersection. So left-turn vehicles begin with their turn maneuvers prior to the main intersection at a signalized crossover, and move into separated lanes to the right of the opposing through movement. The protected left turns are completed simultaneously with through movements, allowing simple two-phase control at the intersection. A CFI has been planned at SH 6 & FM 529, in Houston.



(a) Illustration of CFI



(b) Aerial photo of a CFI intersection,
3500 S & Bangerter Highway, Salt Lake City, UT

Figure 7-30. Typical Full CFI Intersection.

According to the existing literature, the operational and safety performances of the CFI design are summarized in Table 7-13. Reportedly, CFI can increase the intersection capacity, reduce delay, increase speed, and reduce vehicle emissions, crash rate and conflict points at the intersections.

7.4.3 Restricted Crossing U-turn Intersections

According to the existing literature, the operational and safety performances of RCUT intersections are summarized in Table 7-14. Overall, RCUTs can increase the intersection capacity, reduce travel time, increase speed and reduce crash rate at the intersections.

Table 7-13. Operational and Safety Performances of Continuous Flow Intersection.

Performance			Reference
Operational Performance	Capacity	• Overall Capacity: 60% increase	Gordon et al. (1996)
		• Overall Capacity: increase	KLD Associates (1881)
		• Overall Capacity: increase	Simmonite et al. (2004)
		• Right-turn (equivalent to left turns in the United States) capacity: Increase	Hutchinson, T.P. (1974)
		• Turning volume: increase 100%	KLD Associates (1994)
		• Intersection throughput: increase 10% to 25% for full direct left turns • Intersection throughput: increase 10% to 20% for partial direct left turns	Hughes et al. (2010)
	Delay	• Delay: reduce	Hutchinson, T.P. (1974)
		• Average intersection delays: 50% to 85% reduction for full direct left turns • Average intersection delays: 30% to 40% reduction for partial direct left turns	Hughes et al. (2010)
	Speed	• Average speed: significant increases	Gordon et al. (1996)
		• Move-to-total-time-ratio: Highest.	Reid and Hummer (2001)
	Emission	• Emission: reduce	Gordon et al. (1996)
Safety Performance	Conflict points	• Conflict points: 28 for full direct left turns, 30 for partial direct left turns, 32 for conventional intersection.	Hughes et al. (2010)
	Crash rate	• Total crashes per year: reduced by 24% • Severe crashes: reduced by almost 19% • Total crash rates: decreased by almost 24% • Severe crash rates: decreased by 22%	Hughes et al. (2010)

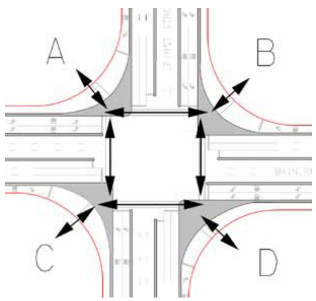
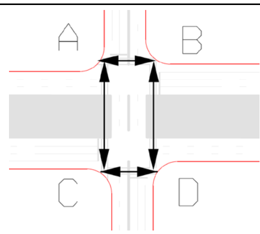
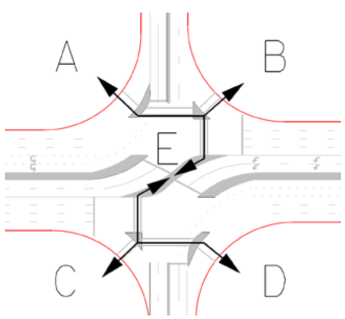
Table 7-14. Operational and Safety Performances of Restricted Crossing U-Turn Intersection.

Performance			Reference
Operational Performance	Capacity	• Throughput capacity: increased 22% to 40% (one U-turn lane) • Throughput capacity: increased 9% to 12% (two U-turn lanes)	Kim et al. (2006)
		• Overall capacity: highest (at lower minor road volumes) • Throughput: 15% to 30 % higher	Hughes et al. (2010)
	Travel Time	• Travel time: reduced by 30% to 40%	Kim et al. (2006)
		• Travel time: decreased 10% (compare with TWLTLs)	Reid and Hummer (2001)
		• Network travel time: reduce 25% to 40% for the high-volume scenarios	Hughes et al. (2010)
	Speed	• Travel speed: 15 percent higher (compare with TWLTLs)	Reid and Hummer (2001)
Safety Performance	Crash rate	• Collision: RCUT caused few collisions	Reid, J.D. (2003)
		• Left-turn and angle collision frequencies: has been lower • Injury collision frequency: has been somewhat lower • Crash averages and average rates: reduce	Simpson (2005)
		• Total crash rates after RCUT installation: lower (compare with crash rates predicted for a four-legged conventional intersection having similar ADTs by *HSM*) • Total crash rates after RCUT installation: lower (compare with the 10-year average crash rates obtained from 25 conventional intersections having similar ADTs in the Charlotte, NC, area)	PBS & J. (2005)
		• Collisions: dramatically reduce 90%	Hughes et al. (2010)

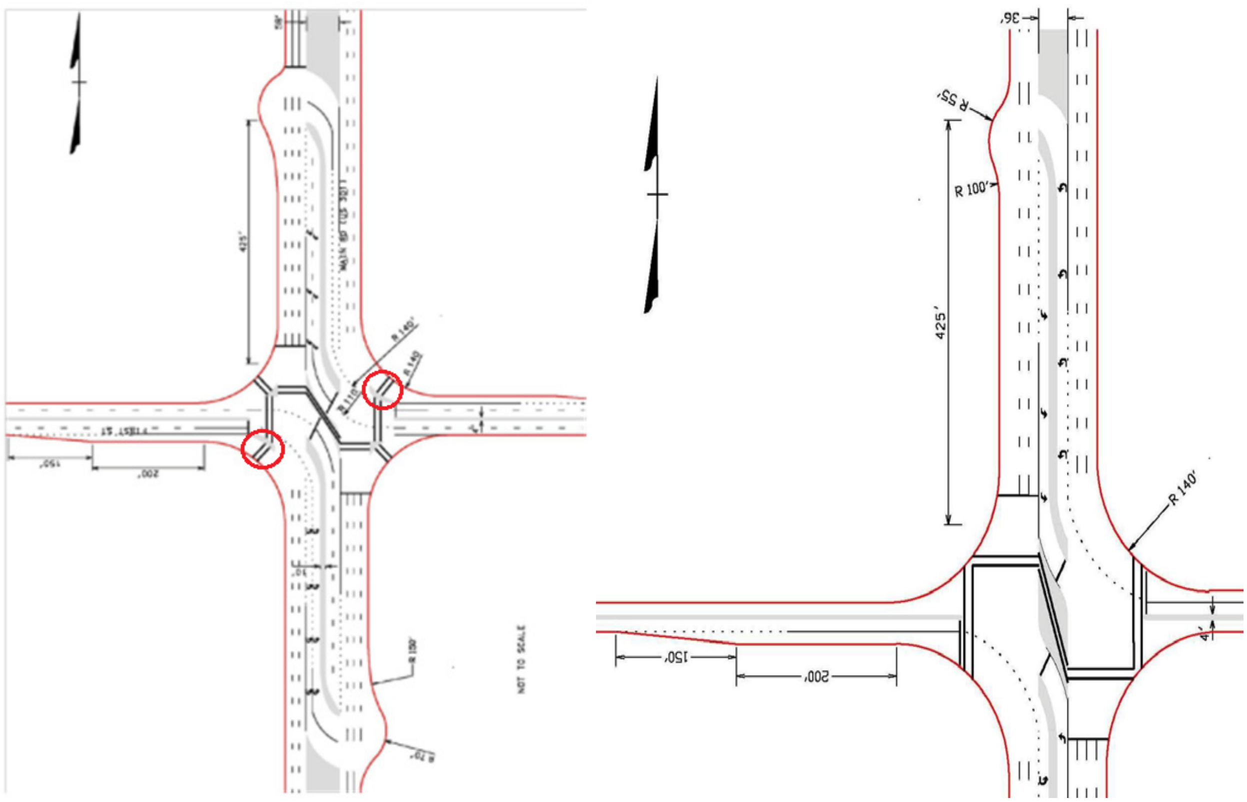
7.4.4 Pedestrian Accommodation Issues

The accommodation of pedestrians at the MUT, CFI, and RCUT designs is an important issue because higher pedestrian activity is likely when these designs are used in urban settings. Compared to traditional intersection designs, the accommodation of pedestrians can be more complex since these designs normally require roadway widening to implement specific treatments in the median. Table 7-15 shows the recommendations summarized from the literature.

Table 7-15. Pedestrian Accommodation.

Design	Illustration of pedestrian movements	Recommendations for better accommodating pedestrian
DLT (CFI)		➢ Provide pedestrian refuges between opposing through lanes to increase pedestrian safety and minimize vehicular delay ➢ Provide wayfinding signing for pedestrians ➢ Design right-turn channelized islands to accommodate pedestrians • Configure the right-turn lane with a tighter radius and narrower lanes • Operate right-turn lane under traffic signal control ➢ Provide accessible devices to assist disabled pedestrians • Locator tones on pedestrian signals and specialized surface treatments are suggested • The use of accessible pedestrian signals (APSs) is recommended
MUT (Michigan-U)		➢ A one-stage crossing is possible if the distance is not too long and if the necessary green time does not adversely affect traffic flow on the major road. Otherwise, a two-stage crossing of the major street is provided. ➢ If pedestrian signals and push-button controllers are provided, the devices need to be installed in the median as well as on the sides of the road.
RCUT (Super Street)		➢ RCUT is preferred where AB, BC, and CD are the major pedestrian movements ➢ Provide wayfinding signing for pedestrians ➢ Use barriers to channelize pedestrians • Barriers should be rigid, especially at higher volume, higher capacity intersections • Alternative breakaway railing system or planting may be considered ➢ Set up accessible devices to assist disabled pedestrians • Locator tones on pedestrian signals and specialized surface treatments are suggested • The use of APSs is also recommended ➢ Use various designs to enhance the ability of pedestrians to cross the main street, such as • Remove the channelized right-turn island, as shown in Figure 7-31 • Shorten the path to cross the arterial, as shown in Figure 7-32

Reference: *Hughes et al. (2010)*



(a) With right-turn island (b) With right-turn island removed

Figure 7-31. Example of RCUT Intersections in which the Side Street Has Two Approach Lanes and One Approach Lane.

Source: Hughes et al. (2010)

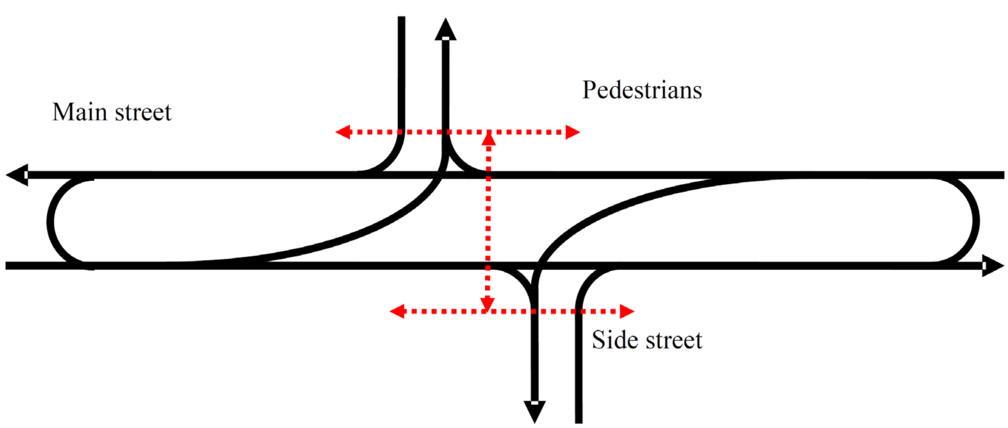


Figure 7-32. RCUT Intersection with Side Street Approaches Offset to Produce a Shorter Pedestrian Crossing.

Source: Hughes et al. (2010)

7.4.5 Advantages and Disadvantages

Based on the findings in the literature, the advantages and disadvantages of three typical types of intersections with alternative movements, i.e., DLT, MUT and RCUT, are summarized in Table 7-16.

Table 7-16. Advantages and Disadvantages of Three Typical Types of Intersections with Alternative Movements.

		Advantage	Disadvantage
DLT	Progression	• Reduced delay and stops for through arterial traffic • Easier progression for through arterial traffic	• Increased stops for left turns from the arterial,
	Safety	• Reduced and separated conflict points	• Driver and pedestrian confusion • It has internal conflict points at the left-turn crossover points
	Accessibility		• Lack of access to the arterial for parcels in the quadrants of the intersection • Restricted U-turn possibilities
	Others	• Less expensive compared to a grade-separated interchange and can be constructed much faster	• Additional construction, maintenance, and operation costs for ramps and extra signals • Widening or adding lanes at a DLT intersection in the future could be difficult
MUT	Progression	• Increased capacity at the main intersection • Easier progression for through arterial traffic • Reduced delay and stops for through traffic	• Increased delay for left-turning traffic • Increased travel distances for left-turning traffic • Increased stops for left-turning traffic
	Safety	• Fewer threats to crossing pedestrians, and fewer and more separated conflict points	• Driver confusion, • Driver may disregard of the left turn prohibition at the main intersection,
	Others		• Larger rights-of-way along the arterial • Higher operation costs for extra signals, and longer cross street minimum green times or two-cycle pedestrian crossing.
RCUT	Progression	• Reduced delay and stops for through arterial traffic and for one pair of left turns (usually left turns from the arterial) • "Perfect" two-way progression at all times with any signal spacing for through arterial traffic	• Increased delay for cross street through traffic and for one pair of left turns (usually left turns to the arterial) • Increased travel distances for cross street through traffic and for one pair of left turns • Increased stops for cross street through traffic and for one pair of left turns
	Safety	• Fewer threats to crossing pedestrians • Lower traffic conflict / crash rate • Reduced and separated conflict points	• May cause driver and pedestrian confusion
	Accessibility		• May adversely affect roadside businesses
	Others		• Additional right-of-way along the arterial is needed

7.5 SUMMARY OF KEY FINDINGS

In this chapter, the TSU research team has conducted simulation studies to analyze the operational and safety impacts of the Super Street. The performance analysis led to the following key findings:

- The crossover distance in a Super Street design should be sufficiently long to provide sufficient storage and deceleration lengths for the U-turn lanes at the crossover and the left-turn lanes at the main intersection. It should also be enough to accommodate the through queue length at the main intersection. Otherwise, the design can cause operational and safety problems.
- The current crossover distances for intersection U.S. 281 & Evans Rd. represent a good design that ensures reasonable safety and operational performance. In addition, the current triple right-turn lanes design for the side streets represents a better option in terms of operational and safety performance as opposed to the dual right-turn lanes.

