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16. Abstract

Over the past decades, many states and local transportation agencies have installed directional median openings on divided roadways to improve arterial safety and operational performance. A directional opening is normally used to restrict crossing and left-turn movements from minor streets to help avoid potential conflicts. A series of potential benefits may be achieved by installing directional-median openings, including reduced crash rates, increased traffic capacity, and better operational performance. However, the benefits of directional median openings depend largely on proper implementation and on various factors, including geometric, traffic control, environmental conditions, and the type and placement of the downstream U-turn provisions. The goal of this research is to investigate the safety impacts of installing directional openings on median-divided urban roadways. To achieve this goal, the research : 1) synthesized existing related research; 2) compared the safety performance of directional median openings and full median openings, at subject opening locations and downstream U-turn locations; and 3) analyzed the contributing factors to the crashes occurred at the downstream U-turn locations of a directional median opening.

The studies led to a number of findings. Some of the highlighted findings include: 1) Converting a full median opening to directional median opening will reduce the crash frequency at the subject opening location. Although directional median opening might increase the crash frequencies at downstream U-turn locations, the total crashes at subject openings and downstream U-turn locations are still lower than that at full median openings.; 2) The total numbers of crashes at downstream U-turn locations of directional median openings were significantly affected by downstream U-turn volume, downstream left-turn volume, and distance to downstream U-turn opening. Higher downstream U-turn volume and downstream left-turn volume would result in more crashes at downstream U-turn locations. The closer the downstream U-turn location to the subject opening, the more crashes at downstream U-turn location. These findings indicates that, since converting a full median opening to a directional median opening will generate more U-turns at downstream opening of directional opening, the selection of U-turn location is critical for the safety performance of directional openings. Diverted left-turn traffic should not be allowed to make U-turns at closely spaced openings that already have significant U-turns or left-turn volumes.

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USE OF DIRECTIONAL MEDIAN OPENINGS ON URBAN ROADWAYS

by

Yi Qi, Ph.D.

Xiaoming Chen, Ph.D.

Yubian Wang, Ph.D.

Guanqi Liu

Yan Lu

Texas Southern University
3100 Cleburne Avenue
Houston, TX 77004

Research Report SWUTC/14/161342-1

Southwest Region University Transportation Center

Center for Transportation Training and Research

Texas Southern University

3100 Cleburne Avenue

Houston, TX 77004

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DISCLAIMER

SUMMARY

Over the past decades, many states and local transportation agencies have installed directional median openings on divided roadways to improve arterial safety and operational performance. A directional opening is normally used to restrict crossing and left-turn movements from minor streets to help avoid potential conflicts.

A series of potential benefits may be achieved by installing directional-median openings, including reduced crash rates, increased traffic capacity, and better operational performance. However, the benefits of directional median openings depend largely on proper implementation and on various factors, including geometric, traffic control, environmental conditions, and the type and placement of the downstream U-turn provisions.

The goal of this research is to investigate the safety impacts of installing directional openings on median-divided urban roadways. To achieve this goal, the research will:

1. Synthesize existing related research;
2. Compare the safety performance of directional median openings and full median openings, at both opening locations and downstream U-turn locations; and
3. Analyze the contributing factors to the crashes occurred at the downstream U-turn locations of a directional median opening.

The studies led to a number of findings. Some of the highlighted findings include:

1. Converting a full median opening to directional median opening will reduce the crash frequency at the subject opening location. Although directional median opening might increase the crash frequencies at downstream U-turn locations, the total crashes at subject openings and downstream U-turn locations are still lower than that at full median openings. ; and
2. The total numbers of crashes at downstream U-turn locations of directional median openings were significantly affected by downstream U-turn volume, downstream left-turn volume, and distance to downstream U-turn opening. Higher downstream U-turn volume and downstream left-turn volume would result in

more crashes at downstream U-turn locations. The closer the downstream U-turn location to the subject opening, the more crashes at downstream U-turn location.

3. For locations with heavy left-turn and U-turn volumes, a closely spaced U-turn location can cause more crashes. For example, for locations with a left-turn volume of 40 vph and U-turn volume of 40 vph, if the U-turn location is too close (e.g. within 200 ft or 300 ft distance), the crash frequencies could be 29 to 44 per five years. For locations with a left-turn volume of 50 vph and U-turn volume of 50 vph, if the U-turn location is within 500 ft distance, the crash frequencies could range from 28 to 93 per five years.

These findings indicate that, since converting a full median opening to a directional median opening will generate more U-turns at downstream opening, the selection of U-turn location is critical for the safety performance of directional openings. Diverted left-turn traffic should not be allowed to make U-turns at closely spaced openings that already have significant U-turns or left-turn volumes.

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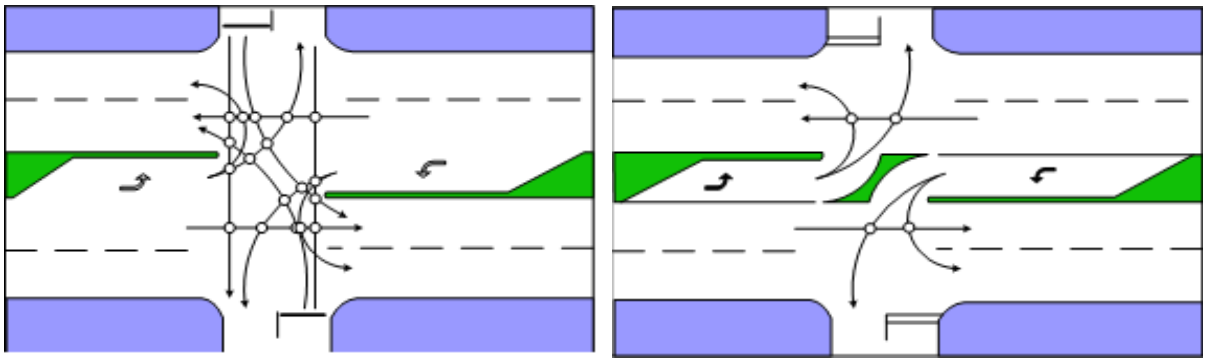
CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Over the past decades, many states and local transportation agencies have installed directional median openings on divided roadways to improve arterial safety and operational performance. A directional opening is normally used to restrict crossing and left-turn movements from minor streets to help avoid potential conflicts (**Figure 1**). At directional openings, vehicles exiting from the driveways have to make an alternative movement to finish the left-turn maneuver, which involves a right-turn followed by a U-Turn.



(a) Full Median Opening, 18 Major Conflicts (Crossing conflicts and U-turn conflicts)

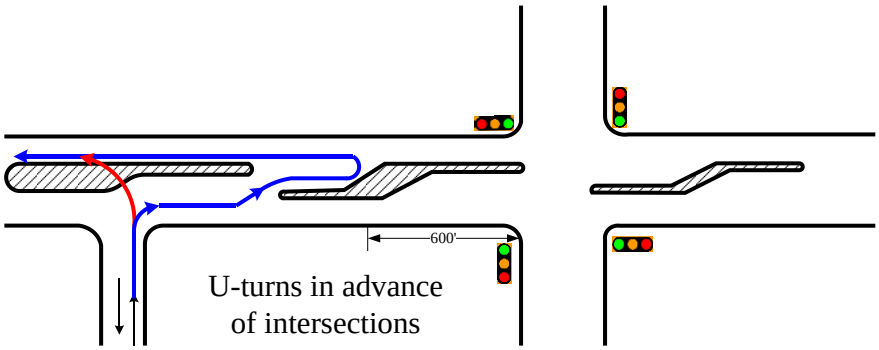
(b) Directional Median Opening, 4 Major Conflicts(Crossing conflicts and U-turn conflicts)

Figure 1. Full Median Opening vs. Directional Median Opening

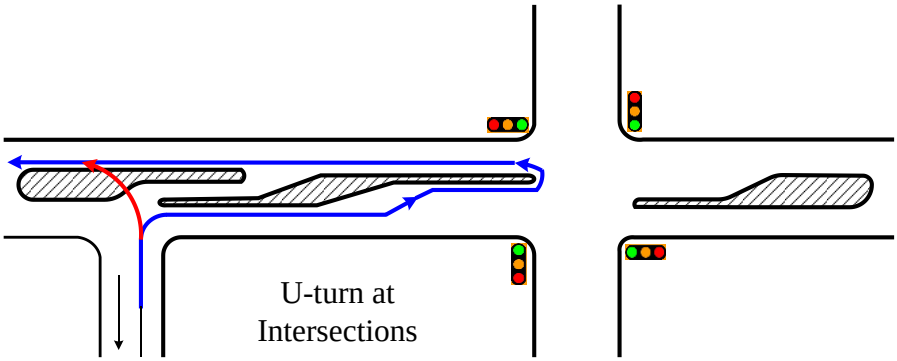
Right turns followed by U-turns (RTUT), an alternative to direct left turns, are increasingly used in order to reduce conflicts and to improve safety along arterial roads. RTUT make it possible to prohibit left turns from driveway connections or at signalized intersections, which may contribute to more efficient signal operations, reduced congestion, and improved progression along the arterial.

Higher volumes along urban arterials (e.g. 700–900 vphpl) would produce high left-turn egress delays. As shown in **Figure 2** (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. Alternative movements, as shown in **Figure 2** (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.



(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. U-Turns as Alternatives to Direct Left Turns From Unsignalized, Minor Streets/Driveways

The case shown in **Figure 2 (a)** removes two major conflict points between direct left turns with through traffic, and present one minor conflict point (weaving to the left curb) and one major conflict point (making a U-turn). The case shown in **Figure 2 (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.

A series of potential benefits may be achieved by installing directional-median openings, including reduced crash rates, increased traffic capacity, and better operational performance(1-6). However, the benefits of directional median openings depend largely on whether it is properly implemented and on several other factors, including geometric, traffic control, environmental conditions, and the type and placement of the downstream U-turn provisions.

In addition, there may be a number of issues associated with the use of directional openings: 1) additional travel distance/time, which may be a result of rerouting driveway-egress, left-turn traffic (using right-turn followed by a U-Turn), 2) increased traffic conflicts at the U-turn locations, and 3) resistance from the business owners who are concerned about the accessibility of their businesses.

1.2 RESEARCH GOALS AND OBJECTIVES

The goal of this research is to investigate the safety impacts of installing directional openings on median-divided urban roadways. To achieve this goal, the research will:

1. Synthesize existing related research;
2. Compare the safety performance of directional median openings and full median openings, at subject opening locations and at downstream U-turn locations (both directions); and
3. Analyze the contributing factors to the crashes occurred at the downstream U-turn locations of a directional median opening.

1.3 OUTLINE OF THIS REPORT

This report documents all the research activities and findings throughout this project. Chapter 2 reviews and synthesizes existing studies associated with the safety impacts of using directional median openings. Chapter 3 describes the study design for the research. Chapter 4

presents the study results. Finally, Chapter 5 summarizes the research findings and provides recommendations.

CHAPTER 2: LITERATURE REVIEW

To provide a full context for this study, existing studies associated with the safety impacts of using directional median openings were reviewed thoroughly. This review focused on the following two aspects: 1) the impacts of directional median openings, and 2) the impacts of indirect left-turns.

2.1 IMPACTS OF DIRECTIONAL MEDIAN OPENINGS

Several studies on the safety impacts of directional median openings have been conducted.

Levinson et al. (2000) analyzed the safety effects of Michigan U (directional opening) versus full median opening (direct left turn) at signalized intersections. This study found that by replacing bi-directional (full) median openings with directional median openings, the average number of accidents per year reduced by 61 percent, angle crashes were reduced by 96 percent; sideswipes were reduced by 61 percent and rear-end accidents were reduced by 17 percent. Injury accidents were decreased by 75 percent. In addition, it was also found that the safety benefits of the replacement increases with the increase of signal density.

