Center for Advanced Multimodal Mobility Solutions and Education

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USE OF INNOVATIVE INTERSECTION DESIGNS FOR IMPROVING MOBILITY AND REDUCING ROADWAY TRAFFIC CONGESTION

Final Report

by

Texas Southern University
Consortium Member

Yi Qi, Ph.D. (ORCID ID: https://orcid.org/0000-0002-6314-2626)
Professor and Chair, Department of Transportation Studies
Texas Southern University
Phone: 1-713-313-6809; Email: Yi.Qi@tsu.edu

Qun Zhao (ORCID ID: https://orcid.org/0000-0003-3760-9234)
Research Associate, Department of Transportation Studies
Texas Southern University
Phone: 1-713-313-1854; Email: qun.zhao@tsu.edu

Mehdi Azimi Ph.D., P.E. (ORCID ID: https://orcid.org/0000-0001-5678-0323)
Assistant Professor, Department of Transportation Studies
Texas Southern University
Phone: 1-713-313-1293; Email: Mehdi.Azimi@tsu.edu

Qiao Sun (ORCID ID: https://orcid.org/0000-0002-9157-3327), Juan Li (ORCID ID: https://orcid.org/0000-0003-2416-5013) and Shaojie Liu (ORCID ID: https://orcid.org/0000-0001-5330-3871)
Graduate Research Assistant, Department of Transportation Studies
Texas Southern University

And

Sahil Shah (ORCID ID: https://orcid.org/0000-0002-2496-6665)
Under-graduate Research Assistant, Civil, Architectural, and Environmental Engineering Department, Cockrell School of Engineering, University of Texas at Austin

for

Center for Advanced Multimodal Mobility Solutions and Education
(CAMMSE @ UNC Charlotte)
The University of North Carolina at Charlotte
9201 University City Blvd
Charlotte, NC 28223

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DISCLAIMER

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EXCUTIVE SUMMARY

The intersection is one of the most congested and dangerous roadway segments in the whole transportation system. With the increasing traffic demand, traditional intersection design cannot accommodate large traffic volumes well. Therefore, their associated problems, such as traffic congestion, travel delay, crashes, and road environment, raise concerns. Innovative intersections, also known as alternative or unconventional intersections, were put forward by transportation engineers to treat these increasing and serious traffic problems. Unlike conventional intersection designs, which usually accommodate traffic by improving signal systems or increasing rights of way by simply widening the road, innovative intersections are more comprehensive design measures, which are intended to utilize the roadway resources fully and to consider how best to benefit different roadway users.

This research focuses on three widely implemented innovative intersections: the Displaced Left Turn (Continuous-flow Intersection), the Medium U-turn (Michigan Left), and the Restricted Crossing U-turn (Superstreet). Previous studies related to those three intersection designs were reviewed and summarized, including geometric design, operational performance, safety performance and others as well as current design standards could apply to or specifically for these new designs. In addition, the displaced left turn intersection was selected to conduct simulation-based operational analysis and collision diagram-based safety analysis. Findings and recommendations were provided.

The objectives of this project are to (1) synthesize existing studies on these three representative innovative intersection designs regarding their aspects of mobility, safety and other performance; (2) examine the design guidelines on critical features of these three innovative intersection types; (3) conduct a simulation-based operational analysis of the displaced left turn intersection; (4) investigate the operational impacts of the left turn crossover distance; and (5) conduct case studies to investigate the safety impacts of implementing the displaced left turn intersection design.

Chapter 1. Introduction

1.1 Problem Statement

The intersection has been the most congested and dangerous roadway segment in the whole transportation system. With the increasing traffic demand, traditional intersection designs cannot accommodate large traffic volumes well. Therefore, the associated problems, such as traffic congestion, travel delay, crashes, and road environment, raised concerns. Innovative intersections, also known as alternative or unconventional intersections, are new designs that have been put forward by engineers to treat these increasing and serious traffic problems. Unlike conventional intersection designs, which usually accommodate traffic by improving signal systems or increasing rights of way by simply widening the road, innovative intersections are more comprehensive design measures, which intend to utilize the roadway resources fully and consider how best to benefit different roadway users.

There are many forms of innovative intersections designed to meet different roadway environments. This research will focus on three widely applied innovative intersection design forms: the displaced left turn (DLT), the medium U-turn (MUT), and the restricted crossing U-turn (RCUT). These three innovative intersection designs share common features; they reroute the left turn phrases out of the main intersection and shift them by using an exclusive left turn crossover a few hundred feet up or downstream of the main intersection. This could assign more travel time to the main intersection traffic by removing the left turn signal phase, reducing the left turn related conflict points at the main intersection, increasing road capacity and mitigating congestion, which will gain improved intersection mobility and safety.