Researchers also reviewed the best practices of RCUTs, MUTs and CFIs. Collectively, existing literature reported that these designs can improve intersection operational efficiency and safety if they are properly implemented.

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CHAPTER 8: GUIDELINES FOR THE USE OF ALTERNATIVE MOVEMENTS

The purpose of this chapter is to develop guidelines for the use of the three selected alternative movement intersection designs, including CFI (also named as Displaced Left-Turn (DLT) intersection), MUT (also named as Michigan U or Michigan Left intersection) and RCUT intersections. These new intersection designs have been implemented or will be implemented in Texas in the future and can offer additional benefits compared to conventional intersections. In addition, guidelines for applying indirect left turns from a driveway were also provided. The recommendations were proposed based on the results of the previous chapters. In this chapter, the recommended guidelines were highlighted in shaded text boxes for easy reference.

8.1 CONTINUOUS FLOW INTERSECTIONS/DISPLACED LEFT-TURN INTERSECTIONS

The CFI, also known as DLT, is characterized by relocating left-turn movements to an upstream location of the main signalized intersection. So left-turn vehicles begin with their turn maneuvers prior to the main intersection at a signalized “crossover,” and move into separated lanes to the right of the opposing through movement. The protected left turns are completed simultaneously with through movements, allowing more green time and fewer phases at the main intersection for the through traffic. In Texas, a CFI has been planned at SH 6 & FM 529, in Houston.

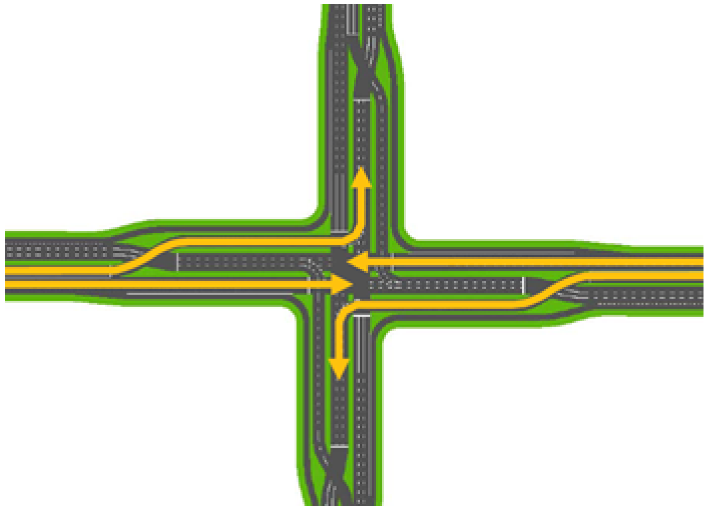


Figure 8-1. Typical Movements at a CFI.

8.1.1 Applicability

Guideline 1.1 – Conditions under which continuous flow intersection (CFI) can be considered:

- Intersections with high through volumes and little demand for U-turns.
- Intersections that are heavily congested with many signal phase failures or left-turn queues spill beyond the left-turn storage bays.
- Some right-of-way is available along the arterial near the intersection.
- Access to the arterial from the parcels located in the quadrants of the intersection can be restricted.

This guideline is based on the literature (FHWA-HRT-09-060, and Hummer and Reid, 2000). The primary reason to choose the CFI design is the ability to process higher intersection volumes, especially left-turn volumes and through volumes. The CFI design is the best for intersections that reach or exceed capacity and there is balanced traffic flow on the DLT approaches. In this design, with the elimination of left-turn movements at the main intersection, U-turns should also be prohibited at the main intersection. Therefore, it is not a good choice for the intersections with substantial U-turn traffic demand. If the median's width is sufficient, U-turn movements can be moved to the left-turn crossovers, which may cause extra delays. In addition, a CFI usually needs a larger footprint to accommodate the left-turn crossovers. Thus, it may not be feasible to apply a CFI in an urban area where right-of-way is limited and costly. Furthermore, at a CFI, access to land parcels located in the quadrants of the intersection is restricted because there are usually turning bays at both sides of the roadway. Please see Figure 8-2 for a bird's eye view of a typical CFI design.

Figure 8-2. A CFI Intersection in Fenton, MO.

Source: Missouri Department of Transportation

8.1.2 Geometric Design

8.1.2.1 Crossover Placement

Guideline 1.2 – where to place the left-turn crossovers for the CFI design:

- Normally, left-turn crossover is placed approximately 300–500 ft upstream of the main intersection.
- The minimum required spacing should be able to accommodate the left-turn lanes with sufficient storage and deceleration lengths. It should also accommodate the maximum queue lengths of the through movements at the main intersection.
- The crossover placement is a balance between the costs of a longer left-turn ramp and the spillback potential from the main intersection.

This guideline is based on the literature (FHWA-HRT-09-060 and Maryland State Highway Administration, 2004). FHWA-HRT-09-060 indicated that in a CFI design, DLT vehicles typically cross the opposing through traffic approximately 300–400 ft upstream of the main intersection. The study conducted by Maryland State Highway Administration (2004) indicated that the left-turn lane crosses the opposing traffic at an intersection 400-500 feet in advance of the cross street. Therefore, the range of 300–500 ft upstream of the main intersection is recommended for placing the left-turn crossover. In addition, the left-turn lane crossovers should be placed at the upstream location where both the left-turn and through queues cannot reach. Furthermore, since the location of left-turn crossovers also determines the length of left-turn ramps, the costs involved in constructing a long left-turn ramp need to be considered.

8.1.2.2 Crossover Angle

The angle between the DLT intersection left-turn lanes and the main through lanes is referred to as the crossover angle. According to the literature, the following general guidelines were provided:

Guideline 1.3 – Crossover angle for the CFI design:

- Normally, a crossover angle is between 10–15 degrees.
- It is influenced by the median width and the alignment of the mainline lanes.
- The angle of crossing for DLT vehicles should be as great as possible to help reduce the possibility of wrong-way entry and to reduce crossing time.

This guideline is based on the State of Louisiana Department of Transportation and Development (2007) and Kalivoda III (2007).

8.1.2.3 Right-Turn Lanes

There are two types of right-turn lanes for the CFI as shown in Figure 8-4, i.e., 1) right-turn lane merging to the CFI leg, and 2) right-turn lane from the CFI leg. The first type of right-turn lane is required. This turn lane channels traffic to the correct roadway and discourages drivers from entering the displaced left turning roadway in the wrong way. The second type of right-turn lane is desirable to allow "red-turn-on-red" and to reduce the interactions between right-turn and through vehicles. It is also desirable to separate this right-turn lane from the outside through lane near the main intersection core by using a sweeping right-turn lane or creating a trip gore between them, which will reduce the tendency of right-turn vehicles to process on through traffic lanes.

8.1.2.4 Median Width and Right of Way

Although the CFI (DLT) usually requires far less right-of-way than the grade-separated interchanges, a CFI has a larger footprint compared to a conventional at-grade intersection due to the presence of left-turn crossovers as shown in Figure 8-3. To reduce the right-of-way requirement, median widths can be reduced to the minimum median widths (18 ft for the median with left-turn lanes according to AASHTO, 2004), but they still need to be adequate to accommodate traffic signs. On the other hand, in a CFI design, wide medians have the following disadvantages (FHWA-HRT-09-060):

- Wide medians can result in large walking distances for pedestrians at the intersection. This can result in long pedestrian clearance intervals, which can be counterproductive to the efficient signal operation.
- Wide medians resulting in a wide intersection footprint lead to longer all-red clearance times for the intersection and consequently longer cycle lengths.

If the median's width is sufficient, U-turn movements on the major road can be executed at the left-turn crossover (Hummer and Reid, 2000). Note that with the elimination of left-turn movements at the main intersection, U-turns should also be prohibited at the main intersection of a CFI. In addition, according to Kalivoda III (2007), widening or adding lanes at a CFI in the future could be difficult. Additional lanes that may be needed in the future should be planned during the initial design of a CFI.

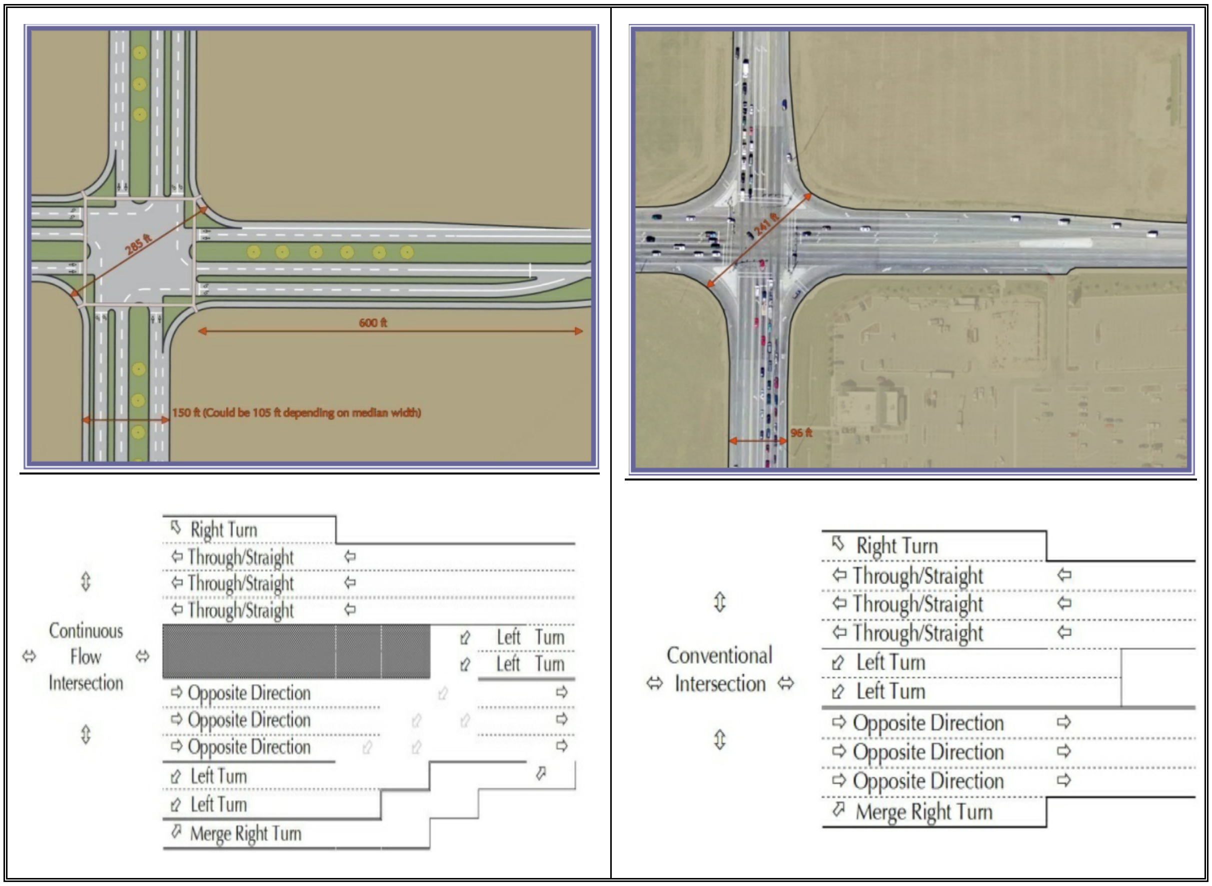


Figure 8-3. Comparison of Footprint of Typical Lane Geometry between a CFI and a Conventional Intersection.

Source: Wilbur Smith, 2008

8.1.3 Access Management

Full implementation of a CFI typically places restrictions on direct access to parcels situated in the quadrants of an intersection. The use of frontage roads can provide access to these businesses. A two-way frontage road is recommended by the State of Louisiana Department of Transportation and Development (2007) to provide sufficient access to the property owners. If a two-way frontage road is not provided, then access will be limited to right-in and right-out on a one-way right-turn roadway as shown in Figure 8-4.

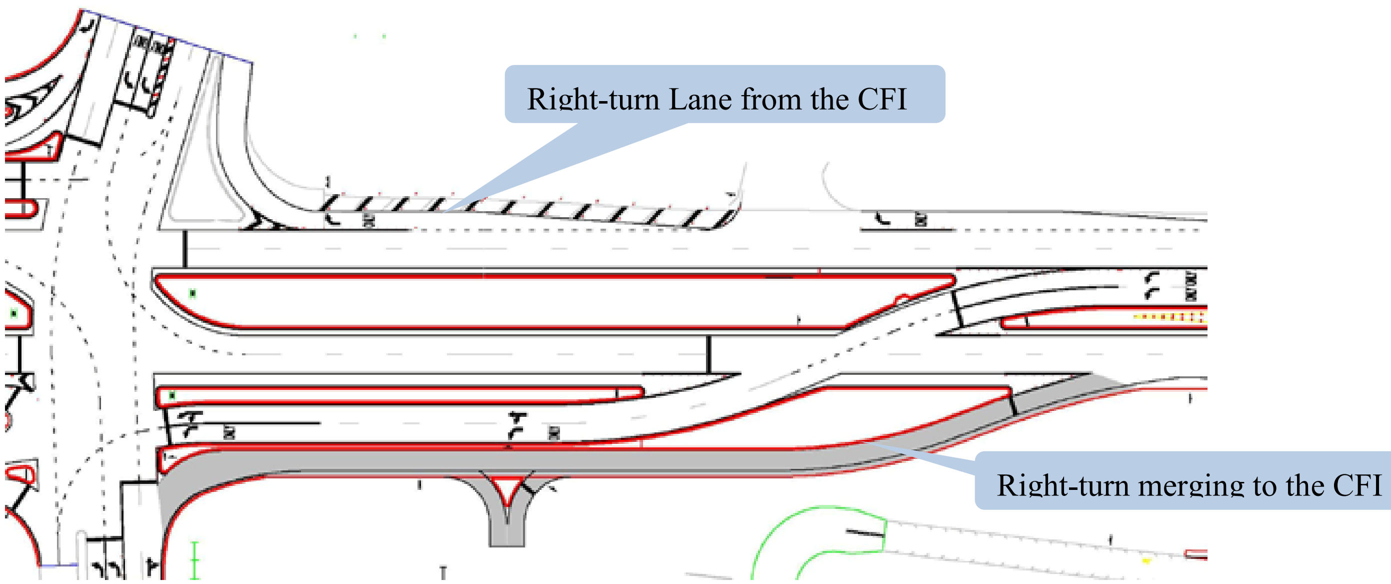


Figure 8-4. Right-turn merge lane/frontage road at CFI in Baton Rouge, LA.