Zhou et al. (2001) collected traffic conflicts data at US 19 @ 115th St. in Pinellas County, Florida, one week before and one week after the full median opening was changed to a directional median opening. This study compared the average daily number of conflicts, conflicts per hour, and conflicts per thousand involved vehicles between directional median openings and full median openings. **Figure 3** shows the conflict counts before and after converting from full median opening to directional median opening. The statistical results showed that, after the installation of directional median opening, the average daily number of conflicts, conflicts per hour, and conflicts per thousand involved vehicles were all reduced. The reduction rates were 46 percent, 30 percent and 15 percent respectively.

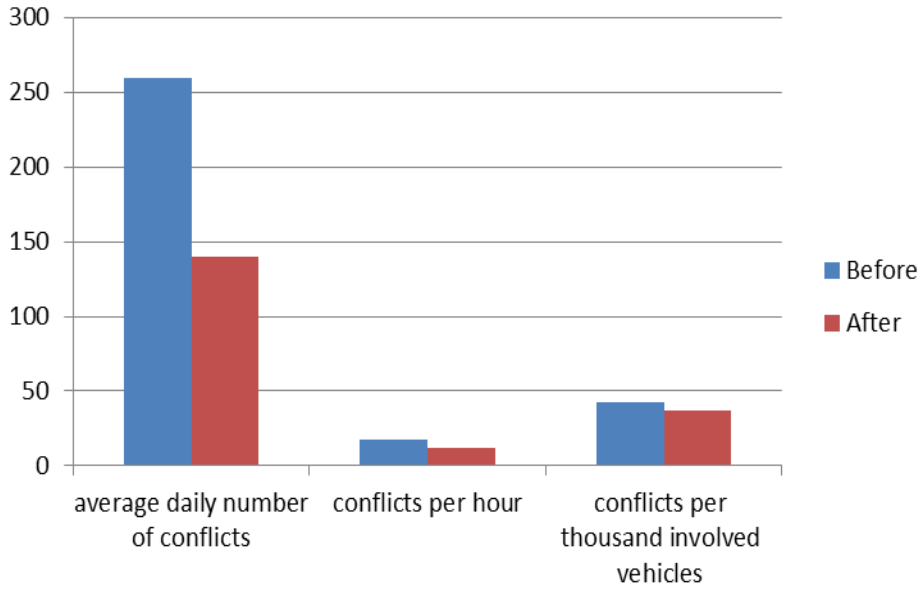
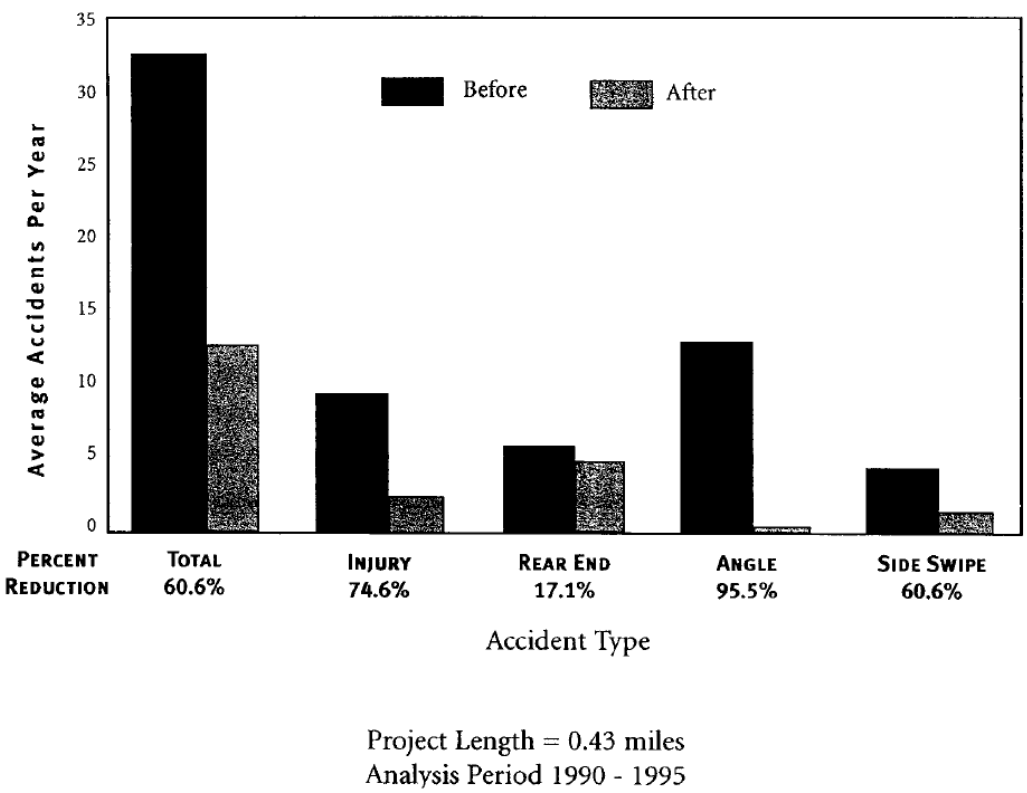


Figure 3. Comparison of Conflicts

Hoffman et al. (1969) evaluated the safety impacts of a project: 1) closing of the median crossover on a Trunkline, US-10 (Woodward Ave.) at a T-intersection of a minor road, (Opdyke Rd.), and 2) the construction of two directional crossovers, one northwest and one southeast of the intersection. The results of this study indicated that replacing a full median opening with a directional median opening reduced the total number of crashes by 62 percent, from 34 to 13, in a one-year period.

Gluck et al. (1999) analyzed the safety impacts of replacing four full median openings on 0.43 mile of Grand River Avenue in Detroit, Michigan, with directional median openings. The results showed that the average number of accidents per year was reduced by 61 percent. Angle accidents were reduced by 96 percent, sideswipes were reduced by 61 percent, and rear-end crashes were reduced by 17 percent. Injury accidents were decreased by 75 percent.



Source: Gluck et al. (1999)

Figure 4. Accident Comparisons Grand River Avenue, Detroit

Taylor et al. (2001) found that rear-end and angle crashes were reduced significantly when directional media openings were installed, and adequate widths for the median and a left-turn bay should be provided. Moreover, Taylor's research also gave the conclusion that an average of over 30 percent reduction in both the total crashes and the crashes involving at least one injured party. This reduction occurred almost exclusively at the locations in which the bidirectional median crossovers were replaced, with no significant change observed at crossovers that were not changed.

Levinson et al. (2005) concluded that the appropriate design of directional median openings at three-leg and four-leg intersections can significantly reduce the crash rate compared with full median openings. This research compared the crash rate from four different study sites where full median openings were replaced by directional median openings. The results were shown in **Table 1**. Overall, replacing full median openings with directional median openings can reduce the accident rate by 14 percent to 61 percent.

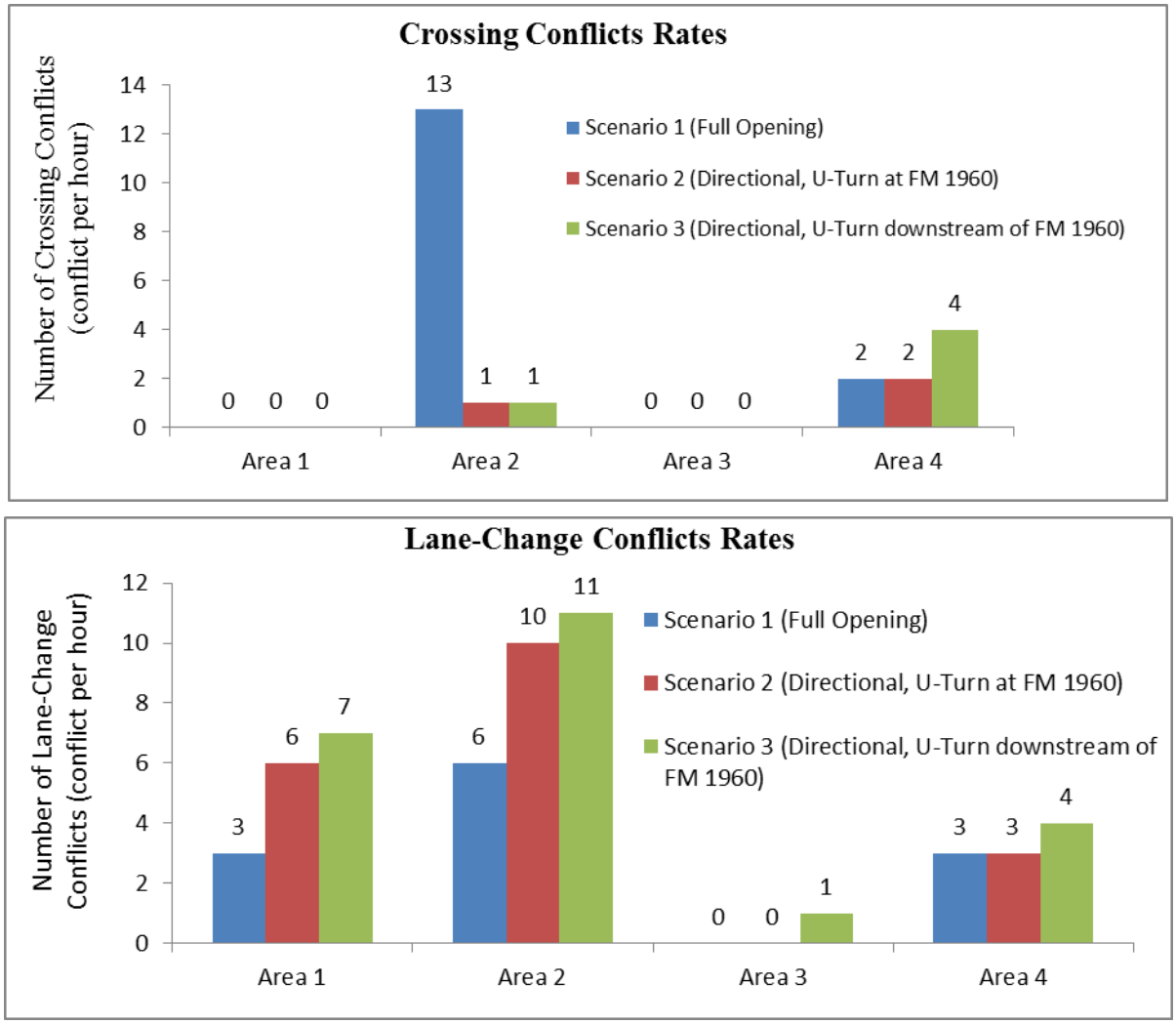
Table 1. Safety Benefits Between Full and Directional Median Openings

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.

HNTB et al. (2002) conducted a corridor analysis along Westheimer Street. It found that when the number of conflict points between turning vehicles increases, the risks for traffic accidents will increase, too. Street intersections with a high number of conflict points have high potential for accidents.

Qi et al. (2014) conducted a case study at a 3,000-ft corridor on Jones Road in Houston, Texas, where four full median openings have been installed. The analysis of historical crash data and simulation-based analysis were conducted to investigate the performance of directional median openings compared with full median openings at the corridor. The results of this study showed, see **Figure 5**, that the use of directional openings significantly reduced crossing-traffic conflicts at the opening locations, while slightly increasing lane-change conflicts in both the downstream and upstream areas.