To date, 12 states have installed and operated DLT designs in the United States, 8 states have installed MUTs and 5 states have installed RCUTs. Table 1-1 lists the states that have implemented these three types of intersection.

Table 1-1: Innovative Intersections Implemented across the United States

Intersection Type	# of States Implemented	Name of the States
DLT	12	New Jersey, New York, Maryland, Louisiana, Missouri, Ohio, Utah, Mississippi, Louisiana, Colorado, Texas, Georgia.
MUT	8	Alabama, Arizona, Louisiana, Maryland, North Carolina, Ohio, Texas, Utah.
RCUT	5	Indiana, Michigan, Minnesota, North Carolina, Texas.

1.2 Objectives

The objectives of this project are to: (1) review and synthesize the state-of-the art/practice associated with implementing these three representative innovative intersection designs regarding their aspects of mobility, safety, and other performance; (2) examine the design guidelines of these three innovative intersections; (3) conduct simulation-based operational analysis of DLT intersection; (4) investigate the operational impacts of different left turn crossover distance; and (5) conduct case studies to investigate the safety impacts of implementing the DLT intersection design.

1.3 Report Overview

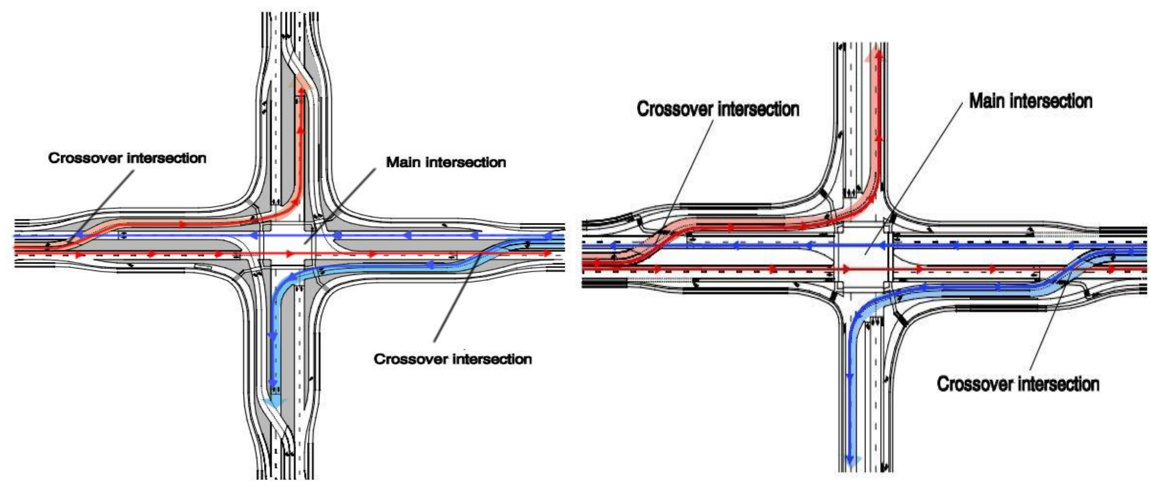
The remainder of this report is organized as follows: Chapters 2, 3 and 4 synthesize existing studies and design guidelines for the displaced left turn (DLT) intersection, median U-turn (MUT) intersection and restricted crossing U-turn (RCUT) respectively. Chapter 5 evaluates the operational performance of DLT intersections. A simulation-based study was conducted to compare the operational performance of the DLT intersection and a conventional intersection. In addition, the operational impact of a critical design element, crossover distance, was investigated. Chapter 6 investigated the safety performance of implementing the DLT intersection. Two DLT intersections located in Texas were selected to perform a diagram-based safety analysis. Chapter 7 concludes this report with a summary and a discussion of the directions for future research.

Chapter 2. Existing Studies and Design Guidelines for the DLT Intersection

2.1 Concepts, Definitions and Applicability

The DLT intersection, also known as the continuous flow intersection (CFI) or crossover intersection (XDL), is one type of innovative intersection design. The objective of the DLT design is to improve vehicle mobility and to alleviate the congestion at the main intersection by eliminating direct left turn movements proceeding through the main intersection. When left turn traffic reaches the crossover intersection, their movements will be protected with a dedicated left turn lane a few hundred feet ahead of the main intersection to complete their travel. Meanwhile, with the coordination of the signal timing, displaced left turn movements are designed to operate simultaneously with the opposing through movements. This will improve the mobility and safety performance of the main intersection, since it will operate under a two-phase signal without accommodating a left turn phase. This means that a longer signal time will be achieved by the through movements. Moreover, when drivers are familiar with the DLT travel path, the number of left turn-related crashes and rear end crashes will also decrease (FHWA, 2014).