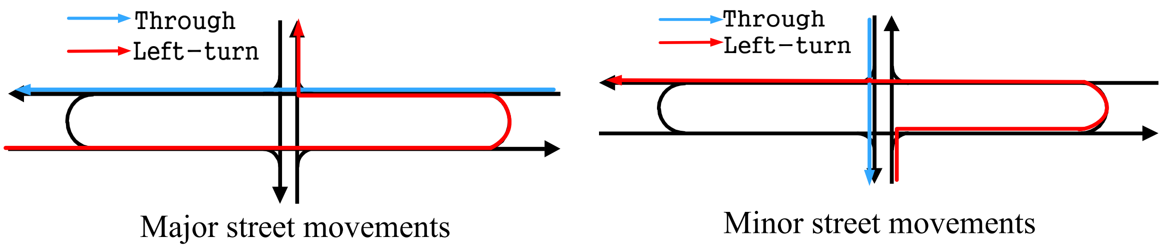
Source: FHWA-HRT-09-060

8.1.4 Others

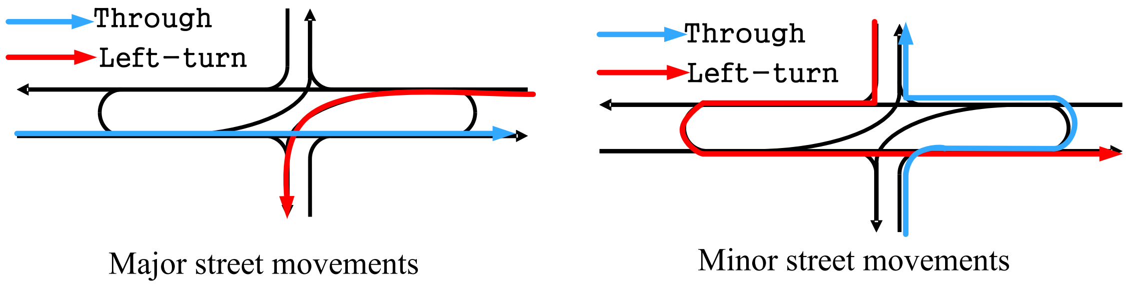
Traffic signing is another issue related to the design of a CFI. Left-turning drivers may be confused when they negotiate the CFI, and it can be counterintuitive to unfamiliar drivers. Hence, additional signings, including guide, warning and regulatory signs, in advance of and within the CFI are needed. According to State of Louisiana Department of Transportation and Development (2007), overhead guide signs are very effective at the CFI crossover locations to provide positive guidance for left-turners maneuvering through the intersection.

8.2 MEDIAN U-TURN INTERSECTION AND RESTRICTED CROSSING U-TURN INTERSECTION

In this section, the guidelines for the MUT and RCUT intersections are presented together because there are many similarities between these two designs. As shown in Figure 8-5, the key differences between them are 1) RCUT intersections allow direct left turns from the major road while MUT eliminates all left turns at the main intersection, and 2) RCUT intersections reroute all minor road movements including both through and left turns while MUT allows minor road through movements. Therefore, a MUT better serves an intersection with more minor-road through traffic than major road left turns, and an RCUT intersection is more appropriate when there are more major-road left turns than minor-street through traffic.



(a) Median U-Turn intersection (also known as "Michigan U")



(b) Median restricted crossing U-turn intersection

Figure 8-5. Comparison of Median U-Turn and Median Restricted Crossing U-Turn Intersections.

8.2.1 Applicability

8.2.1.1 Median U-Turn Intersection

Guideline 2.1 – Conditions under which median U-turn (MUT) should be considered:

- Intersections with heavy through volumes and moderate left-turn volumes on all approaches.
- Intersections that are heavily congested with many signal phase failures for through traffic.

This guideline is based on the literature (FHWA report #FHWA-HRT-09-060, Hummer and Reid, 2000). A primary reason to choose the MUT intersection is the ability to process higher volumes on the major road, especially through volumes. The MUT intersection is typically a corridor treatment. This type of design is typically used for high-speed, median-divided highways with some intersections that have high through volumes and moderate to low left-turn demands. Intersections that are heavily congested due to signal timing delays caused by left turns are also good candidates for this treatment.

8.2.1.2 Restricted Crossing U-turn Intersections

Guideline 2.2 – Conditions under which restricted crossing U-turn (RCUT) should be considered:

- Intersections with heavy through and left-turn volumes on major road approaches, and low to moderate left-turn and through volumes on minor street approaches.
- Intersections that are heavily congested with many signal phase failures for through and left-turn traffic on major roads.

This guideline is based on the literature (FHWA report #FHWA-HRT-09-060, Hummer and Reid, 2000). A primary reason to choose the RCUT intersection is the ability to process higher volumes on the major road, especially left-turn volumes and through volumes. An RCUT intersection is a corridor treatment. This type of design is typically used for high-speed divided highways with intersections that have heavy major-road through and left-turn demands and low to moderate minor street left-turn and through movement demands. This treatment is typically applied to heavily congested intersections for the purposes of reducing traffic delay and simplifying traffic signal timings at these intersections. In addition, an RCUT intersection also can be chosen as a safety measure or collision countermeasure due to its capability in reducing the number of traffic conflicts at the intersections, especially for the crossing type of conflicts.

8.2.2 Geometric Design

8.2.2.1 Median Width and Right of Way

Median width is a crucial design element for both MUT and RCUT intersections. Sufficient median width should be provided to accommodate the U-turn maneuver. From the AASHTO Green Book, the minimum required median widths for vehicles making U-turns can be determined according to the design vehicle types. Assuming 12-ft-wide lanes and 10 ft of shoulder, the desirable minimum median widths between 47 and 71 ft are typically needed to accommodate large trucks without allowing vehicles to encroach on curbs or shoulders. Under this assumption, desirable right-of-way widths range from approximately 140 ft for four-lane arterials to approximately 165 ft for eight-lane arterials.

However, if sufficient right of way is not available continuously through the whole corridor, there are several ways highway designers can reduce the amount of right-of-ways needed.

<u>Guideline 2.3 – Methods for reducing the amount of needed right-of-way to accommodate median U-turn crossovers:</u>

1. Allow larger vehicles to turn onto a shoulder that has been strengthened with full-depth pavement.
2. Provide loons or bulb out at the U-turn crossovers to facilitate the large turning path of large-size vehicles. A loon is an expanded paved apron opposite a median crossover. Please see Figure 8-6 for this treatment.
3. Widen the median for a short distance at a crossover and then narrow it back down beyond the crossover. Please see Figure 8-7 for this treatment.
4. Provide some median openings that only accommodate smaller vehicles, but ensure adequate signage that prohibits trucks from using these crossovers.

This guideline is based on the literature (FHWA-HRT-09-060, Jagannathan, R., 2007, and MDOT, 2010). Figure 8-6 shows a schematic diagram of a loon design, and Figure 8-7 shows a design in which the median is widened in the vicinity of the crossover to better accommodate U-turns. Using any of these methods, the overall right-of-way required for a corridor of RCUT intersections can be as narrow as 84 ft for four-lane arterials and as wide as 132 ft for eight-lane arterials.

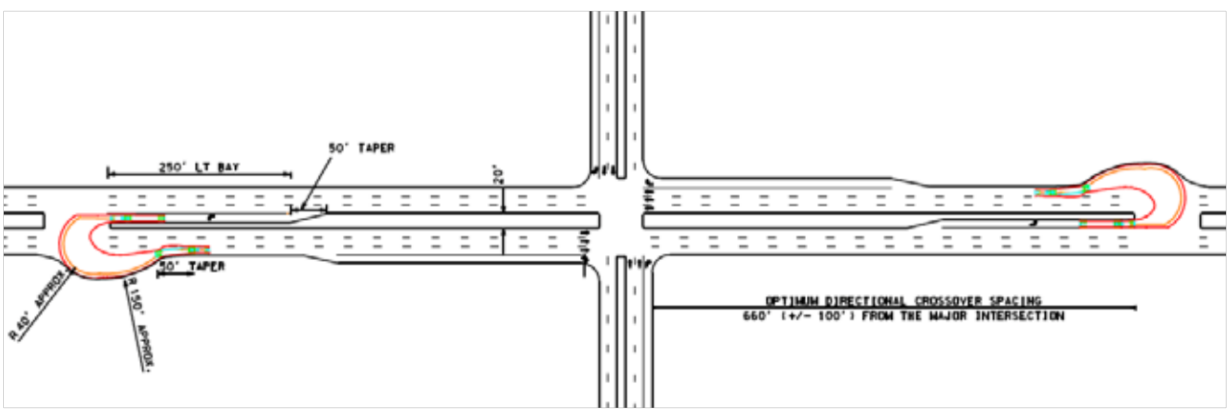


Figure 8-6. Illustration of Loon Implementation for an MUT Intersection.

Source: FHWA-HRT-09-060

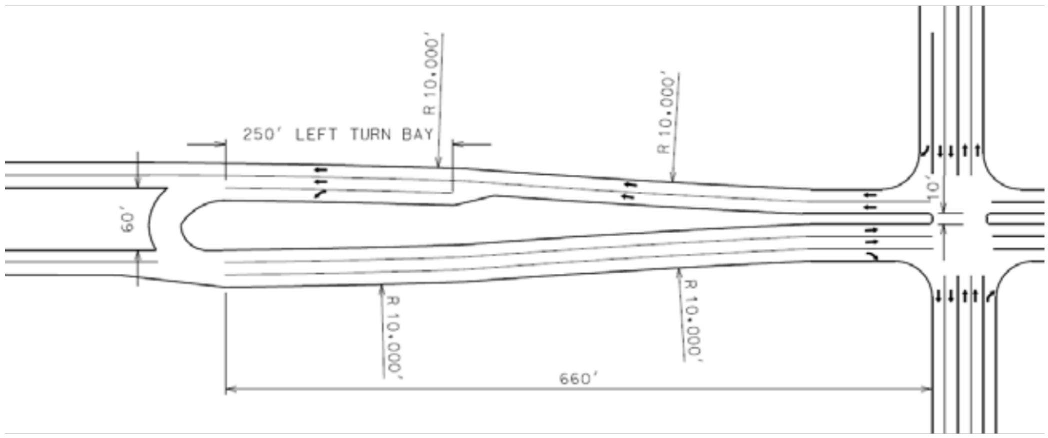


Figure 8-7. Illustration of a Transition from a Wide Median Section to a Narrow Median Section on MUT Intersection Corridors.

Source: Jagannathan (2007)

8.2.2.2 Crossover Spacing

Designers should consider several issues when determining the distance from a main intersection to the median U-turn crossover. Longer distances to crossovers decrease probability of left-turn queues at the main intersection or U-turn queues at crossovers blocking the main street through traffic. In addition, longer distances also provide more space for signs and more time for drivers to position themselves in the proper lane for their direction. Shorter distances to crossovers mean shorter driving distances, shorter travel times, and lower volumes at each crossover because each serves fewer driveways between the main intersection and the crossover. The selection of the spacing from the median crossover to the intersection is also a tradeoff between preventing queue spillback from the turning lanes and the adverse impacts of additional travel distance for the rerouting vehicles. According to the exiting literature and the results of Chapter 7, the following general guidelines were recommended:

Guideline 2.4 – The crossover spacing for the MUT and RCUT designs:

- Normally, the required spacing can be 400 ft to 1,000 ft, depending largely on traffic volumes.
- The minimum required spacing should be able to accommodate the turning lanes with sufficient storage and deceleration lengths, including U-turn lanes at the crossover (Q_U) and left-turn lanes at the main intersection (Q_{LT}). It should also accommodate the maximum queue lengths of the through movements at the main intersection (Q_{TH}), as shown in Figure 8-8.

The required spacing is normally 400 to 1,000 ft between the main intersection and crossover in the MUT or RCUT design. This guideline is based on the literature reviewed (Bared, 2009). Note that the AASHTO *Green Book* recommends a distance of 400 to 600 ft for the minimum spacing between the median crossover and the main intersection. MDOT's experience with MUTs has led it to establish 660 ± 100 ft as the standard spacing. NCDOT's standard minimum spacing between main RCUT intersections and crossovers is 800 ft.

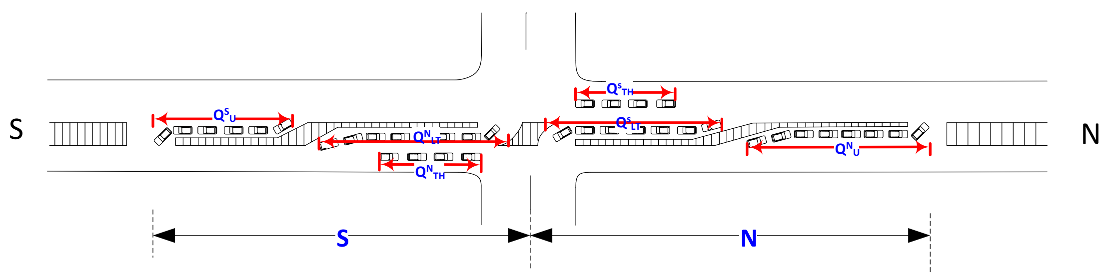


Figure 8-8. The Minimum Required Lengths for the Spacing between Crossovers and Main Intersection.

In terms of minimum required spacing, it should be able to accommodate the turning lanes with sufficient storage and deceleration lengths, including U-turn lanes at the crossover (Q_U) and left-turn lanes at the main intersection (Q_{LT}). It should also accommodate the maximum queue lengths of the through movements at the main intersection (Q_{TH}). Therefore, the minimum required spacing should be the maximum values of these lengths, i.e., S=max [Q^S_U, Q^N_{LT}, Q^N_{TH}] or N=max [Q^N_U, Q^S_{LT}, Q^S_{TH}]. The method in the TxDOT Roadway Design Manual can be used to calculate the necessary pocket lane lengths for left turns and U-turns. For instance, given the field observed conditions and optimized signal timing at the U.S. 281 and Evans Rd. intersection, the minimum required spacing for the northern opening is 600 ft, and the minimum required spacing for the southern opening is 550 ft. The simulation experiment results in Chapter 7 showed that failure to provide the calculated required spacing or required turning lane length resulted in queue spillback from the turning lanes and traffic congestion. On the other hand, when sufficient lengths of the turning lanes can be accommodated by the spacing, the placement of the crossover has little impact on the performance of the intersection.