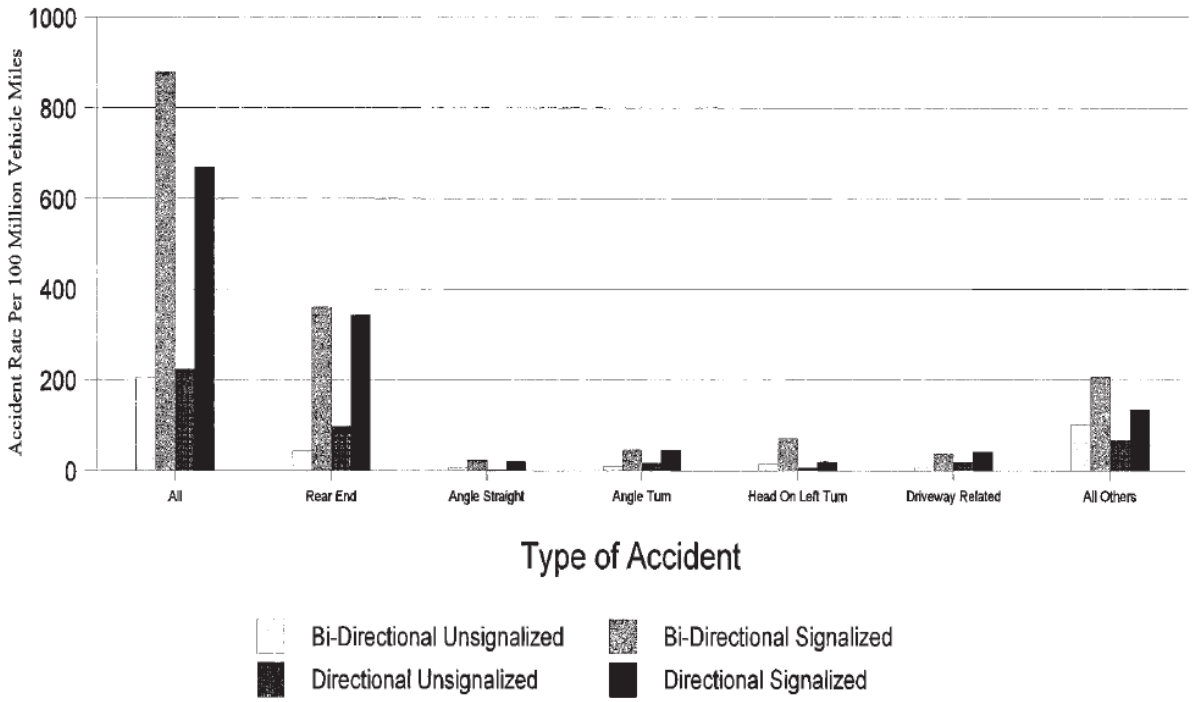
Source: Qi et al. (2014)

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

Potts et al. (2004) found that the crash rates on urban roadways for directional median openings were 48 percent and 15 percent lower than for full median openings at three-leg and four-leg directional median openings, respectively.

Castronovo et al. (1998) indicated that for unsignalized segments, directional median openings have significantly lower mean accident rates for angle-straight and "all others" accident types. However, it has significantly higher mean accident rates for rear-end, angle-turn, and

driveway accidents. A storage lane for left-turn vehicles was suggested to reduce rear-end related crashes at directional median openings.



Source: Castronovo et al. (1998)

Figure 6. Boulevard Accident Rates for Crossovers

Zhou et al. (2003) conducted a before-and-after crash analysis at the median opening of 46th street at Fowler Avenue. The median opening was converted from full median opening to directional median opening in early 1996. Crash data were collected for four years before and four years after the median modification.

Table 2 shows the number of traffic crashes at the 46th street and U-turn median opening. The results showed that there was 68 percent reduction of crash rates when converting the full median opening to a directional median opening. However, there was no crash increase at the U-Turn opening after installation of directional median opening.

Table 2. A Before and After Comparison of the Number of Traffic Crashes at the 46th Street and U-turn Median Opening

	BEFORE				AFTER			
	1992	1993	1994	1995	1996	1997	1998	1999
46th Street	4*	3	7	8	1	3	2	1
U-turn Median opening	1	0	0	1	1	0	0	0

*Note: * Number of Traffic Crashes in 1992*

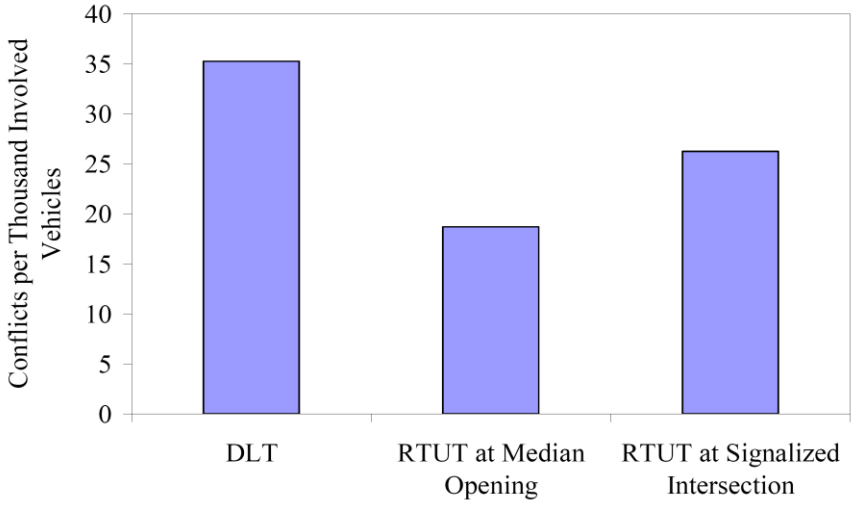
Source: Zhou et al. (2003)

2.2 IMPACTS OF INDIRECT LEFT-TURNS

Levinson et al. (2005) found that indirect left turns can improve safety performance when two or more directional median openings are applied to serve one full median opening. 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.

Liu et al. (2007) described the research results on right-turns followed by U-turn. 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 that, if U-turn location is provided at unsignalized median opening, vehicles making an alternative movement will generate 47 percent fewer conflicts than those egress vehicles making direct left turns (DLT) from a driveway. If U-turn location is provided at a signalized intersection, as is shown in **Figure 7**, vehicles making an

alternative movement will generate around 26 percent fewer conflicts than direct left turns from a driveway.



Source: NCHRP Report 420, Impacts of Access Management Techniques

Figure 7. Conflict Rates for DLT and RTUT Movements

Potts et al. (2004) concluded that crashes associated with U-turns and left-turn movements occurred infrequently. There is no strong evidence to show that the number of U-turns and left turns at a median opening has a strong connection with crash rates and frequencies.

Maki et al. (1996) evaluated the safety benefits of replacing existing conventional signalized intersections with indirect left-turn. The study was conducted 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 degree or on a skew. Crash data for the years 1986-1990 were obtained for each site. The results showed the safety performance of the Michigan U turns in comparison to conventional intersections. The statistics showed a reduction of crash rates from 9 percent to 30 percent by using Michigan U to replace direct left-turns.

Dissanayake et al. (2002) collected crash data for three years at 133 sites with DLT and 125 sites with RTUT to determine the crash characteristics; 2,175 crashes and 1,738 crashes

were identified for DLT and RTUT respectively. The average number of crashes and average crash rates were compared by all crashes, crash severity, and crash type. As seen in **Table 3**, for all of the categories expect sideswipe crashes; directional median opening was much safer than full median opening. The higher sideswipe crash rates at directional median openings may be caused by the excessive weaving effects.

Table 3. Comparison of Crash Experiences of the Two Left-turn Movements

Crash characteristic		Average number of crashes				Average crash rate (crashes per MVM)			
		DLT	RTUT	Difference[a] %	Significantly different[b]	DLT	RTUT	Difference[a] %	Significantly different[b]
All crashes		16.35	13.9	14.98	No	3.20	2.63	17.8	Yes
By severity	Property damage only	11.08	10.52	5.05	No	2.18	2.04	6.4	No
	Injury/fatality	6.31	4.92	22.02	Yes	1.21	0.88	27.3	Yes
By type	Rear-end	6.80	6.49	4.56	No	1.28	1.12	13.3	No
	Sideswipe	1.75	2.31	–32.0	Yes	0.36	0.44	–19.5	No
	Angle	5.35	4.20	21.5	Yes	1.06	0.81	24.5	Yes

[a] *Difference = 100 (DLT – RTUT)/DLT.* [b] *Tests the null hypothesis of equal number of crashes or crash rates.*

Source: Dissanayake et al. (2002)

2.3 SUMMARY

Overall, the results from the previous studies indicated that directional median openings can improve safety performance if they are well designed and planned. However, no studies have focused on the safety impacts of directional median openings on downstream U-turn locations. According to Potts et al. (2004), the installation of directional median opening will transfer egress direct left-turns into a right-turn followed by a U-turn at downstream of the directional median opening, which would increase the U-turn demands at the downstream opening and may increase the crash risk at this location. Therefore, this research will investigate the safety impacts of directional median openings, both at subject opening locations and at the downstream U-turn locations.

CHAPTER 3: DESIGN OF STUDY

To achieve the research objectives, two studies are conducted: 1) cross-sectional comparison study- this study is to compare the safety performance of directional median openings and full median openings, at both opening locations and downstream U-turn locations; and 2) contributing factors analysis study- this study is to develop a Poisson regression model to analyze the contributing factors to the crashes occurred at the downstream U-turn locations.

3.1 CROSS-SECTIONAL COMPARISON STUDY

To analyze the safety impacts of directional median openings, the cross-sectional comparison study is designed to 1) compare the crash frequencies at selected directional median openings and full median openings, and 2) compare the crash frequencies at downstream U-turn locations of the selected directional median openings and full median openings.

3.1.1 Description of Study Location

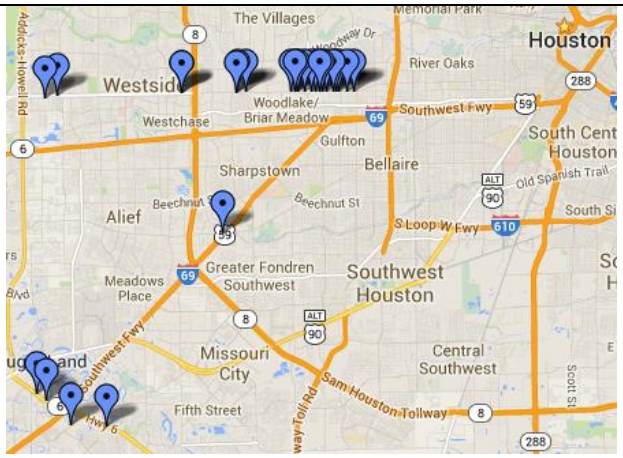
To compare the safety performance of directional median openings and full median openings, directional median opening sites and full median opening sites under similar traffic conditions are selected.

The research team contacted traffic engineers at City of Houston, City of Austin, City of Fort Worth, City of Addison, City of Richardson, and City of Beaumont for candidate study sites. To the end, a total of 34 sites with directional median openings and 20 sites with full median openings were recommended by traffic engineers. Those selected study sites all have relatively high traffic volumes and have safety issues. **Table 4** lists those cities along with the number of sites selected in those cities. **Figure 8** and **Figure 9** show the detail study site locations.

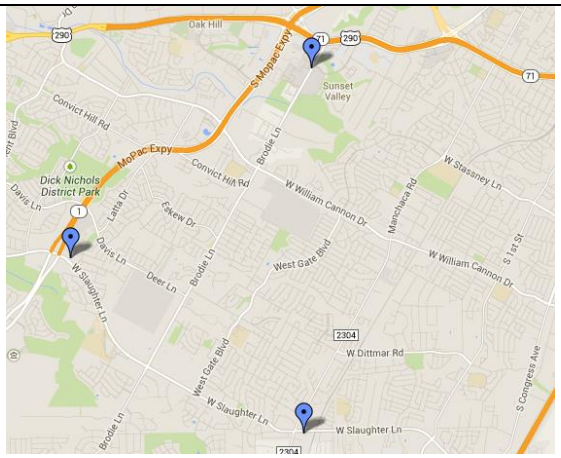
As seen in **Table 4**, most of the selected sites are from Houston. As seen in **Figure 8** and **Figure 9**, most of the directional median opening sites in Houston are at Westheimer Street, while most of the full median opening sites in Houston are at Richmond Avenue. According to the H-GAC (2013), the unsignalized median openings at Westheimer Street are all converted from full median openings to directional median openings from 2002 to 2006. Richmond Avenue, parallel to Westheimer Street, is only one block away and has similar traffic patterns and driver populations. Therefore, the full median openings selected at Richmond Avenue are considered to be comparable to the directional median openings at Westheimer Street.