Furthermore, once the minimum spacing requirement is met, designers have flexibility in selecting the crossover spacing. Crossovers can be shifted toward or away from a main intersection to accommodate constraints related to drainage, sight distances, or available right-of-way.

8.2.3 Access Management

Designers can develop MUT and RCUT intersections that safely and efficiently manage access with minimum adverse impacts to adjacent land users. When designing MUT and RCUT intersections, there is flexibility in locating crossovers depending on the locations of existing access points. As mentioned in Guideline 2.4, once the minimum spacing requirement is met, moving a crossover by several hundred feet will not significantly affect the efficiency of the overall intersection operation. Thus, crossovers can be placed beyond the locations of driveways with high volume to accommodate the left turns into or out of these driveways if there are no safety issues (such as limited sight distance). However, according to the results of existing studies, the following general guidelines are recommended.

Guideline 2.5 – Access management for the MUT and RCUT designs:

- No driveways should be allowed in close proximity to the main intersection.
- If a loon is used at the U-turn crossover, driveways are undesirable on the opposite side of the arterial from a loon.

This guideline is based on the literature (FHWA-HRT-09-060 and NCDOT, 2005). Since MUT and RCUT are high type intersection designs, no driveways should be allowed in close proximity to the main intersection for the safety and operational efficiency of the intersection. In addition, driveways are undesirable on the opposite side of the arterial from a loon. According to NCDOT (2005), if a driveway is placed across from a loon, there is possibility of conflicts between U-turning vehicles using the crossover and right-turning vehicles emerging from the driveway.

8.2.4 Others

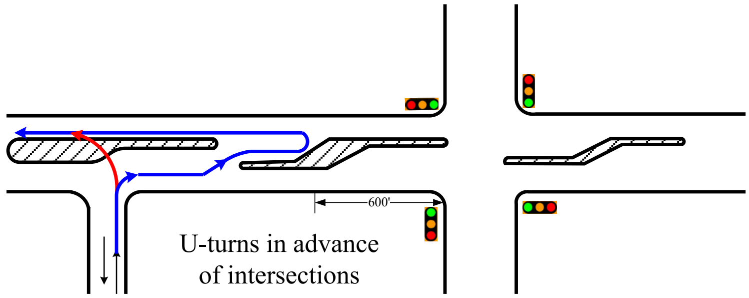
Adequate signing and markings at MUT and RCUT intersections are critical to their operational success because drivers are unfamiliar with these new designs. Signs should be placed in particular areas to provide adequate warning and direction to help the drivers to find the proper lanes for their directions. In addition, these unique intersection designs can cause driver confusion and may result in unintentional illegal left-turn maneuvers. Thus, extra enforcement during the periods (about 3 months) after the intersections are initially opened to traffic is imperatively needed.

8.3 INDIRECT LEFT TURNS FROM A DRIVEWAY

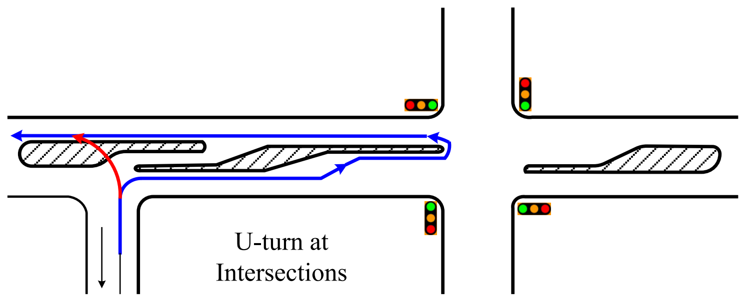
Guideline 3.1 – Conditions under which indirect left turns, i.e., a right turn followed by a U-turn (RTUT), should be considered for egress left turns from a driveway at a median opening:

- Where the provision of a median opening can result in operational or safety issues, e.g., the opening is within the functional areas of intersections or the opening has a poor sight distance for left-turn drivers to judge gaps appropriately, AND
- Where the most likely U-turn location downstream of the driveway has sufficient capacity to accommodate the rerouted left-turning vehicles traveling through the potential RTUT path.

This guideline is based on the simulation experiments conducted in Chapter 5. The RTUT can also be a promising alternative for when closure of an opening is being considered at locations that have high accident rates from historical crash record. From operation standpoint, a RTUT maneuver typically results in increased delays for the egress left turns from driveways, but generally provides safer and easier access than the direct left-turn maneuver.



(a) U-turns located in advance of signalized intersections



(b) U-turns located at signalized intersections

Source: NCHRP Report 420, Impacts of Access Management Techniques, 1999

Figure 8-9. RTUT Maneuvers as Alternatives to Direct Left Turns from Unsignalized, Minor Streets/Driveways.

Guideline 3.2 – Desirable offset distance between driveway exits and downstream U-turn locations for vehicles making RTUT

To make RTUTs, vehicles turning right from a driveway will need distance to safely weave to the next opening to make U-turns. The desirable offset distance between driveway exits and downstream U-turn locations is provided in Table 8-1.

This guideline is based on the literature (Median Handbook of Florida Department of Transportation, 2006). The basic idea is that the more lanes on the roadway, the longer the offset distances needed to allow RTUT vehicles to safely weave to U-turn locations.

Table 8-1. Desirable Offset Distances for RTUT.

Source: Median Handbook of Florida Department of Transportation, 2006

U-turn Location	Number of Lanes	Offset Distance (ft.)
Median Opening	4	400
	6 or more	500
Signalized Intersection	4	550
	6 or more	750

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CHAPTER 9: CASE STUDY

The purpose of this chapter is to demonstrate the applications of some representative guidelines developed in Chapter 6 and Chapter 8. A study segment was selected, i.e., Tidwell Rd. between Hollister St. and Langfield Rd. in Houston, Texas. The effectiveness of the developed guidelines was assessed by using a simulation-based approach.

9.1 SELECTED ROAD SEGMENT FOR THE CASE STUDY

The study location is the segment on Tidwell Rd., in Houston, Texas, that is bounded by Hollister St. and Langfield Rd. The length is 1,420 ft, approximately a quarter mile. Two signalized intersections are on each end, i.e., Tidwell Rd. & Hollister St. and Tidwell Rd. & Langfield Rd. Tidwell Rd. is a four-lane arterial road with a median of 29 ft in width, and the posted speed limit is 35 mph. As shown in Figure 9-1, three full median openings are provided along the road segment and the spacing between them is even, with a distance of about 305 ft. A couple of shopping plazas are located on this road segment with eleven driveways present (Figure 9-2). No dedicated left-turn lanes are provided at the openings.

Figure 9-1. Study Segment on Tidwell Rd. between Hollister St. and Langfield Rd.

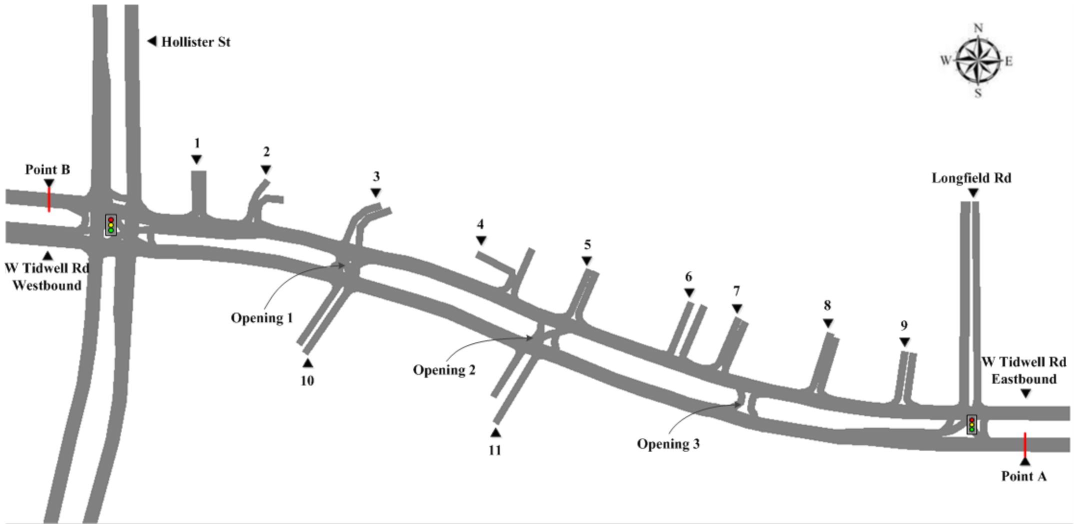


Figure 9-2. Driveways and Openings at the Study Segment on Tidwell Rd.

For this case study, while the real-world geometrics were used, heavy traffic volumes were hypothesized, i.e., the through volume inputs were 420 vphpl, the left-turn volume from the mainline was 50 vph at each opening for each direction, and the left-turn volume from driveways was 50 vph at each opening for each direction.

9.2 APPLICATIONS OF THE DEVELOPED GUIDELINES

In Chapters 6 and 8, a series of guidelines was developed. The following are those guidelines that are potentially applicable to this case.

9.2.1 Applicable Guideline 1

Chapter 6: Guideline 3 – Placement of median openings:

When and where not to place a median opening:

Openings should be avoided in the functional areas of intersections, especially when traffic conditions (e.g., heavy left turns egress from driveways) pose operational or safety problems.

Implications to this location: On the study road segment, the intersection Tidwell Rd. & Hollister Rd. was the critical facility that was running near capacity. Given the assumed traffic volume levels, median opening 1 was located in the functional areas of the intersection Tidwell

Rd. & Hollister Rd. The queue length of the westbound approach to the intersection frequently spilled back to opening 1, which results in undesirable operational and safety issues.

First, from an operational standpoint, as shown in Figure 9-3, the vehicles egressing from the driveways frequently interfere with the through vehicles traveling westbound to the signalized intersection, which results in excessive travel time for the westbound through traffic.

Figure 9-3. Interference between Through Vehicles and Left-Turn Vehicles Egressing from the Driveways in the Base Case.

Second, from a safety standpoint, excessive crossing conflicts occurred, i.e., 413 conflicts/hour (as simulated) at opening 1 because it is located in the functional area of the signalized intersection. Please see Figure 9-4, in which the red points represent the crossing conflicts simulated.

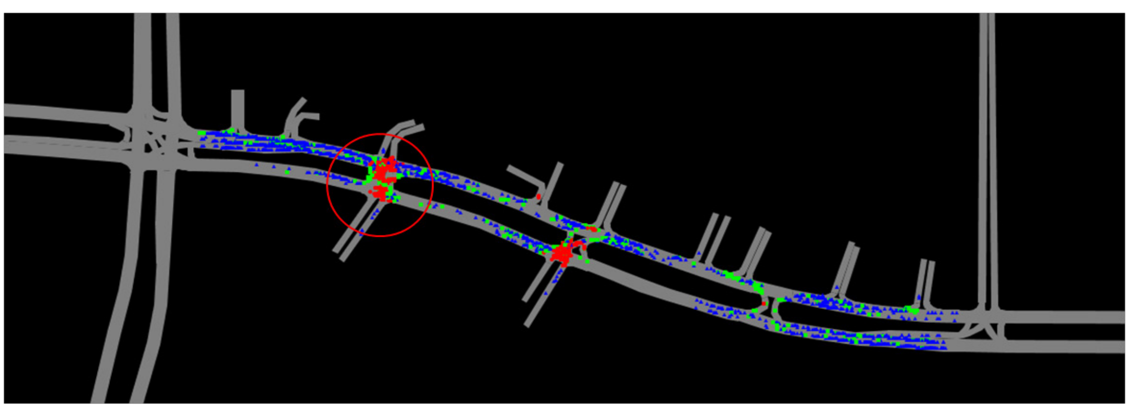
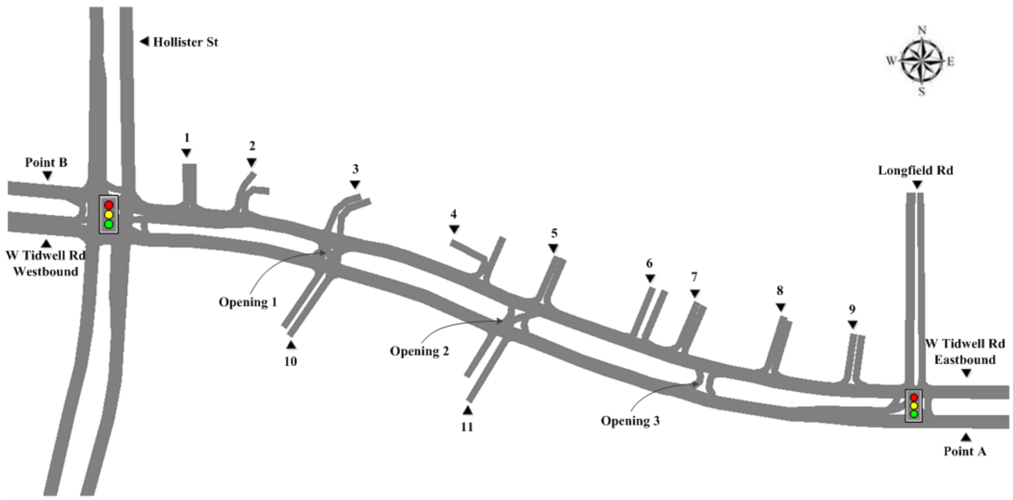
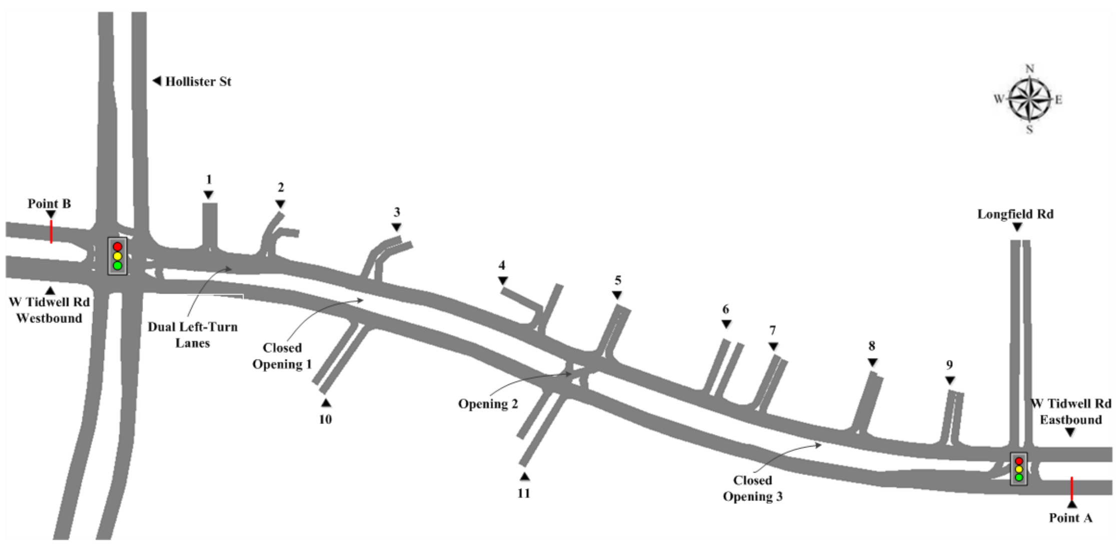


Figure 9-4. Excessive Crossing Conflicts at Opening 1 in the Base Case.

These issues triggered the consideration of closing the opening 1 based on Applicable Guideline 1. Please see Figure 9-5 for the first recommended change (from Scenario I to Scenario II) at this location.



Scenario I: Base case with existing geometric conditions



Scenario II Improved case with the closing of opening 1.

Figure 9-5. First Recommended Change.

9.2.2 Applicable Guideline 2

Chapter 8: Guideline 3.1 – Conditions under which indirect left turns, i.e., a right turn followed by a U-turn (RTUT), should be considered for egress left turns from a driveway at a median opening:

- Where the provision of a median opening can result in operational or safety issues, e.g., the opening is within the functional areas of intersections or the opening has a poor sight distance for left-turn drivers to judge gaps appropriately, AND
- Where the most likely U-turn location downstream of the driveway has sufficient capacity to accommodate the rerouted left-turning vehicles traveling through the potential RTUT path.

Implications to this location: Changing from Scenario I to Scenario II, the re-routing of the egress left-turn vehicles from driveway 3 might place operational/safety issues along the re-routing paths for these egress left turns. Therefore, before any changes were made to opening 1, the re-routing paths were examined carefully to make sure sufficient capacity was provided, in light of Applicable Guideline 2.

Given the traffic volumes assumed, the westbound left-turn movement to the intersection Tidwell Rd. & Hollister Rd had a v/c ratio of 0.63 in Scenario I. If opening 1 was closed and no other change was made in Scenario II, many vehicles from the driveways could no longer turn left directly through opening 1, but rerouted themselves through the signalized intersection. As a result, the westbound left-turn movement at the intersection had an increased v/c ratio of 0.93. This could result in overflow of the westbound left-turn movement at the intersection.

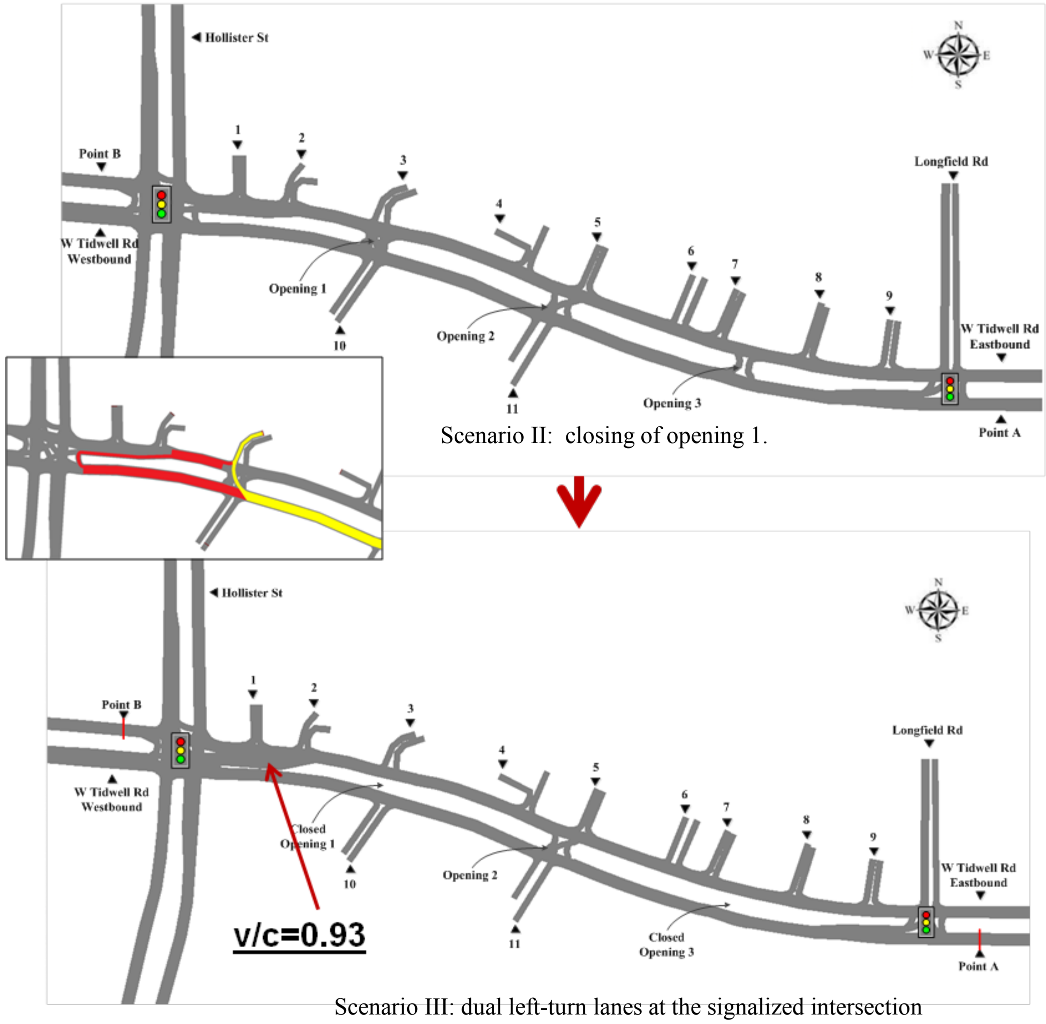


Figure 9-6. Second Recommended Change.

Therefore, in conjunction with the closure of opening 1, other improvements along the rerouting path should be made. In Scenario III, dual left-turn lanes were used in replacement of the single left-turn lane for the westbound left-turn movement at the intersection. As a result, the westbound left-turn movement to the intersection (Tidwell Rd. & Hollister Rd) had a v/c ratio reduced to about 0.68.

9.2.3 Applicable Guideline 3

<u>Chapter 6: Guideline 6 – Conditions under which a median left-turn lane should be considered for four-lane highways</u>

- The thresholds suggested by Harmelink (1967) can be used to determine the need for a dedicated median left-turn lane on four-lane highways (Figure 9-7).

Implications to this location: For opening 2, which was the only opening remaining open, the left-turn volume was approximately 300 vph because the rerouted traffic increased the demand, and the opposing volume was 840 vph. Under these conditions, dedicated median left-turn lanes should be installed at opening 2, which led to Scenario IV.

In Scenario IV, a pair of dedicated left-turn lanes was provided at opening 2, in addition to installing the dual left-turn lanes.

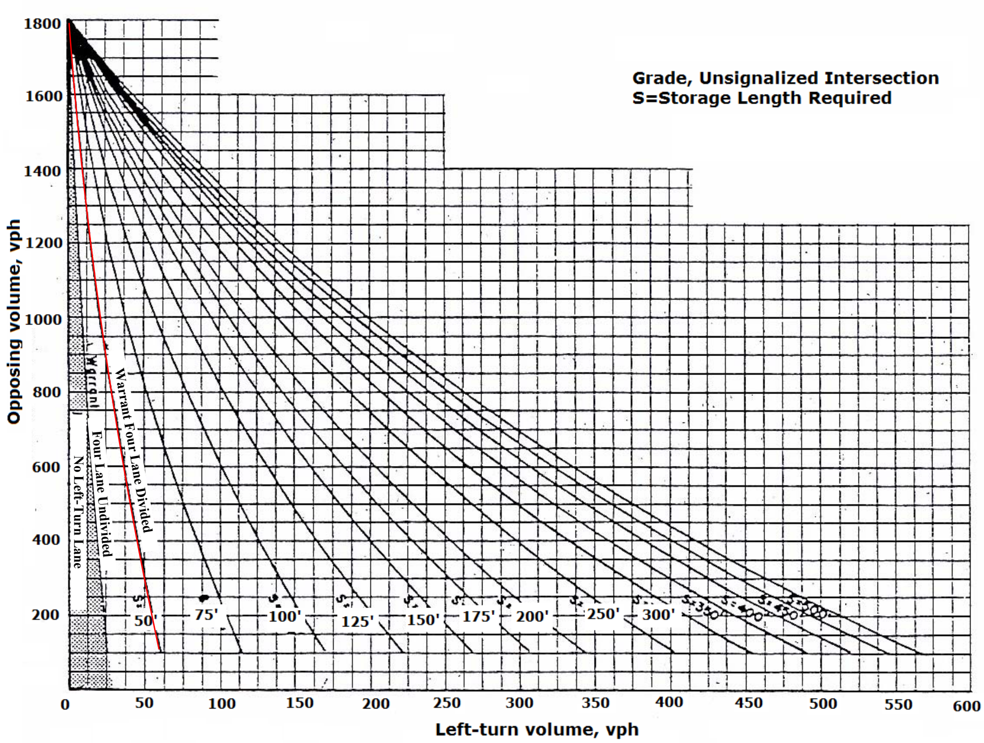
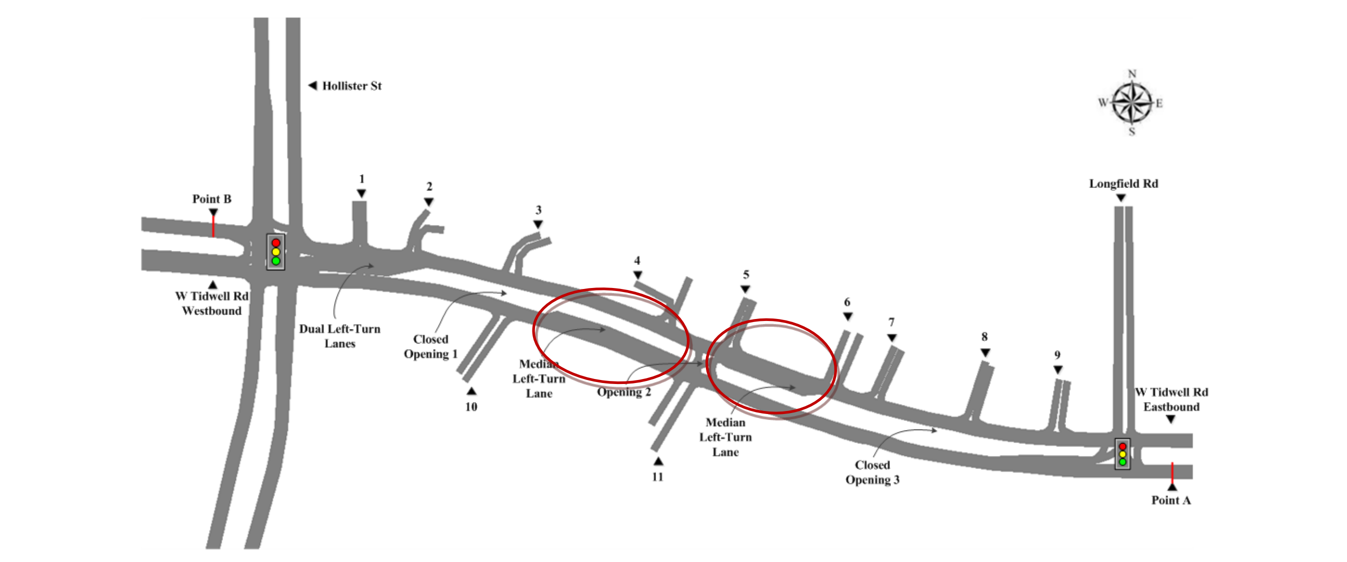


Figure 9-7. Warrants for a Left-Turn Lane at Unsignalized Intersections.

Source: Harmelink 1967



Scenario IV: adding dedicated left-turn lanes at opening 2

Figure 9-8. Third Recommended Change.

The conditions of the above four scenarios are summarized as follows.

Table 9-1. Geometric, Traffic Control and Traffic Conditions (in Seconds for Heavy Left-Turn and Heavy Through Traffic).

Scenarios	Number of openings	Westbound left-turn lane at Hollister Intersection (actual demand)	Signal Timing	Left-turn lane at opening 2 (actual demand)	Driveways where egress traffic had to make indirect LT (RTUT)
I	3	1 exclusive	Optimized	None	Driveways 1, 2, 4, 5, 6, 7, 8, and 9
II	1	1 exclusive	Optimized (same as Scenario I)	None	Driveways 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10
III	1	2 exclusive	Optimized	None	Driveways 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10
IV	1	2 exclusive	Optimized (same as Scenario III)	Exclusive Left-turn lanes at opening 2	Driveways 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10

The above analysis is an example of how to apply Applicable Guidelines 1-3. The effectiveness of implementing the guidelines will be examined in the simulation tests in the following section.

9.3 TESTS OF EFFECTIVENESS IN APPLYING THE GUIDELINES

To test the effectiveness in applying the guidelines, we performed a simulation study to evaluate the safety and operational impacts of implementing each guideline. Four simulation scenarios were developed given the assumed traffic volumes and the geometric settings in the four designed scenarios.

9.3.1 Operational Implications of the Results

9.3.1.1 Movement-Specific Performance

In Table 9-2, the simulation results are presented for various scenarios given different geometric settings. As mentioned before, the assumed volumes for the through traffic and left-turn traffic are quite heavy.

Table 9-2. Travel Times (in Seconds) for Heavy Left-Turn and Heavy Through Traffic.