Table 4. Study Sites and Cities

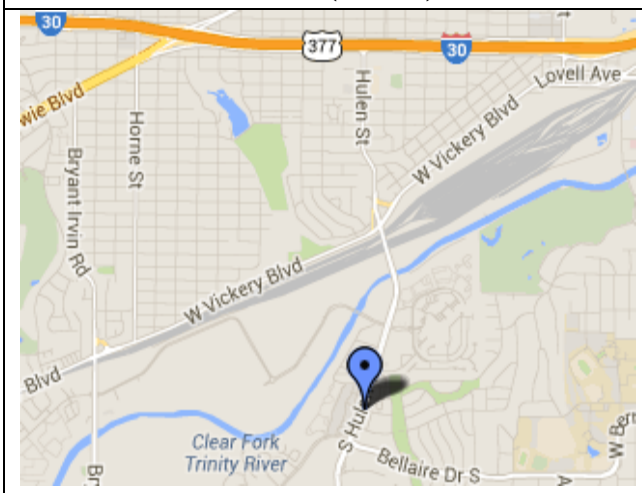
Cities	Directional Median Openings Sites	Full Median Openings Sites
Houston	27	13
Austin	3	3
Fort Worth	1	1
Addison	1	1
Richardson	1	1
Beaumont	1	1
Total	34	20



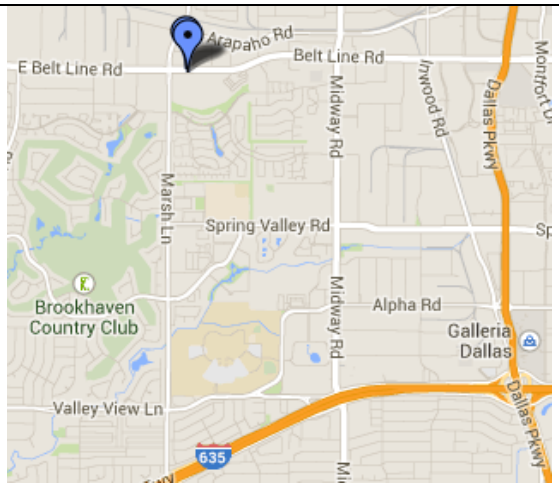
Houston (27 sites)



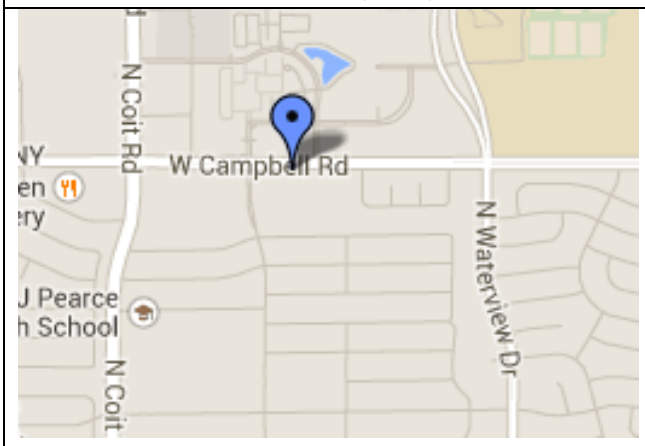
Austin (3 sites)



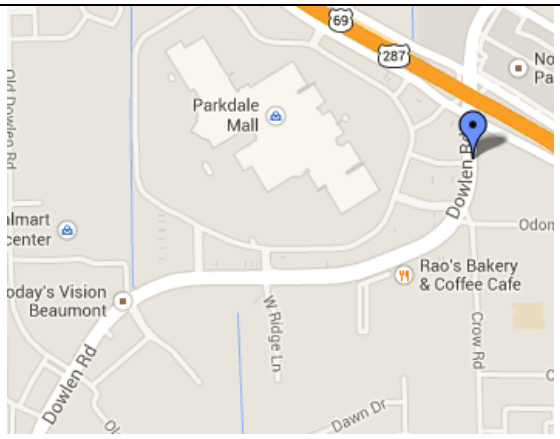
Fort Worth (1 site)



Addison (1 site)

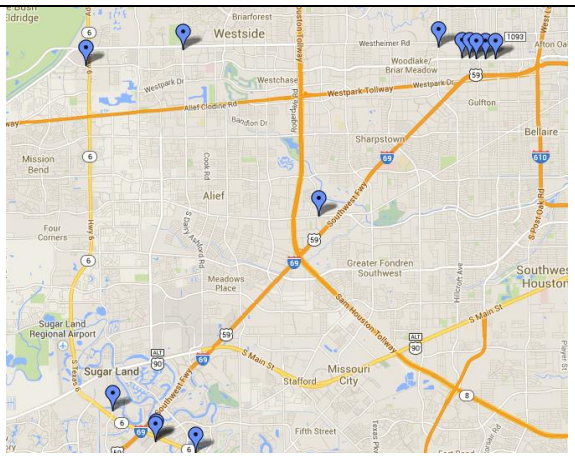


Richardson (1 site)

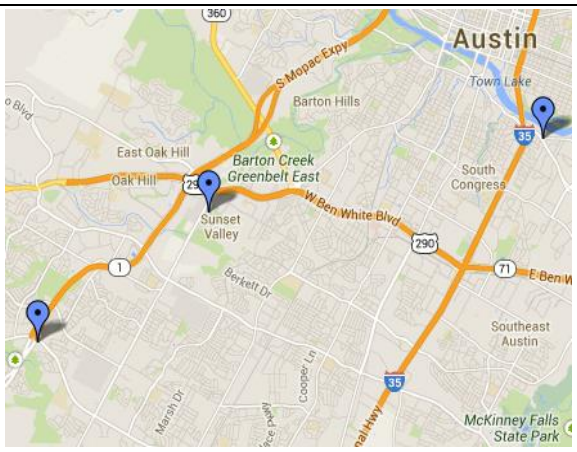


Beaumont (1 site)

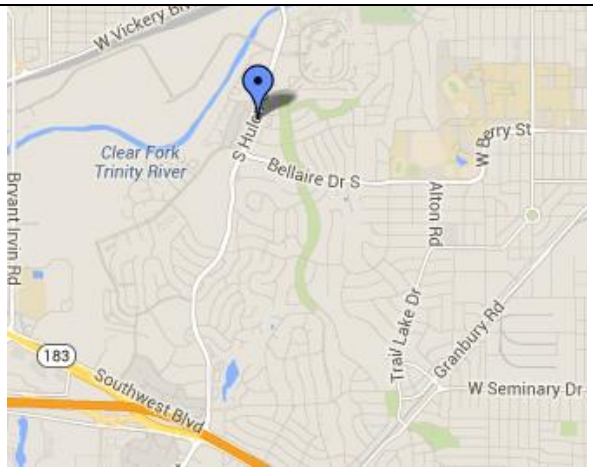
Figure 8. Directional Median Opening Sites



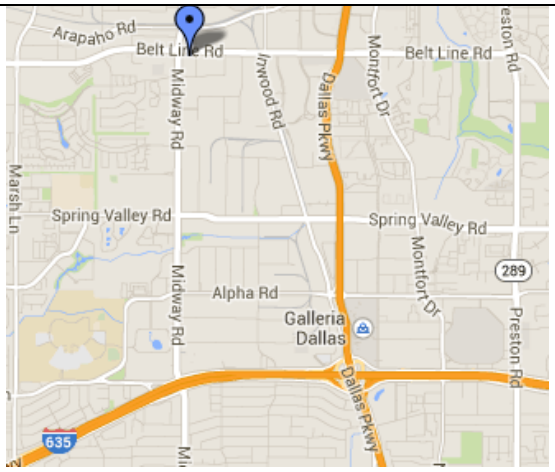
Houston (13 sites)



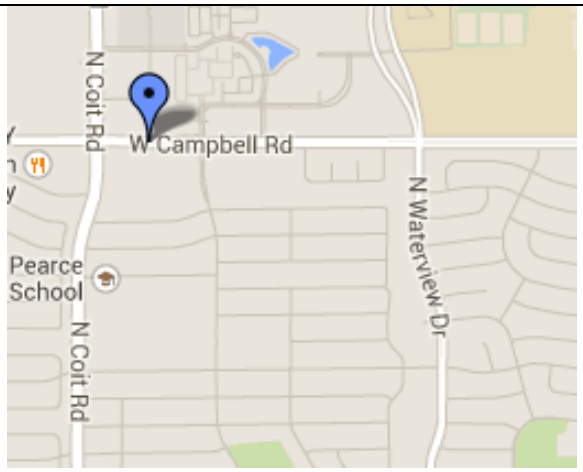
Austin (3 sites)



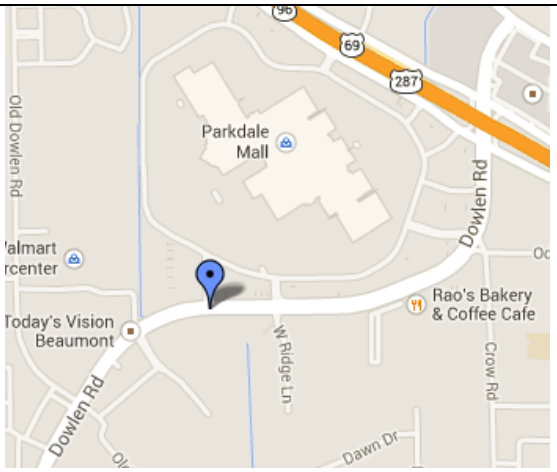
Fort Worth (1 site)



Addison (1 site)



Richardson (1 site)



Beaumont (1 site)

Figure 9. Full Median Opening Sites

3.1.2 Crash Data Collected at Study Location

At each study site, the U-turn and left-turn related crash data at the subject median openings and downstream U-turn locations (for both directions) were retrieved over a five-year period from January 2007 to December 2011. The data were available from the Texas Department of Transportation (TxDOT) Crash Record Information System (CRIS). The crash records in CRIS were processed by using ArcGIS.

Each data sample in CRIS contains the longitude and latitude of the crash location, which enables a spatial distribution analysis. Using ArcGIS software, the locations of crashes can be displayed on background maps as a dot, see **Figure 10** for an example of all crash data in Houston area from 2007 to 2011. By zooming in the ArcGIS maps, crashes at each selected study site were identified.