Scenario		Travel times along the corridor		Travel times for egress LT from driveway				
		Eastbound	Westbound	3→A	5→A	8→A	10→B	11→B
I	Original settings, 3 openings	85	130	88	105	100	102	152
II	Openings consolidated, 1 opening, no other change	91	207	252	337	212	134	130
III	Openings consolidated, 1 opening, double LT [3] lane at Hollister, updated signal [2]	84	101	106	94	89	105	96
IV	Consolidated opening, 1 opening, double LT lane at Hollister, updated signal, midblock turn lane [2]	78	99	111	92	82	97	82

The results showed that under the given traffic conditions, the rerouted traffic as a result of closure of median openings 1 and 3 in Scenario II, the through traffic increased approximately 11%. Therefore, travel time for the westbound through traffic significantly increased (from 130 s in Scenario I to 207 s in Scenario II). In addition, in Scenario II, the rerouted traffic resulted in left-turn lane overflow at the westbound approach of the intersection (Tidwell Rd. & Hollister Rd) (Figure 9-9), as the left-turn and U-turn volume at the intersection increased due to the rerouted traffic from driveways 3 and 4.

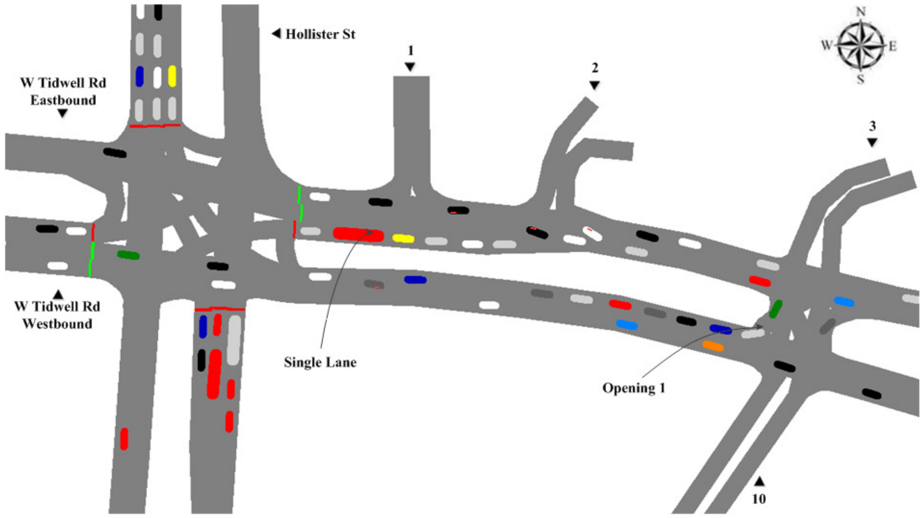


Figure 9-9. Left-Turn Lane Overflow at the Westbound Approach of Tidwell Rd. & Hollister Rd.

In Scenario III, addressing the left-turn overflow issue at the Hollister Rd signalized intersection, dual left-turn lanes were provided at the problematic approach in replacement of the single left-turn lane. The results showed that the travel times along the corridor were improved, which was even better than Scenario I (i.e., the original case with three openings).

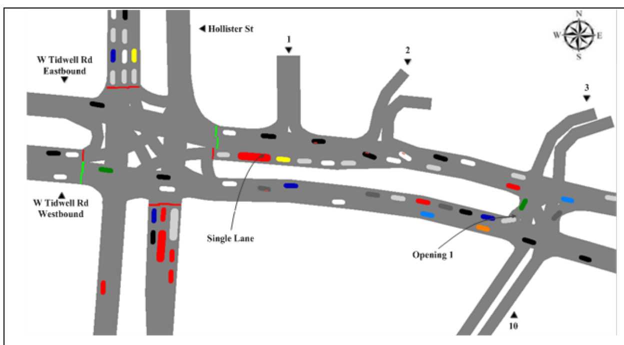
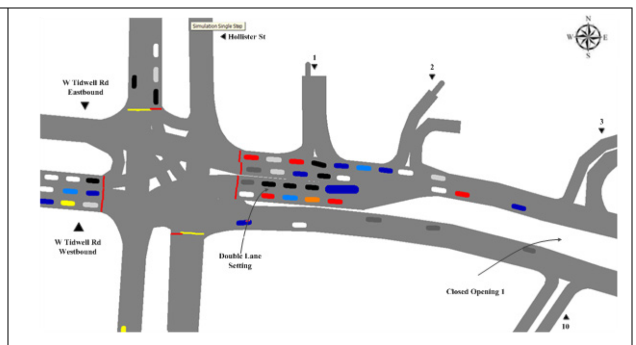
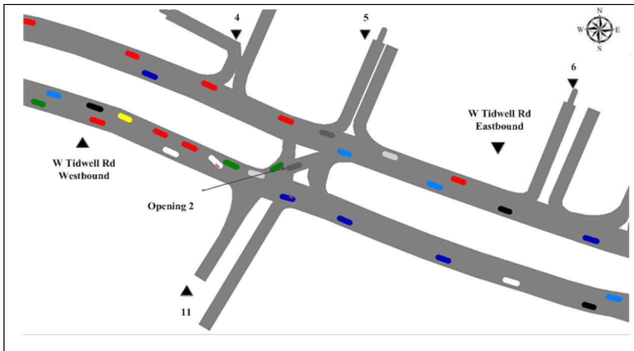
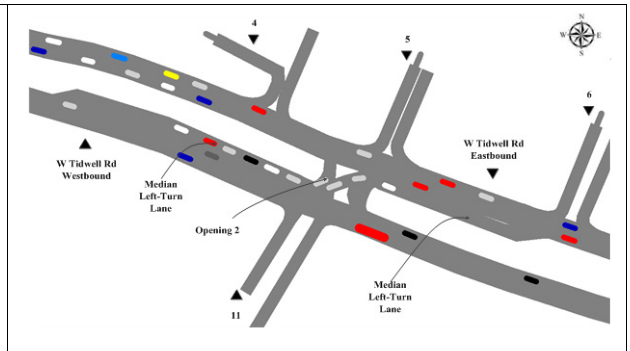
	
Scenario II: Single left-turn lane	Scenario III: Dual left-turn lanes

Figure 9-10. Overflow of Left-Turn Lanes and Corresponding Improvement in Geometrics.

In Scenario IV, further geometric improvement was made by adding left-turn lanes at the opening 2 (the only opening after closing median openings 1 and 3). We can see that the average travel times along the corridor were further improved to 105 seconds per vehicle westbound and 81 seconds per vehicle eastbound.



Scenario III: No left-turn lane in advance of median opening 2



Scenario IV: Left-turn lane installed in advance of median opening 2

Figure 9-11. Overflow of Left-Turn Lanes in Advance of Median Opening.

9.3.1.2 Network Performance

The simulated network operational performance is shown in Table 9-3.

Table 9-3. Network Operational Performance of the Scenarios.

	Average delay, s	Average speed, kmph	Total travel time, h
Scenario I	65.3	15.3	363.8
Scenario II	144.8	9.4	524.7
Scenario III	64.9	15.5	364.8
Scenario IV	61.1	16.0	354.7

9.3.1.3 Summary

The simulation experiments validated the developed guidelines for operationally effective raised medians. Changing the geometrics from Scenario I to IV, the operational performance was significantly improved.

9.3.2 Safety Implications of the Results

To supplement the operational analysis, a simulation-based surrogate safety study was also conducted. A computational tool—SSAM—was used for facilitating the analysis. Researchers acquired the simulated traffic conflicts, including crossing, lane-change, and rear-end conflicts for the safety analysis.

9.3.2.1 Results of the Safety Performance

The results of the safety analysis showed that Scenario II (with openings 1 and 3 closed) presented the highest rates of traffic conflicts. The compromised safety performance was associated with the overflow at the westbound left-turn lane at Hollister & Tidwell. By contrast, when sufficient capacity was provided by converting the left-turn lane into dual left-turn lanes, the safety performance was significantly improved in Scenarios III and IV.

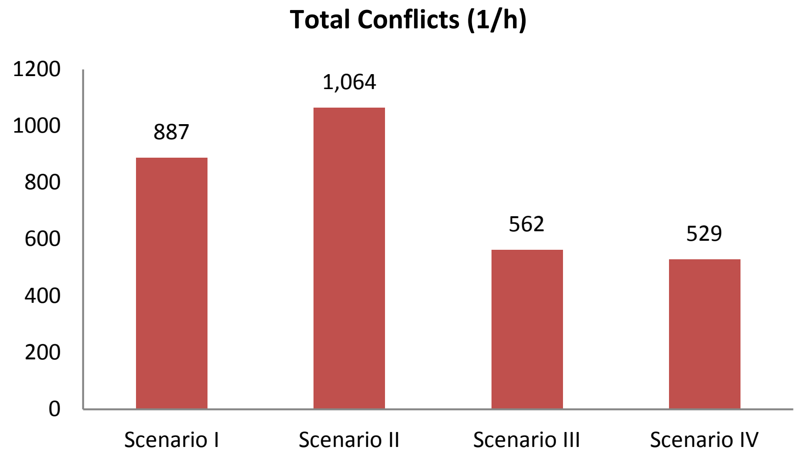


Figure 9-12. Comparison of Total Number of Conflicts among Various Scenarios.

For crossing conflicts, in Scenario I, the opening was located within the influence area of the signalized intersection, which posed a considerable number of crossing traffic conflicts. By closing opening 1, the problem was significantly mitigated, with crossing conflicts reduced by more than 60%.

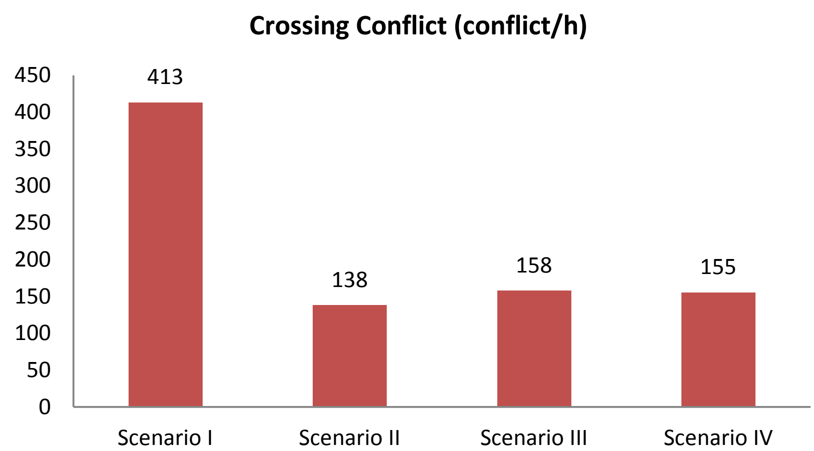


Figure 9-13. Comparison of Number of Crossing Conflicts among Various Scenarios.

In terms of lane-change conflicts, Scenario II presented the highest number of this type of conflict because the overflow of the westbound left-turn lane at Hollister & Tidwell caused congestion, which increased the potential for interactions between lane-changing vehicles. The congestion also resulted in more rear-end conflicts in Scenario II.

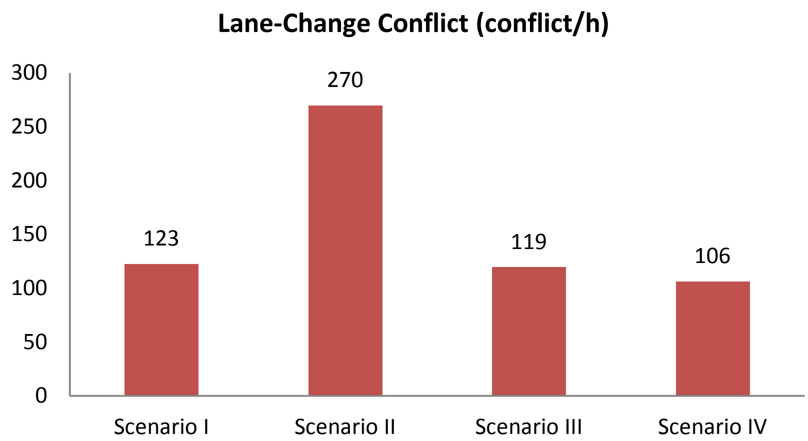


Figure 9-14. Comparison of Number of Lane-Change Conflicts among Various Scenarios.

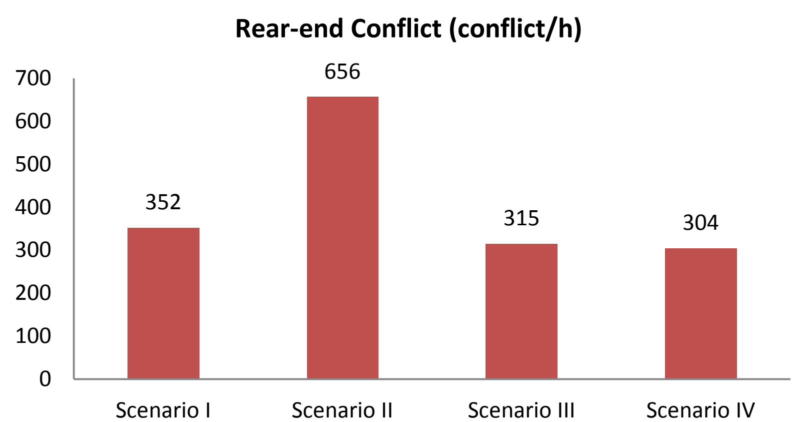


Figure 9-15. Comparison of Number of Rear-End Conflicts among Various Scenarios.

From the results, we can see that the safety performance can be improved when (1) an opening located within the influence area of a major intersection is closed, and (2) sufficient capacity is provided at the U-turn location downstream of the rerouted driveway traffic.

9.3.2.2 Summary

The SSAM analysis showed that the relative safety performance of the study site was significantly correlated with its operational performance. Meanwhile, the results indicate the application of the guidelines developed in Chapters 6 and 8 do improve the safety and operational performance of this study site.

9.4 SUMMARY

In this chapter, the applications of representative guidelines developed in Chapter 6 and/or Chapter 8 were demonstrated through a case study. In addition, the simulation studies were conducted to verify the applicability and effectiveness of the developed guidelines. The results of the simulation studies indicated that implementing the recommended guidelines can improve the safety and operational performance of the study site.

CHAPTER 10: KEY FINDINGS AND RECOMMENDATIONS

The primary goal of the proposed project is to develop guidelines for operationally effective raised medians and the use of alternative movements on urban roadways. To fulfill these goals, researchers have performed the following key tasks:

- Reviewed and synthesized national and peer states' practices.
- Conducted a survey of traffic engineers.
- Conducted field studies.
- Analyzed operational and safety impacts of raised medians and representative alternative movements.
- Developed guidelines for future implementation in Texas.
- Conducted a case study to demonstrate the application of the developed guidelines.