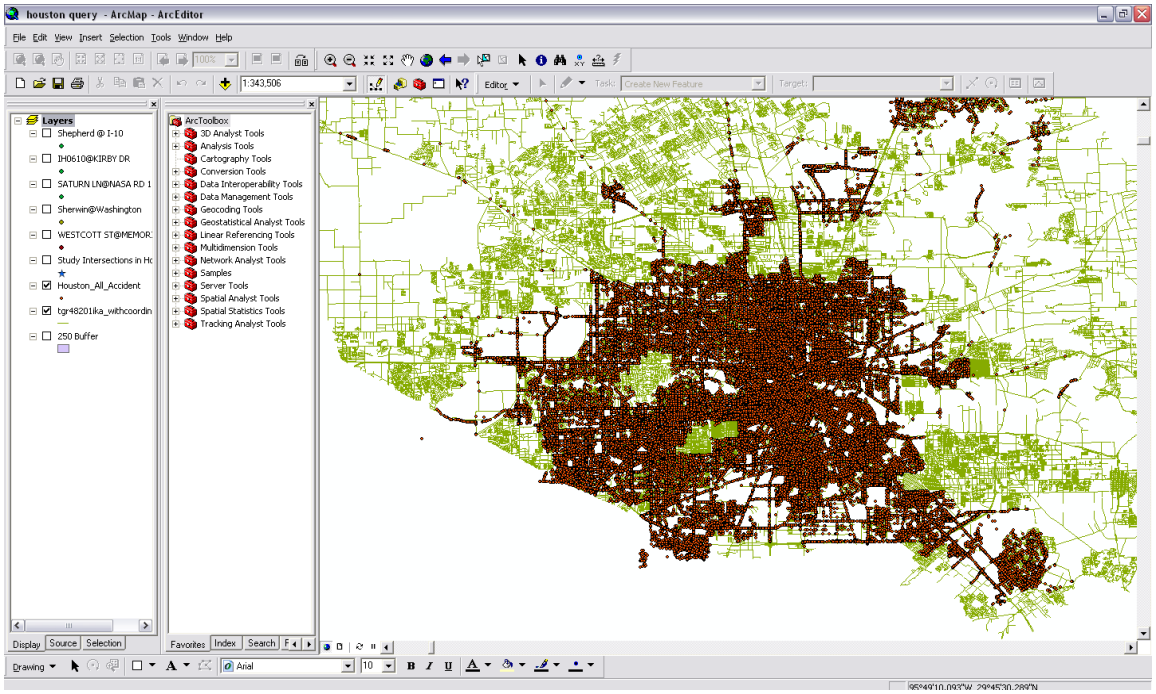


Figure 10. Crash Map in Houston

Table 5 shows the number of crashes at the subject median openings and the downstream U-turn locations (both directions) for each study site.

Table 5. Number of Crashes at Study Sites

Directional Median Openings		
Site no.	# of crashes at subject openings	# of crashes at downstream U-turn locations (both directions)
1	6	20
2	1	6
3	2	12
4	36	7
5	9	7
6	7	7
7	6	10
8	39	12
9	13	14
10	8	0
11	0	0
12	15	7
13	4	7
14	7	5
15	5	2
16	3	0
17	8	5
18	2	3
19	1	7
20	5	13
21	2	13
22	4	4
23	1	2
24	5	3
25	2	0
26	2	11
27	4	6
28	0	0
29	18	11
30	1	6
31	4	6
32	5	6
33	5	4
34	0	7
Average	6.76	6.56
Standard deviation	8.84	4.71

Full Median Openings		
Site no.	# of crashes at subject openings	# of crashes at downstream U-turn locations (both directions)
35	1	3
36	2	0
37	1	7
38	3	4
39	1	3
40	26	17
41	0	1
42	11	2
43	89	5
44	1	0
45	3	2
46	4	2
47	20	0
48	6	0
49	3	0
50	6	0
51	13	0
52	13	2
53	12	1
54	14	9
Average	11.45	2.90
Standard deviation	19.60	4.15

3.2 CONTRIBUTING FACTORS ANALYSIS STUDY

To analyze the contributing factors to the crashes occurred at the downstream U-turn locations of directional median openings, Poisson regression models are to be developed.

3.2.1 Description of Study Locations

In this study, to analyze the contributing factors to the crashes occurred at the downstream U-turn locations, 16 directional median openings were selected from the 34 sites for the cross sectional comparison study (see **Figure 8**.) These 16 directional median openings are all located on Westheimer St, Houston, Texas, which is an 8-lane arterial road operated by Harris County and has multiple directional median openings installed. **Figure 11** shows the study openings on the roadway segment.

The reasons for selecting these 16 directional median openings include:

1) To identify the contributing factors to the crashes at downstream U-turn locations, U-turn volumes, left-turn volumes, or other traffic or geometric condition data need to be collected at study locations. Since these 16 directional median openings are all located in Houston, it is feasible and more cost effective to collect traffic volume data or other geometric data at these sites;

2) These 16 directional median openings are all located at the same street with similar geometric designs, which would eliminate the impacts of other influencing factors, such as the general geometric condition and driver characteristics, on the safety performance.

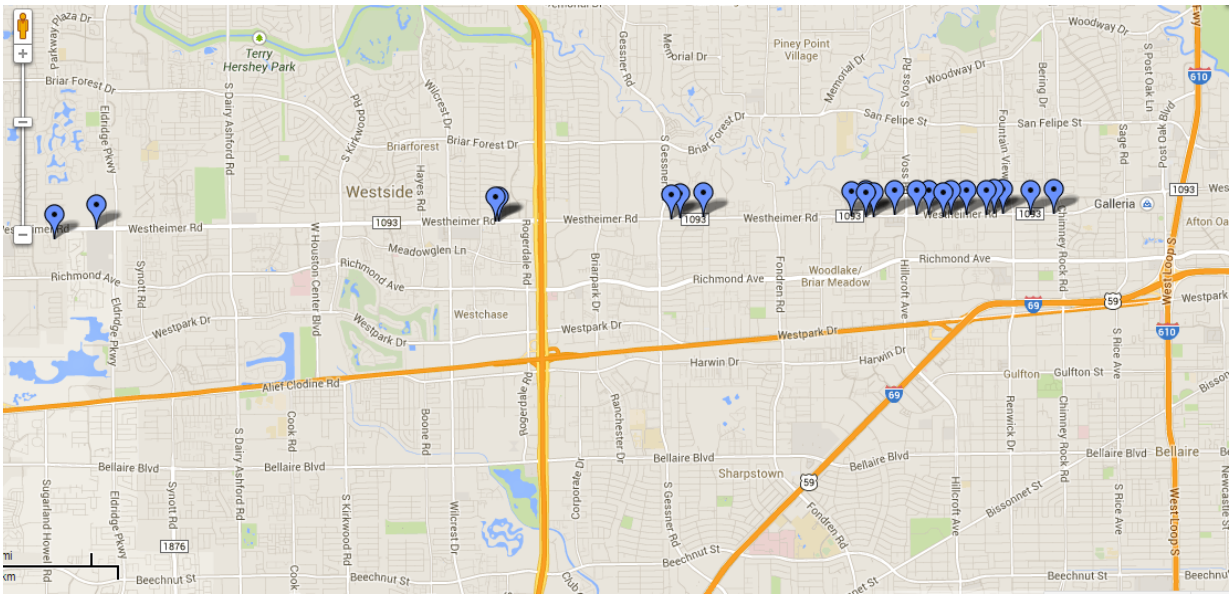


Figure 11. Studied Roadway Segment on Westheimer Road, Houston, Texas

3.2.2 Data Collected at Study Locations

The basic roadway and traffic conditions at this roadway segment are collected by filed observation, which is summarized as follow:

- Eight-lane, major arterial road connecting I-610 Freeway and Interstate Hwy 6
- Posted speed limit is 45 mph
- A total of 16 directional median openings along Westheimer Street from Chimney Rock Road to Highway 6 were selected for the safety analysis
- Peak-hour traffic is approximately 1,200 to 1,600 vph in the peak direction.
- A mixture of residential and business areas exists along study openings.

This study is focusing on the relationship between U-Turn/Left-turn volumes and historical crash rates downstream of the directional median opening. For this purpose, traffic volume data were collected at U-Turn locations (i.e., unsignalized opening) downstream of the studied directional median openings and U-Turn/Left-turn related historical crashes

corresponding to each studied opening were also identified by ArcGIS. The following field data were collected at the study sites:

1. Downstream U-turn Volume was collected during the afternoon peak hours. All U-Turn movements happened downstream of studied directional median openings were counted.

2. Downstream Left-Turn Volume was collected during the afternoon peak hours. Collected Left-Turn Volume was collected at the same location where the Downstream U-turn Volume was collected.

3. Distance to Downstream U-turn Opening was measured from study direction median opening to the nearest location where U-Turn movements could be made.

Traffic Video Recording was used to collect the U-turn volume and left-turn volume at study sites. At each study site, one hour of traffic video was recorded during the afternoon peak. Figure 12 shows the sample traffic videos.

Figure 12. Traffic Video Recording

After recording the traffic video, traffic volume data were retrieved at the research lab by manually counting the number of vehicles recorded in the traffic video making left-turns or making U-turns. **Table 6** and **Table 7** show the geometric condition, traffic volume, and crash records at each study site.

Table 6. Illustration of Study Locations

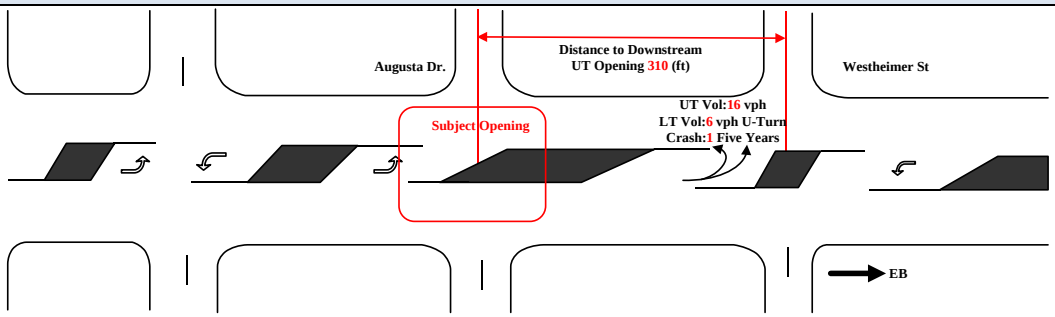
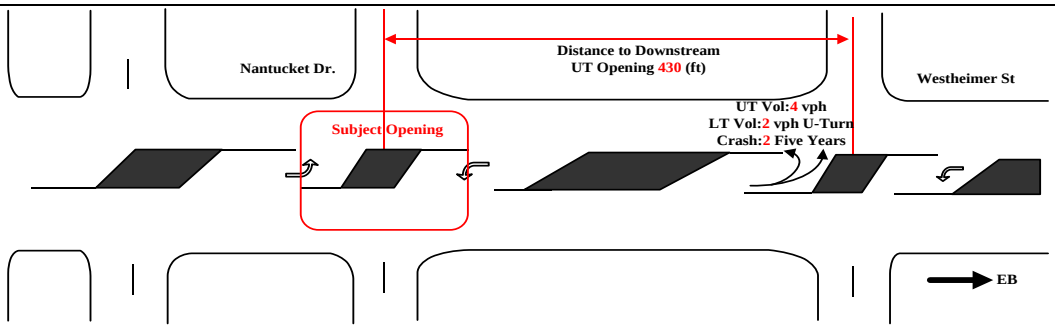
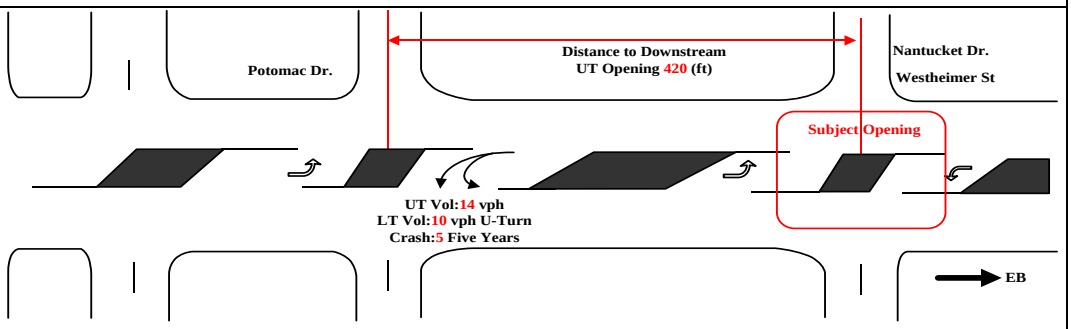
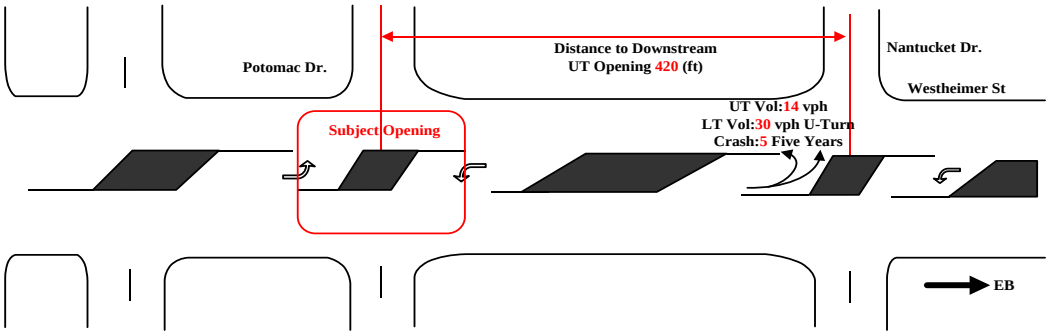
Opening ID	Illustrations of Subject Openings
1	
2	
3	
4	

Table 6. Illustration of Study Locations (Continued)

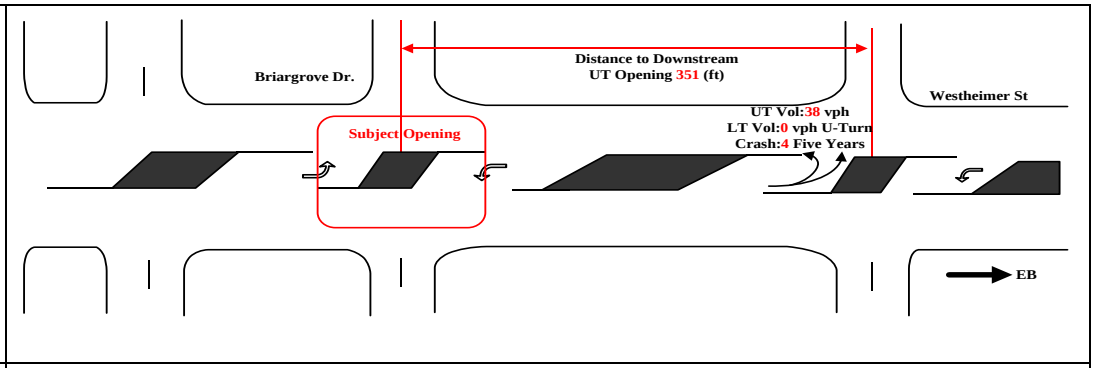
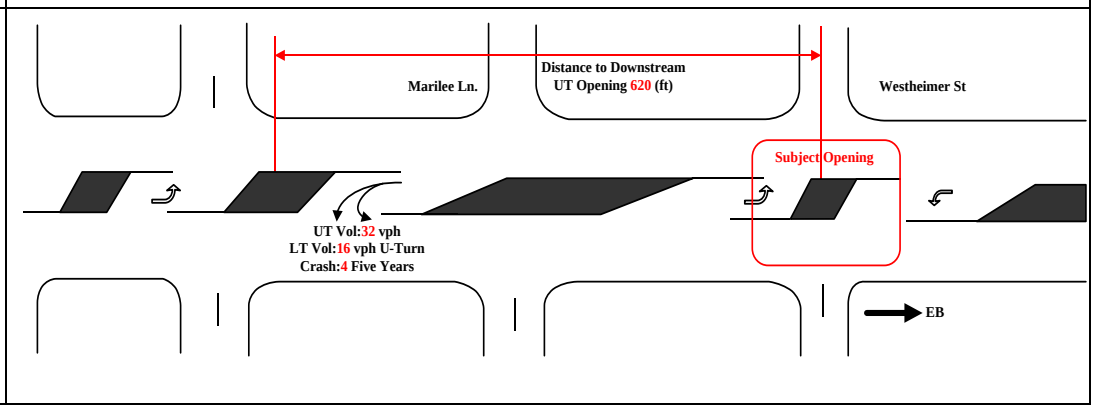
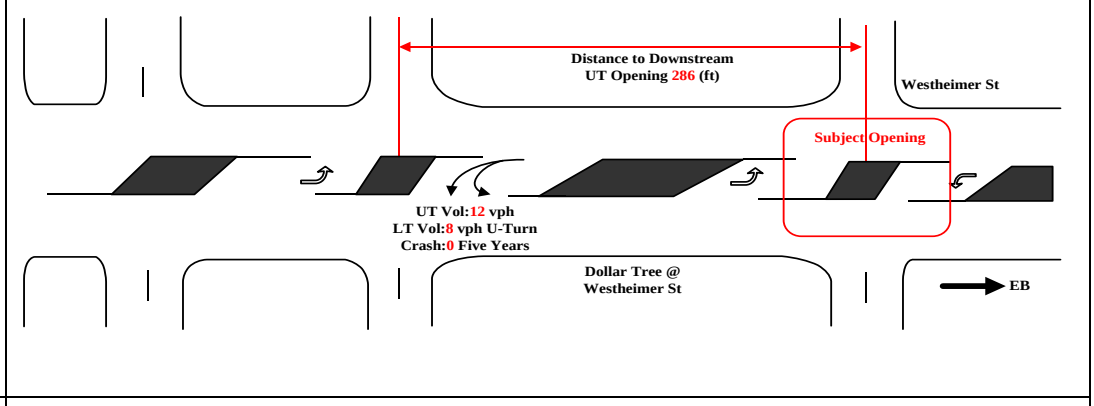
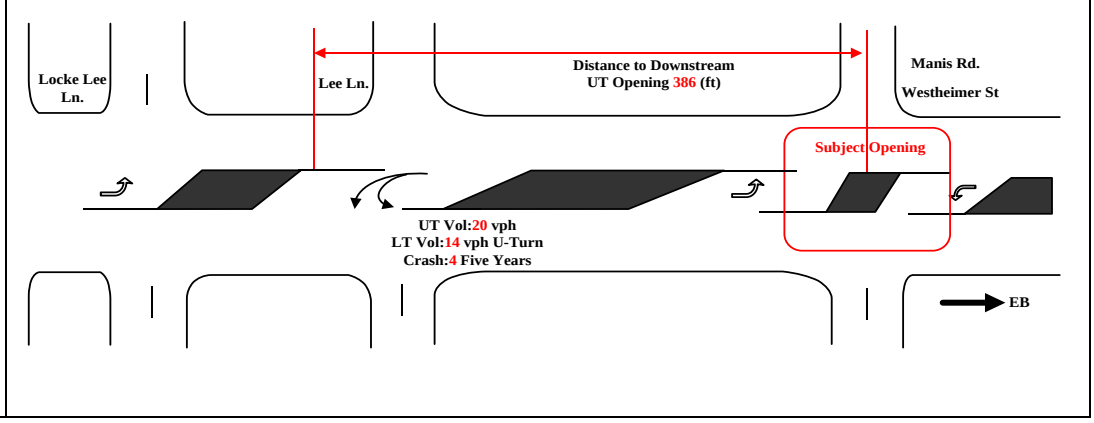
5	
6	
7	
8	

Table 6. Illustration of Study Locations (Continued)

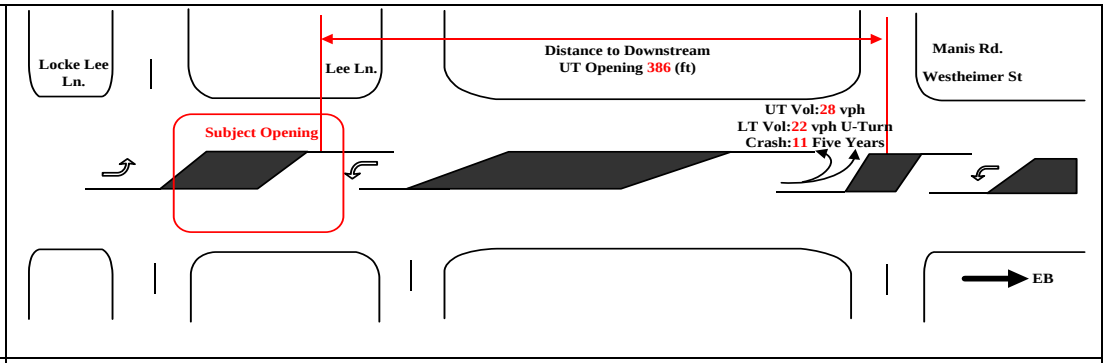
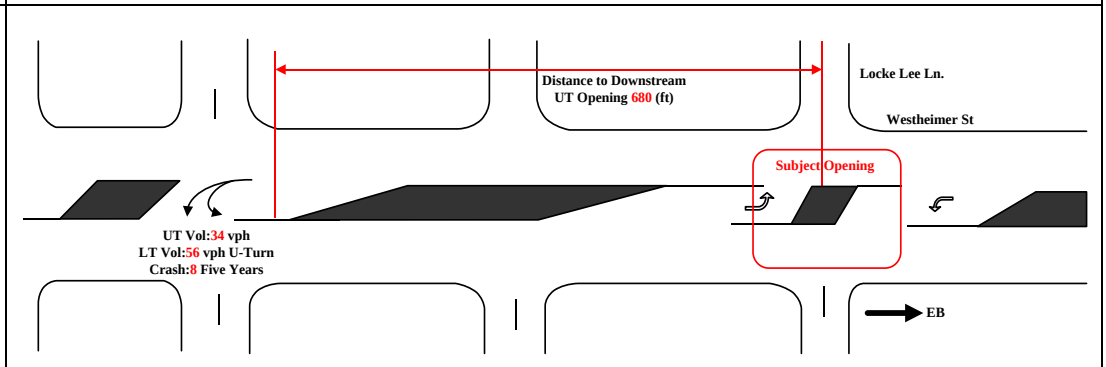
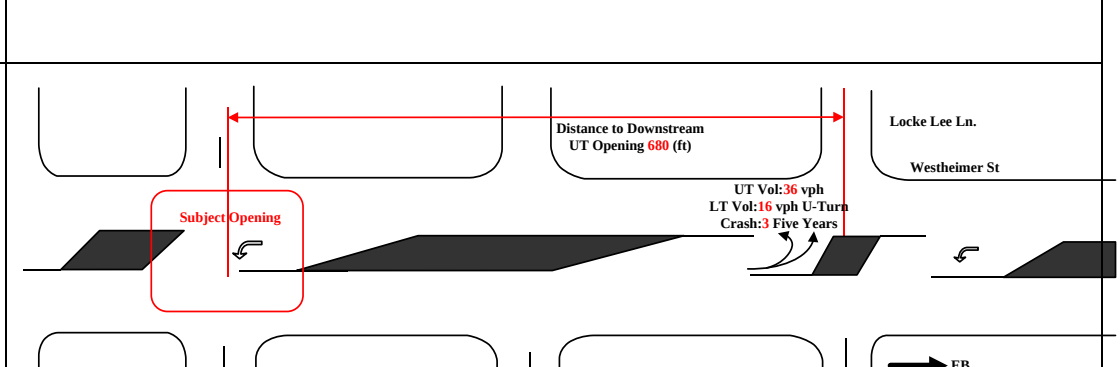
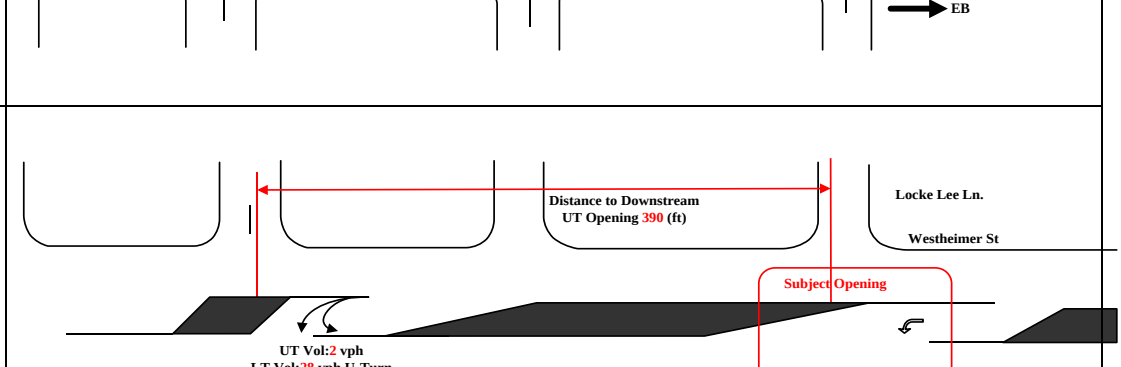
9	
10	
11	
12	