The review of the prior research and survey of traffic engineers indicated that the operational and safety benefits of raised medians depend on a wide range of design elements, such as median widths, median left-turn lane lengths, placement of median openings, and types of median openings (directional vs. full). This study led to a number of findings and recommendations associated with these design elements of raised medians. Some key findings and recommendations include the following.

10.1 MEDIAN WIDTHS

- Where the right-of-way is available, a median width of 25 ft that can provide sufficient refuge for at least one left-turn vehicle from side streets/driveways is recommended.
- The Roadway Design Manual suggests a minimum median width of 16 ft (17 ft if a pedestrian refuge is needed). The use of a median with this minimum width on a four-lane curbed roadway does not provide adequate space for mid-block U-turn movements by pick-up trucks, SUVs, or vans. In this study, the appropriate median widths were suggested for various design vehicles according to the results of swept path analysis.

10.2 MEDIAN LEFT-TURN LANE LENGTHS

- The deceleration and storage lengths for turning vehicles required by the Roadway Design Manual often exceed the available length along the roadway centerline due to the high turning demand at the median openings. This study found that use of a left-turn lane shorter than the TXDOT standards at median openings may not result in significant operational and safety problems if it does not cause recurrent left-turn lane overflow.

- A median turn lane that is shorter than full lengths will incur additional delay to the through traffic. Even though the delay caused by using the substandard median turn lanes is relatively small, the resulting delays can add up, causing significant delays, if such lanes are used consistently along a corridor. Therefore, the standards provided by the TxDOT Roadway Design Manual for left-turn lane lengths should be followed whenever it is practical.

10.3 PLACEMENT OF MEDIAN OPENINGS

- Openings should be avoided in the functional areas of intersections, especially when traffic conditions (e.g., heavy left turns egressing from driveways) pose operational or safety problems.
- Median openings that allow the movements across exclusive right turn lanes should be avoided.

10.3.1 Directional Median Openings

- A directional opening can be considered in replacement of a full opening that is located in the functional areas of intersections when operational or safety problems are caused by the heavy crossing or left-turning traffic exiting from the driveways at the opening. Before the conversion, traffic engineers should carefully examine whether the capacity of the rerouted paths, especially the U-turn location downstream of the driveway, can accommodate the additional demands of the egress vehicles performing an RTUT maneuver.

In addition, the use of alternative movements was investigated based on the literature review, survey of traffic engineers and field studies. From the field studies conducted at the U.S. 281 Super Street in San Antonio and the previous experience about the “Michigan U” intersection in Plano, Texas, it was found that:

- The Super Street implemented along U.S. 281 can save approximately 30–40% of the travel times and significantly reduce head-on and rear-end collisions.
- The Michigan U intersection implemented in Plano, Texas, reduced back-up queue by 60% and reduced traffic delay by 35 sec/veh.

Collectively, existing literature reported that alternative movements, e.g., RCUTs, MUTs, and CFIs, can improve intersection operational efficiency and safety if they are properly implemented. In this study, based on the results of a literature review, survey of traffic engineers and field studies, a set of implementation-oriented guidelines regarding the applicability, geometric design and access management of the three typical alternative movements, i.e., RCUTs, MUTs and CFIs, were developed.

APPENDIX A: SURVEY DOCUMENT

Traffic Engineer Survey for TXDOT Research Project 0-6644

Raised medians and alternative movements are recognized as representative access management techniques that may help preserve capacity, maintain mobility, and improve safety. Texas Southern University (TSU) and the University of Texas at Austin (UT) are collaboratively conducting a research project entitled "Development of guidelines for operationally effective raised medians and the use of alternative movements on urban roadways" for the Texas Department of Transportation (TxDOT).

Typical designs for raised medians and alternative movements are presented in Figures A-1 and A-2.

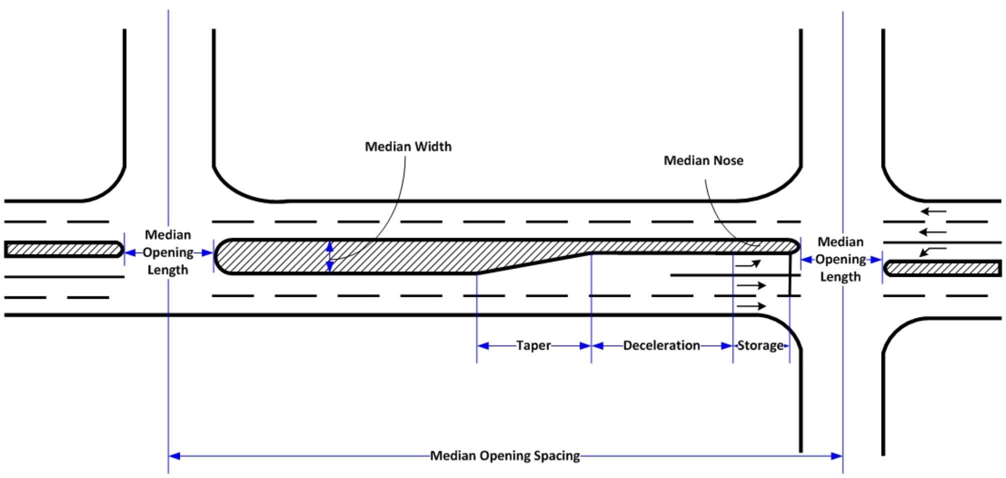
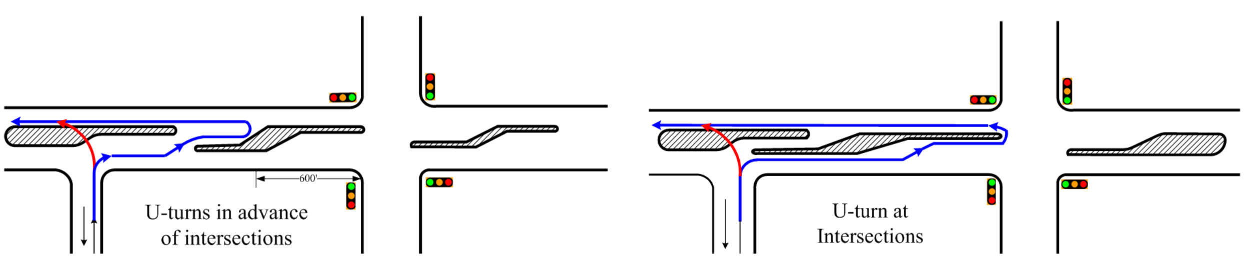


Figure A-1: Typical design elements of a raised median



Red lines depict direct left turn; blue lines represent **indirect left turn**

Figure A-2: U-turns as alternatives to direct left turns from unsignalized, minor streets/driveways (alternative movement)

This survey is being conducted to collect your professional opinions and experiences regarding the use of raised medians and alternative movements. Your valuable input and support are greatly appreciated!

1. Under what circumstances would the installation of a raised median be an option for consideration? Please specify the guidelines directing this consideration.

- ☐ High ADT volume — Please specify if applicable__________________.
- ☐ High midblock left-turn volume — Please specify if applicable__________________.
- ☐ Excessive number of driveways — Please specify if applicable__________________.
- ☐ High accident rate — Please specify if applicable__________________.
- ☐ High design speed — Please specify if applicable__________________.
- ☐ Others — Please specify ____________________________.

2. Under what circumstances will your agency consider to place a median opening?

- ☐ On divided highways at all public roads and major traffic generators
- ☐ Where a full length left-turn lane can be developed
- ☐ Where median openings are proven necessary by traffic impact study
- ☐ When the original road construction failed to meet required opening spacing criteria
- ☐ Others — Please specify________________________.

3. Does your agency limit the spacing of median openings in any way? Has your agency noticed any operational effects related to median opening spacing?

4. What guidelines and standards are in place for your agency regarding arterial median width? Is preference given to designing medians wide enough to allow for vehicles to stop between the two roadways?

5. Does your agency have a preference regarding full median openings versus directional median openings? If so, why?

6. Are median-specific guidelines in place regarding turn lanes, or are the same turn-lane guidelines used for roadways with or without medians? If there are median-specific guidelines, how do they differ?

7. Which of the following factors do you think would significantly affect traffic safety performance of raised medians?

- ☐ Median opening density
- ☐ Median width
- ☐ ADT demand
- ☐ Speed limit
- ☐ Adjacent land use
- ☐ Travel lane number and width
- ☐ Presence of curb or shoulder on a raised median
- ☐ Others Please specify___________________________.

8. When installing a new raised median, the major obstacle(s) you encountered/expect is:

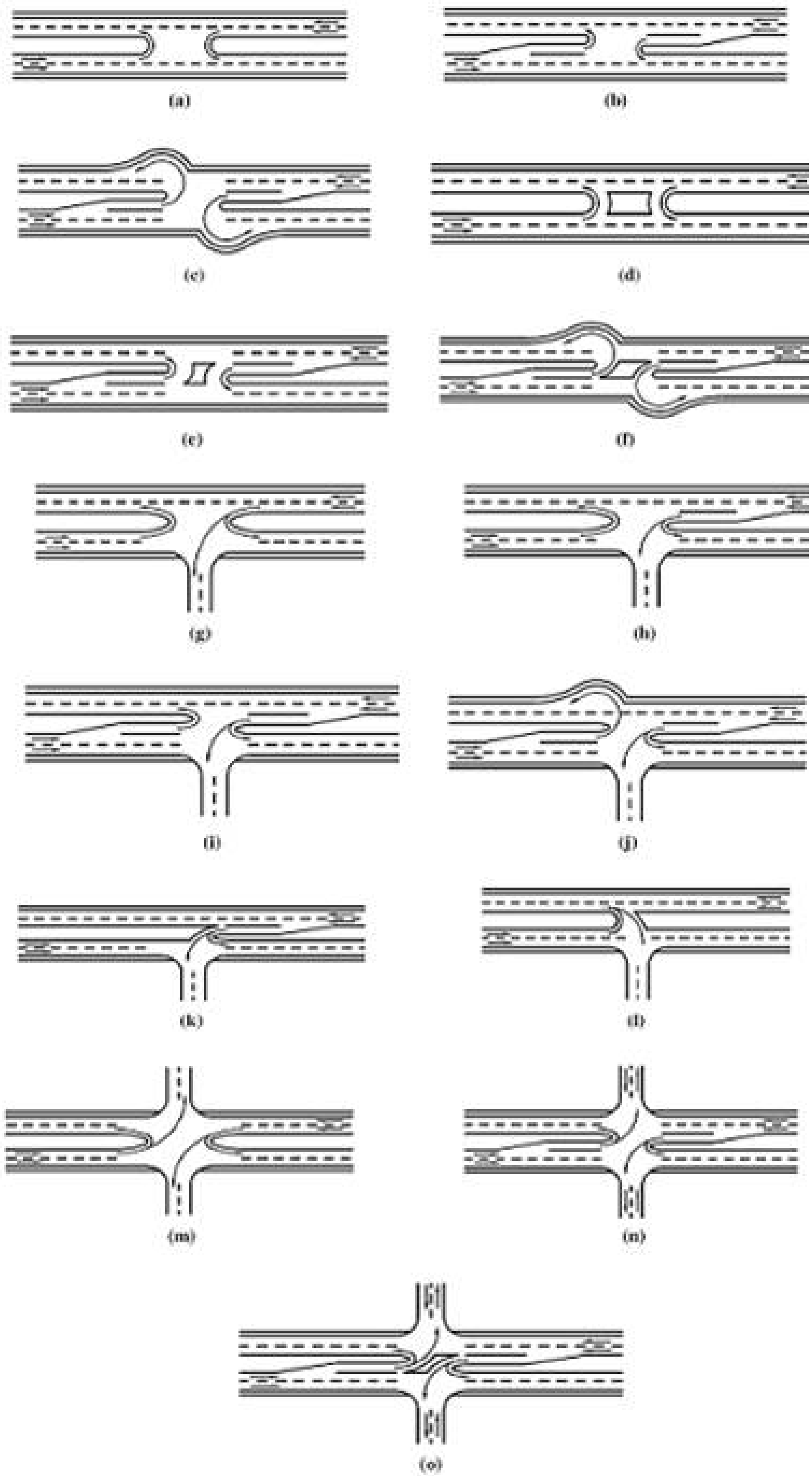
- ☐ Objection from abutting business owners
- ☐ Objection from abutting residents
- ☐ High construction costs
- ☐ Limited land availability
- ☐ Others. Please specify__________________________.
- ☐ No obstacles

9. If you and your agency have experience with alternative movements (please see Fig. 2), do they work well? What operational objectives led to their installation and have they accomplished these goals?

10. Based on your experience/judgment, what kind of impacts will "indirect left turn" treatment (please see Fig.2) bring?

☐ Improved safety for left-turn vehicles egress from a driveway
☐ Increased travel time for left-turn vehicles egress from a driveway
☐ Reduced delay for left-turn vehicles egress from a driveway
☐ Negative effects on mainline traffic flows
☐ Others. Please specify______________________________.

11. Which of the following typical median opening designs are used by your agency (if any) to accommodate U-turns? Please list____________________.


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)

General Questions

12. Do you have any suggestions for addressing the following specific issues in raised median design:

(a) The requirements for the deceleration and storage of turning vehicles may exceed the available length between two openings, especially for the arterials with high design speeds and high demand for left-turn movements. On the other hand, if the frequency of median openings is reduced, the demand for mid-block U-turns will increase and will result in longer storage length requirements. How did/will you deal with the median treatment under this circumstance?

(b) In areas of restricted rights-of-way, the median width is limited to provide adequate U-turn radii for vans or trucks (especially on four-lane arterials). How did/will you deal with the median treatment under this circumstance?

13. What other challenges have you encountered in implementing raised medians and/or alternative movements?

Acknowledgement

We appreciate your valuable time. Please fill the following information for further contact:

Your Agency Name:

Can we further contact you for more information? ☐ YES ☐ NO

IF YES, THE BEST WAY TO CONTACT (PLEASE LEAVE YOUR NAME AND PHONE/EMAIL):

APPENDIX B: EXISTING GUIDELINES IN TXDOT MANUALS

When considering new construction or retrofit of urban streets, the guidelines in the "TxDOT Access Management Manual" and the "TxDOT Roadway Design Manual" are the official tools available for the design of raised medians. The related guidelines and standards in these two manuals are presented as follows.