Table 6. Illustration of Study Locations (Continued)

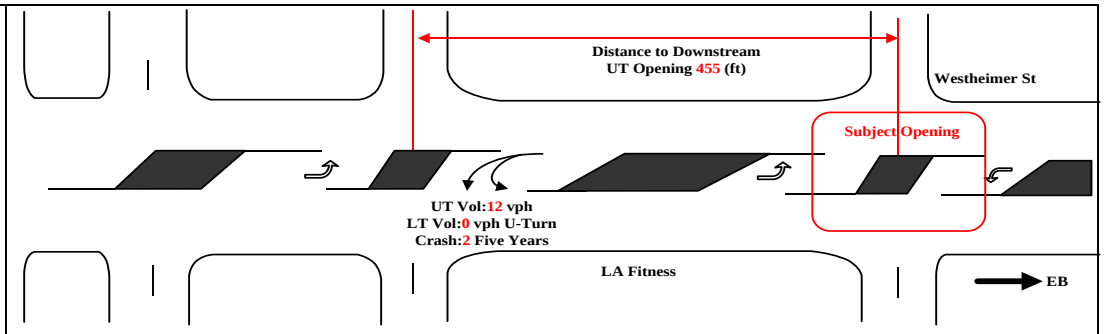
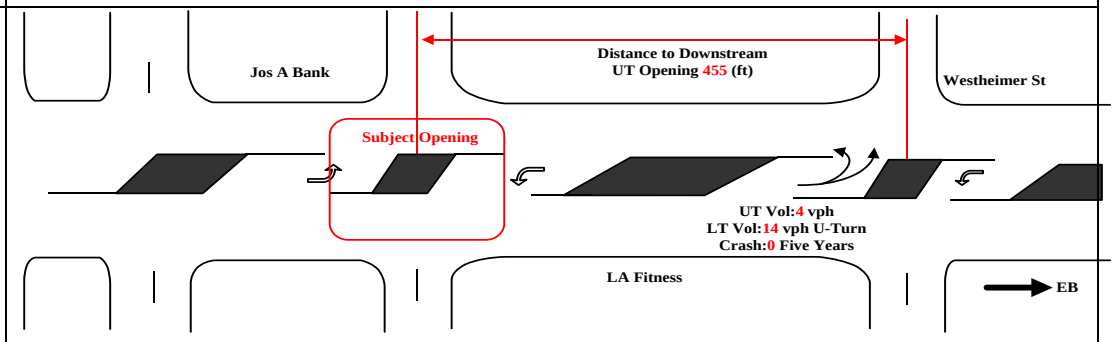
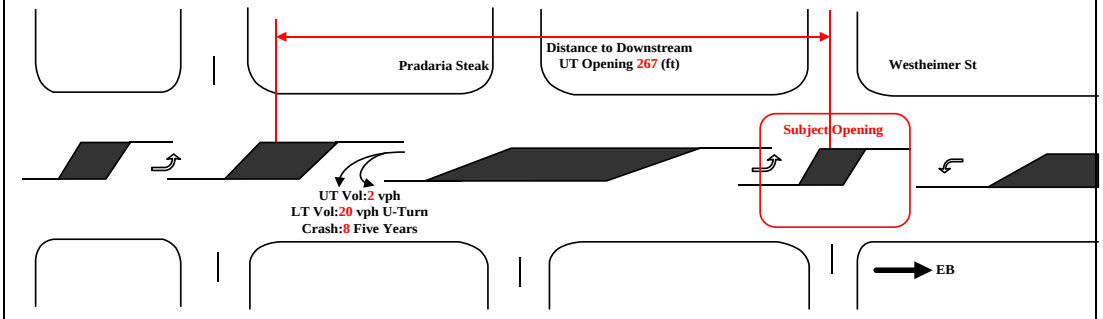
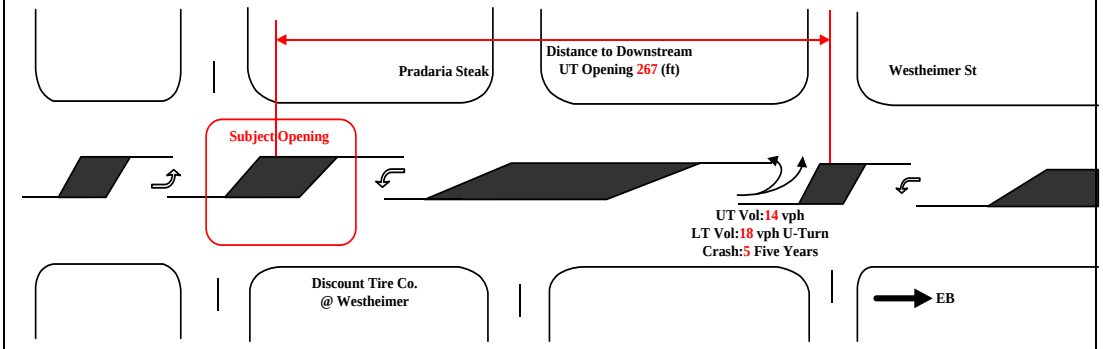
13	
14	
15	
16	

Table 7. Other Data Collected for the Intersections

Subject Opening ID	Subject Opening Direction	Downstream U-Turn Volume (vph)	Downstream LT Volume (vph)	Distance to Downstream UT Opening (ft)	Crash at U-Turn Location (in 5 Years)
1	EB	16	6	310	1
2	EB	4	22	430	2
3	WB	14	10	420	6
4	EB	14	30	420	5
5	EB	38	0	351	4
6	WB	32	16	620	4
7	WB	12	8	286	0
8	WB	20	14	386	4
9	EB	28	22	386	11
10	WB	34	56	680	8
11	EB	36	16	680	3
12	WB	2	28	390	1
13	WB	12	0	455	2
14	EB	4	14	455	0
15	WB	2	20	267	8
16	EB	14	18	267	5

3.2.3 Poisson Regression Model

In this study, the Poisson regression model was used to investigate the influencing factors on crashes occurred at the downstream U-turn locations of directional median openings. The Poisson regression model is a classical model for counted data.

Critical events are randomly distributed and the frequency of critical events is discrete and positive numbers. The relationship between the expected number of critical events y_i occurring at an intersection approach pair i (dependent variable y_i) and a set of explanatory variables D_1, D_2,…D_n that represent the features of study locations (i.e., downstream U-Turn

Volume, downstream left-turn volume, distance to downstream median opening) could be modeled as following equation:

$$P\ (y_i|D_i) = \frac{\exp(-u_i)u_i^{y_i}}{y_i!}$$

Where y_i denotes the total numbers of crashes that occurred at downstream U-Turn unsignalized opening of study opening, u_i is the conditional mean of y_i, which is a non-linear function of D_i and can be expressed as follows:

$$\ln u_i = \beta D_i = \beta_0 + \beta_1 D_1 + \beta_2 D_2 + \cdots + \beta_n D_n$$

Then, the expected numbers of crashes y_i can be estimated by:

$$E(y_i|D_i) = u_i = \exp(\beta D_i)$$

Where ß is the vector of regression coefficients that can be estimated by the standard maximum likelihood method with the likelihood function given by:

$$L(\beta) = \prod_i \frac{\exp[-\exp(\beta D_i)][\exp(\beta D_i)]^{y_i}}{y_i!}$$

In the model, the dependent variable was defined as the number of historical crashes at downstream U-turn locations occurred from 2007 to 2011. The candidate independent variables included "Downstream U-Turn Volume" (D_{UT}), "Downstream Left-Turn Volume" (D_{LT}), "Distance to Downstream U-Turn Opening" (D_{DUT}) (**Table 8**).

Table 8. Dependent and Independent Variables with Description

Dependent Variables	Description
yi	Total Number of Crash in 5-YearPeriod
Independent Variables	Description
D_{UT}	Downstream U-Turn Volume
D_{LT}	Downstream LT Volume
D_{DUT}	Distance to Downstream UT Opening

CHAPTER 4: RESULTS

This chapter presents the results from the cross-sectional comparison study and the contributing factors analysis study.

4.1 CROSS-SECTIONAL COMPARISON STUDY

This study compared the crash frequencies of directional median openings and full median openings, including the crashes occurred at both the opening locations and at the downstream U-turn locations.

A statistical t-test was used to compare the mean of the crash frequencies for directional median openings and full median openings. Note that, the sample size for directional median openings and full median openings, which is 34 and 20 respectively, is not equal. The variances for the crash frequencies are not equal either. Therefore, the Nonpaired-Two-Samples-Assuming-Unequal-Variance-t-test was selected.

Table 9 presented the t-test results. As seen in **Table 9**, at the subject openings, directional median openings have a lower average crash frequency (6.76 per five years) than full median openings (11.45 per five years). At the downstream U-turn locations (both directions), directional median openings have a higher average crash frequency (6.56 per five years)) than full median openings (2.90 per five years). The crash reduction shows that, if converting from a full directional median opening to directional median opening, the average crash frequencies at the subject openings will reduce by 4.69 per five years, while the average crash frequencies at the downstream U-turn locations will increase by 3.66 per five years. The total crash frequencies at subject openings and downstream U-turn locations will reduce by 1.03 per five years. The t-test results were not significant for the crashes at the subject openings and for the total crashes, which might be because of the limited sample size.

Table 9. T-Test Results-Comparison of Median of Crash Frequencies

Description	Full Median Openings	Directional Median Openings	Changes in Crash frequency (# of crashes per five years)	T-test results
Crashes at the subject openings	11.45	6.76	4.69	Not significant
Crashes at the downstream U-turn locations (both directions)	2.90	6.56	-3.66	Significant
Total crashes at subject openings and downstream U-turn Locations	14.35	13.32	1.03	Not significant

It can be concluded, from the results in **Table 9**, that converting a full median opening to directional median opening will reduce the crash frequency at the subject opening location. Although directional median openings might increase the crash frequencies at downstream U-turn locations, the total crashes at subject openings and downstream U-turn locations are still lower than that at full median openings.

4.2 CONTRIBUTING FACTORS ANALYSIS STUDY

In this study, the Poisson regression model was used to investigate the influencing factors on the crashes occurred at the downstream U-turn locations of directional median openings. The Poisson regression model is a classical model for counted data. The statistic software package SPSS was used for developing this model.

The results of the Poisson regression model are presented in

Table 10.

Table 10. Results of Poisson Regression Analysis

Model		**Dependent Variable: Crash**	
Regression Results	Independent Variable	Coefficients	P-Value
	Constant	1.525	0.002
	D_{UT}	0.041	0.005
	D_{LT}	0.035	0.000
	D_{DUT}	-0.004	0.005
	Sample Size	16	
	Log Likelihood	-34.130	

The statistical analysis results in

Table 10 showed that the total numbers of crashes at downstream U-turn locations were significantly affected by the following variables: "Downstream U-Turn Volume" (D_{UT}), "Downstream Left-turn Volume" (D_{LT}) and "Distance to Downstream U-Turn Opening" (D_{DUT}) at the confidence level of 95 percent. Therefore, the total numbers of crashes at downstream U-turn locations can be estimated by the following equation:

$$y = e^{(1.525+0.041*D_{UT}+0.035*D_{LT}-0.004*D_{DUT})}$$

Where,

y is the total number of crashes in 5-year period

D_{UT} is the downstream U-turn volume

D_{LT} is the downstream left-turn volume

D_{DUT} is the distance to downstream U-turn opening

In the above equation, the coefficient of D_{UT} and D_{LT} is 0.041 and 0.035 respectively. The positive coefficients indicate that higher U-turn volume and left-turn volume would result in more crashes. This is expected as higher U-turn and left-turn volume means more exposure. The coefficient may also be interpreted that every 10 vph increase in U-turn volume will increase the total number of crashes to 1.5 times ($e^{0.041*10} = 1.5$); and every 10 vph increase in left-turn volume will increase the total number of crashes to 1.4 times ($e^{0.035*10} = 1.4$).

The coefficient of D_{DUT} is -0.004 which indicates that the closer the downstream U-turn opening, the more crashes. Decreasing the distance by 100ft would result in 1.5 times total number of crashes ($e^{-0.004*(-100)} = 1.5$). This may be because, if the downstream opening is too close, egress vehicles do not have enough time and distance to change to the leftmost lane to make U-turn, therefore, they might make unsafe lane changes, which might cause more crashes.

Figure 13 further visualized the relationship of crash frequency (number of crashes in five years) with the three contributing factors. As seen in **Figure 13**, for different combination of left-turn and U-turn volumes, the longer the distance to downstream U-turn location, the less crashes. Higher left-turn and U-turn volumes lead to more crashes. For locations with heavy left-turn and U-turn volumes, a closely spaced U-turn location can cause more crashes. For example, for locations with a left-turn volume of 40 vph and U-turn volume of 40 vph, if the U-turn location is too close (e.g. within 200ft or 300 ft distance), the crash frequencies could be 29 to 44 per five years. For locations with a left-turn volume of 50 vph and U-turn volume of 50 vph, if the U-turn location is within 500 ft distance, the crash frequencies could range from 28 to 93 per five years.

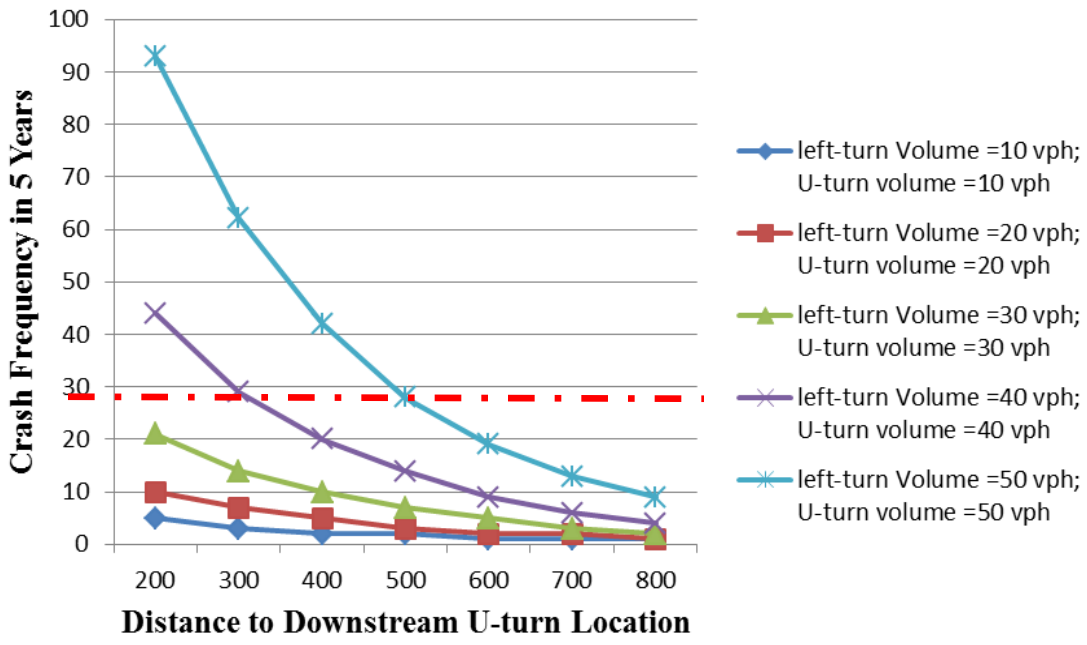


Figure 13. The Relationship of Crash Frequency with Contributing Factors

Figure 14 plotted the observed crash count against the Poisson regression model predicted crash count. The plotted data points all scatter around the 45-degree line. The fitted line that passes through the origin has a gradient of 1.083, which is very close to 1.0. The result indicates that the Poisson regression model produced satisfactory estimates of crash count.

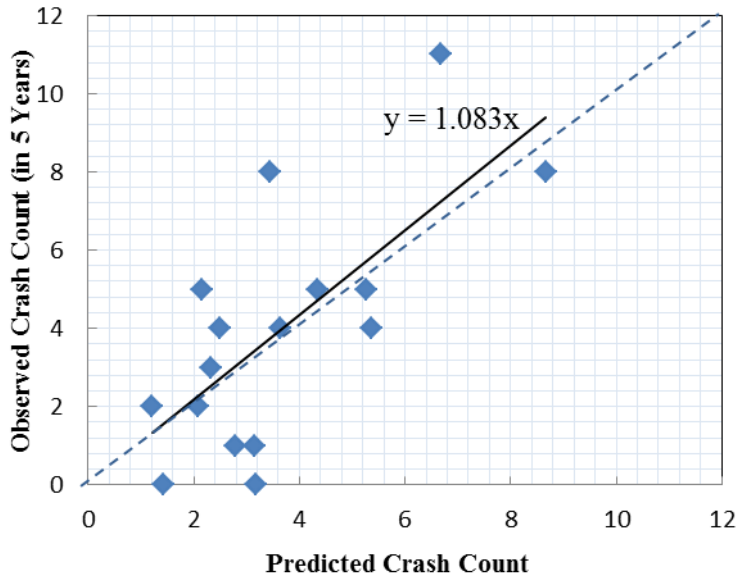


Figure 14. Predicted Crash/Observed Crash Count Validation

4.3 Crash Modification Factors (CMFs) and Case Study

The Poisson regression model indicates that the total numbers of crashes at downstream U-turn locations of directional median openings were significantly affected by downstream U-turn volume, downstream left-turn volume, and distance to downstream U-turn opening. Since converting a full median opening to a directional median opening will generate more U-turns at the downstream opening of directional opening, therefore, the selection of U-turn location is critical for the safety performance of directional openings.

This section will develop a CMF to predict the impacts of selecting different U-turn locations. A CMF is a quantitative measure of the change in expected average crashes at a site caused by implementing a particular treatment. The developed crash prediction model can be used to quantify the safety impacts of selecting different U-turn locations. Based on the results from the Poisson regression analysis, the expected crash frequency (in number of crashes per five years) at downstream U-turn locations can be estimated by the following equation,

$$y = e^{(1.525+0.041*D_{UT}+0.035*D_{LT}-0.004*D_{DUT})}$$

Therefore, if assuming there are two candidate u-turn locations (location 1 and location 2) at downstream of a subject directional median openings, the percentage of change in crash frequency of placing U-turn location at location 2 instead of location 1 can be estimated as follows,

$$CMF = \frac{e^{(1.525+0.041*D_{UT}^{Location2}+0.035*D_{LT}^{Location2}-0.004*D_{DUT}^{Location2})}}{e^{(1.525+0.041*D_{UT}^{Location1}+0.035*D_{LT}^{Location1}-0.004*D_{DUT}^{Location1})}}$$

The developed CMF can be used to estimate the impacts of selecting different U-turn locations as demonstrated by the following case study:

Case Study: Study Site No. 4

For study site No. 4, there are two downstream unsignalized median openings that could be used for U-turns. See Figure 15. Location 1 is 420 ft away from subject opening, while Location 2 is 840 ft away from subject opening.

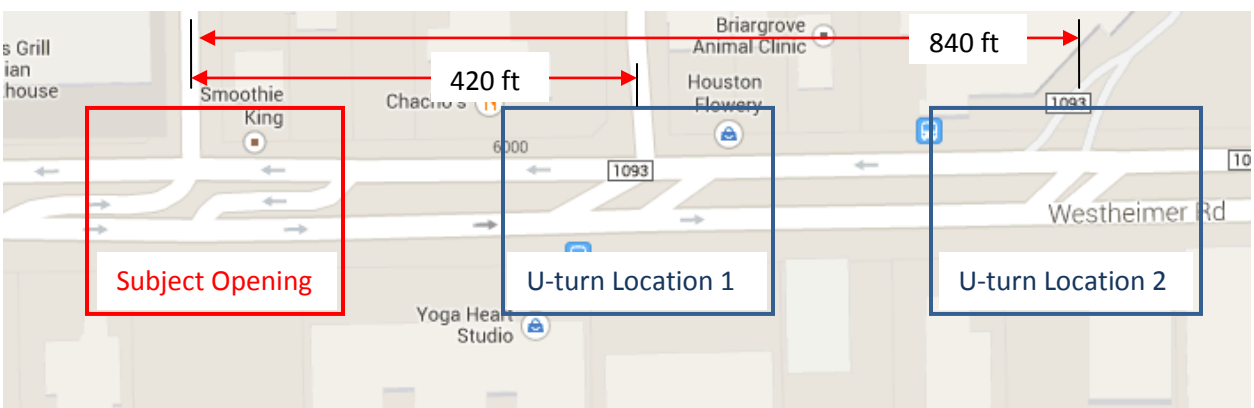


Figure 15 Two Downstream U-turn Locations at Study Site No. 4

Currently, U-turns generated by subject openings are allowed at U-turn Location 1, which lead to a u-turn volume of 14 vph at location 1. Location 1 also has a left-turn volume of 30 vph. As seen in Table 7, the crash frequency at Location 1 is five in the five-year period.

The following equation will calculate the CMF if U-turns are redirected to Location 2 instead of Location 1, assuming Location 2 has the same left-turn volume as Location 1.

$$CMF = \frac{e^{(1.525+0.041*14+0.035*30-0.004*840)}}{e^{(1.525+0.041*14+0.035*30-0.004*420)}} = \frac{1}{5} = 20\%$$

This result indicates that, if placing U-turns at Location 2 instead of Location 1, the crash will reduce by 80percent.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

In this research, two studies were conducted to investigate the safety impacts of installing directional openings on median-divided urban roadways. The first study compared the crash frequencies at the selected directional median openings and the comparable full median openings. It also compared the crash frequencies at the downstream U-turn locations of these openings. The second study developed a Poisson regression model to investigate the influencing factors on the crashes occurred at the downstream U-turn locations of directional median openings.

These studies led to a number of findings. Some of the highlighted findings include:

1. Converting a full median opening to a directional median opening will reduce the crash frequency at the subject opening location. Although directional median openings might increase the crash frequencies at downstream u-turn locations, the total crashes at subject openings and downstream u-turn locations are still lower than that at full median openings.

2. The crash frequencies at downstream U-turn locations of directional median openings were significantly affected by downstream U-turn volume, downstream left-turn volume, and distance to downstream U-turn opening. Higher downstream U-turn volume and downstream left-turn volume would result in more crashes at downstream U-turn locations. The closer the downstream U-turn location to the subject opening, the more crashes at downstream U-turn location.

3. For locations with heavy left-turn and U-turn volumes, a closely spaced U-turn location can cause more crashes. For example, for locations with a left-turn volume of 40 vph and U-turn volume of 40 vph, if the U-turn location is too close (e.g. within 200ft or 300 ft distance), the crash frequencies could be 29 to 44 per five years. For locations with a left-turn volume of 50 vph and U-turn volume of 50 vph, if the U-turn location is within 500 ft distance, the crash frequencies could range from 28 to 93 per five years.

These findings indicate that, since converting a full median opening to a directional median opening will generate more U-turns at the downstream opening of directional opening, the selection of U-turn location is critical for the safety performance of directional openings. Diverted left-turn traffic should not be allowed to make U-turns at a closely spaced opening that already have significant U-turns or left-turn volumes.

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