Warrants for installation of a raised median: installation of a raised median can be considered where an ADT exceeds 20,000 vehicles per day or new development is occurring (the Access Management Manual and the Roadway Design Manual);

Placement/Spacing of median openings: the frequency of median openings varies with topographic restrictions and local requirements. Spacing is often selected to provide openings at all public roads and at major traffic generators such as industrial sites or shopping centers. Additional openings should be provided so as not to surpass a maximum of one-half mile (2,640 ft) spacing. In rural areas, the minimum spacing should be not less than one-quarter mile (1,320 ft). Openings should be located where adequate stopping sight distance is available and where the median is sufficiently wide to permit an official design vehicle to turn between the inner freeway lanes (the Roadway Design Manual);

Urban median widths: typical median width is 16 ft (12 ft lane plus a 4 ft divider) (the Roadway Design Manual);

Median opening length: Median opening length should be not less than 40 ft, nor less than crossroad pavement width plus 8 ft. Turning templates (swept path) for a selected control radius and design vehicle are often used as the basis for minimum design of median openings, particularly for multilane crossroads and skewed intersections (the Roadway Design Manual);

Left-turn lanes: Left-turn lanes should be provided at all median openings; the minimum length of a left-turn lane is the sum of the deceleration length plus queue storage. In order to determine the design length, the deceleration plus storage length must be calculated for peak and off-peak periods, the longest total length will be the minimum design length (the Roadway Design Manual).

Table B-1: Lengths of deceleration lengths in left-turn lanes on urban streets

Speed (mph)	Taper Length (ft)	Deceleration Length (ft)
30	50	160
35	50	215
40	50	275
45	100	345
50	100	425
55	100	510

Source: The TxDOT Roadway Design Manual

The minimum storage length is 100 ft as defined in the Roadway Design Manual, which shall apply when (1) the required queue storage length calculated is less than the minimum length, or (2) there is no rational method for estimating the left-turn volume. The calculated queue storage at unsignalized location using a traffic model or simulation model or by:

$$L = (V/30)\cdot(2)\cdot(S) \qquad (1)$$

where (V/30) is the left-turn volume in a two-minute interval, S = queue storage length, in feet (or meters), per vehicle.

APPENDIX C: DETERMINING MINIMUM REQUIRED DISTANCES BETWEEN CROSSOVERS AND MAIN INTERSECTION IN SUPER STREET DESIGN

C.1 DESCRIPTION OF APPROACH

The minimum required distances between the crossover and the main intersection should be able to accommodate the length of the U-turn lanes (Q_U) at the crossovers and the length of the left-turn lanes (Q_{LT}) and through queue length (Q_{TH}) at the main intersection. Thus, the minimum required distances can be calculated as follows:

Min. required distances = max [Q_{U}, Q_{LT}, Q_{TH}]

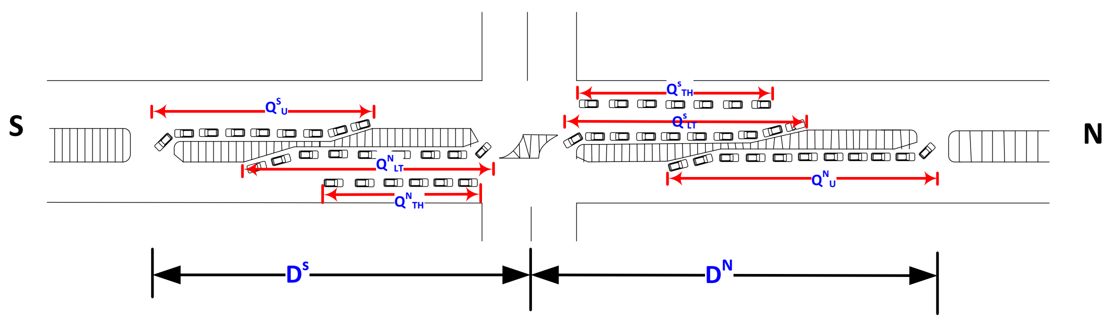


Figure C-1: Illustration of minimum required distances

The researchers suggest the use of the rule-of-thumb method in the TxDOT Roadway Design Manual to calculate the necessary length of U-turn pocket lanes (Q_U) and the length of left-turn pocket lanes (Q_{LT}). The pocket lanes consist of storage and deceleration lengths. The storage length can be calculated as:

$L=K*(V/N_C)*S$

where

L = storage length (ft)

V = left-turn / U-turn flow rate during the peak hour (vph)

K = a constant to reflect random arrival of vehicles (usually equal to 2)

N_C = number of cycles per hour (for signalized intersection)

S = average queue storage length per vehicle (the average distance, from front bumper to front bumper in a queue). Usually, a length of 25 ft is typically assumed as the average queue storage length of a vehicle when truck or bus percentage is less than 5%.

The deceleration length can be determined in light of the following table.

Table C-1: Deceleration lengths suggested by the TxDOT Roadway Design Manual (2009)

Posted Speed Limit (mph)	Deceleration Length
30	160 ft (49 m)
35	215 ft (66 m)
40	275 ft (84 m)
45	345 ft (105 m)
50	425 ft (130 m)
55	510 ft (155 m)

To estimate the through queue length (Q_{TH}), the progression adjustment factor introduced in Highway Capacity Manual 2000 was used. The average back of queue is determined first by assuming a uniform arrival pattern and then adjusting for the effects of progression for a given lane group. The average back-of-queue is calculated using Equation A.1.

$$Q = PF \frac{\frac{v_L C}{3600}(1-\frac{g}{C})}{1-[\min(1.0, X_L)\frac{g}{C}} \quad \text{(A.1)}$$

where

Q = queued vehicles,

PF= adjustment factor for effects of progression,

v_L = lane group flow rate per lane (vphpl),

C = cycle length (s),

g = effective green time (s), and

X_L= ratio of flow rate to capacity (v_L/c_L ratio)

$$PF=\frac{(1-R_P\frac{g}{C})(1-\frac{v_L}{s_L})}{\left(1-\frac{g}{C}\right)[1-R_P\left(\frac{v_L}{s_L}\right)]} \quad (A.2)$$

where

s_L = lane group saturation flow rate per lane (vphpl),

Rp = platoon ratio [P(C/g)], where P is the proportion of all vehicles in movement arriving during green phase.

C.2 NUMERICAL EXAMPLE

This section shows an example of how to calculate the minimum distances between the crossovers and the main intersection. The observed traffic conditions were used as input in the calculation. All the signal timings were optimized using Synchro/SimTraffic software. Figure C-2 shows the optimized signal timing based on the observed traffic conditions.

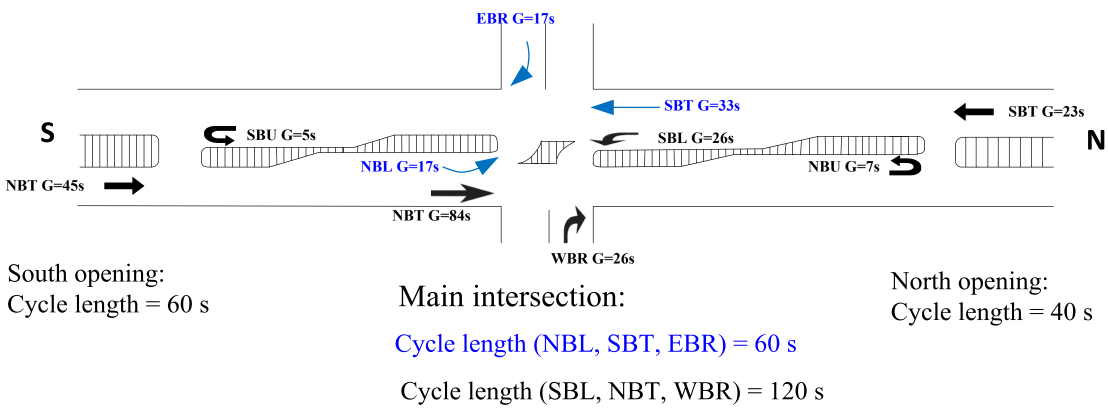


Figure C-2: Signal timing in the simulation scenarios

<u>For the northern crossover</u>

Min. required distances = max [Q^N_U, Q^S_{LT}, Q^S_{TH}]

See Figure C-1 for the denotations.

Calculation of Q^N_U

The cycle length of the signals at the northern opening is 40 s, and thus, there are 3600/40 = 90 cycles per hour. N_C=90. The U-turn volume at the northern crossover is 448 vph. Then, the storage length can be estimated as:

SL = K*(V/N_C)*S / (Number of turn lanes) = 2*(448/90)*25/2 = 125 ft

Note that dual U-turn lanes are installed at the crossover.

The actual operating speed is approximately 20-40 mph as the simulation results showed, which is much lower than the posted speed limit near the intersection functional areas. A deceleration length of 275 feet was actually adequate for turning vehicles to come to a complete stop (Table C-1). Therefore, the length of the pocket lanes can be estimated as:

Q^N_U = 125+275= 400 ft.

Calculation of Q^S_{LT}

The green interval for the southbound left-turn movement is 26 seconds and the cycle length is 120 seconds at the main intersection. There are 3600/120=30 cycles per hour, and thus N_C =30. The southbound left-turn volume is 389 vph. Then, the storage length can be estimated as:

SL= K*(V/N_C)*S / (Number of turn lanes) = 2*(389/30)*25 /2= 325 ft

Note that dual left-turn lanes are installed at the main intersection. Considering a deceleration length of 275 ft, **Q^S_{LT} = 325+275=600 ft**.

Calculation of Q^S_{TH}

The traffic volume for southbound through movement is 2130 vph with three lanes. And the green interval is 33 seconds with the cycle length of 120 seconds.

v_L = 2130/3= 710 vphpl

C = 60 s

g = 33 s

There is 4% heavy vehicles, and lane widths are 3.6 m. The saturation flow rate is:

$s_L = s_0 * f_{HV} = 1900*(\frac{1}{1+4\%*(1.1-1)})$ = 1892.4 vphpl

Since the Super Street intersections are normally well coordinated for the through traffic on the major street, we assume P=0.90.

R_p=P*(C/g) = 0.90*(60/33) = 1.6

$c_L = s_L$*g/C= 1892.4*33/60 = 1040.8

$X_L = v_L/c_L$ = 710/1040.8 =0.68

Using equation A.2 to calculate the progression factor:

$$PF = \frac{(1-R_P\frac{g}{C})(1-\frac{v_L}{s_L})}{\left(1-\frac{g}{C}\right)[1-R_P\left(\frac{v_L}{s_L}\right)]} = \frac{\left(1-1.6*\frac{33}{60}\right)(1-\frac{710}{1892.4})}{\left(1-\frac{33}{60}\right)(1-1.6*\frac{710}{1892.4})} = 0.42$$

Queue length can be estimated by equation A.1.

$$Q= PF\,\frac{\frac{v_L C}{3600}(1-\frac{g}{C})}{1-[\min(1.0,X_L)\frac{g}{C}} = 0.42*\frac{710*\frac{60}{3600}*(1-\frac{33}{60})}{1-0.68*\frac{33}{60}} = 4 \text{ veh}$$

Usually, a length of 25 ft is typically assumed as the average queue storage length of a vehicle when truck or bus percentage is less than 5%. So the queue length is:

Q^S_{TH} = 4*25 = 100 ft

<u>For the southern opening</u>

Min. required = max [Q^S_{U}, Q^N_{LT}, Q^N_{TH}]

Calculation of Q^S_U

The signal cycle length of the southern crossover is 60 s; then, there are 3600/60 = 60 cycles each hour. N_C=60. The U-turn volume at the southern crossover is 271 vph. The required storage length can be estimated as:

SL= K*(V/N_C)*S / (Number of turn lanes) = 2*(271/60)*25/2 = 115 ft.

Considering a deceleration length of 275 ft, the length of the U-turn lanes should be:

Q^S_U = 115+275=390 ft.

Calculation of Q^N_{LT}

The green time for the northbound left turn is 17 s with a cycle length of 60 s. There are 3600/60=60 cycles per hour, so N_C =60. The northbound left-turn volume is 667 vph.

SL=2*(667/60)*25/2 = 275 ft

Considering a deceleration length of 275 ft, $\mathbf{Q^N_{LT}}$ **= 275+275=550 ft**.

Calculation of $\mathbf{Q^N_{TH}}$

The traffic volume for northbound through movement is 2338 vph with two lanes. The green interval is 84 seconds with the cycle length of 120 seconds.

v_L = 2338/2=1169 vphpl

C = 120 s

g = 84 s

There is 4% heavy vehicles, and lane widths are 3.6 m. The saturation flow rate is:

$s_L = s_0 * f_{HV} = 1900*(\frac{1}{1+4\%*(1.1-1)}) = 1892.4$ vphpl

We assume P=0.90.

R_p=P*(C/g) = 0.90*(120/84) = 1.29

$c_L = s_L$*g/C= 1892.4*84/120 = 1324.68

$X_L = v_L/c_L$ =1169/1324.68=0.88

Using equation A.2 to calculate the progression factor:

$$PF = \frac{(1-R_P\frac{g}{C})(1-\frac{v_L}{s_L})}{\left(1-\frac{g}{C}\right)[1-R_P\left(\frac{v_L}{s_L}\right)]} = \frac{\left(1-1.29*\frac{84}{120}\right)(1-\frac{1169}{1892.4})}{\left(1-\frac{84}{120}\right)(1-1.29*\frac{1169}{1892.4})} = 0.61$$

Queue length can be estimated by equation A.1.

$$Q = PF\frac{\frac{v_L C}{3600}(1-\frac{g}{C})}{1-[\min(1.0, X_L)\frac{g}{C}} = 0.61*\frac{1169*\frac{120}{3600}*(1-\frac{84}{120})}{1-0.88*\frac{84}{120}} = 19 \text{ veh}$$

$\mathbf{Q^N_{TH}}$ **= 19*25 = 475 ft**

Final Results

For the northern crossover: Min. required distances = max [400, 600, 100] = 600 ft

For the southern crossover: Min. required distances = max [390, 550, 475] = 550 ft

The experiments showed that failure to provide the minimum required distances or adequate pocket lane length resulted in overflow from the pocket lanes and serious congestion. On the other hand, when sufficient lengths of the pocket lanes can be accommodated by the distances, the placement of crossovers has little impact on the performance of the intersection.