According to the number of DLT crossovers on the intersection, we can classify them into full DLT and partial DLT designs. Figure 2-1 illustrates the different design configurations of those types. The full DLT design has 4 crossovers on each approach, while the partial DLT design may have up to 3 crossovers.



(1) Full DLT design with 4 crossovers (2) Partial DLT design with 2 crossovers

Figure 2-1: Displaced Left Turn Configurations
(Source: Displaced Left Turn Informational Guide)

By December 2017, the DLT design has been applied in 12 states in the United States. In most cases, the DLT intersections were placed on the major roads in urban and suburban areas with high through and left turn movements. A study showed that the DLT intersection would bring remarkable improvement when there are heavy and balanced traffic flows on opposing approaches (Dhatrak et al. 2010). In addition, LaDOTD suggested that the higher the volume of left turn percentage in the total volume, the greater will be the benefits generated by the DLT designs. To specify, left turn volume percentages ranged from 7.1% to 16.5% during p.m. peak hours, which was its best operational performance (LaDOTD, 2007).

2.2 Existing Design Guidelines

In this section, design guidelines and peer studies related to unique DLT geometric design features are summarized, including left turn crossover design, median width and right turn lane design.

2.2.1 Left Turn Crossover

Crossover placement has a significant meaning as a way to improve the whole intersection's mobility (LaDOTD, 2007). Short crossover spacing will not able to store the left turn vehicles, which will easily cause left-turn queue spillback to the through lanes; whereas, longer crossover spacing will occupy a larger space to build the displaced left turn lanes, which will increase the DLT footprint and investment. Other crossover related elements, such as crossover angle, crossover lane width, and reverse curve, are also critical and will affect vehicle type and turning movement. In view of this, we summarized existing guidelines on designing crossovers.

AIIR (Hughes, W., and et.al. 2010)

- It recommended a distance ranging from 300-400 feet as the upstream crossover spacing to the main intersection.
- The left-turn movements' radii at crossover are suggested to be 150 to 200 feet to accommodate large vehicles.
- The crossover reverse curve is referred to as a transitional section where crossing with the opposing through movements occurs by transferring the displaced left turn vehicles to the receiving left turn storage lanes as shown in figure 2-2 below. A lane width wider than 12 feet at this section is suggested to accommodate a large vehicle, while up to a 15-foot width is recommended for the receiving left turn storage lanes.

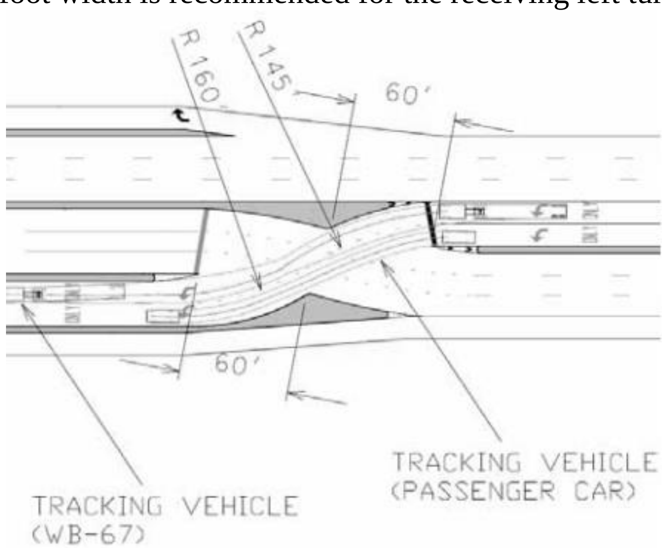


Figure 2-2: Crossover Reverse Curve at DLT Intersection Designs
Source: AIIR (2010)

LaDOTD CFI Report (10-07-2007)

- Cycle length, traffic demand and site conditions are factors that will affect the location of the crossover, and the crossover location will influence the whole CFI intersection's operational performance by allowing displaced left turning vehicles to run with the opposing vehicles at the same time.
- The distance that starts from the stop bar at the CFI crossover to the stop bar at the main intersection is comprised of two segments, crossover length and the remaining CFI-leg length, and ranges from 400 to 500 feet. Crossover length usually ranges from 175 to 225 feet. The CFI leg length ranges from 225 to 325 feet.
- The crossover angle refers to the point where the displaced left turn vehicles cross the opposing through lanes. The angle is recommended to be 10 to 15 degrees.
- Crossover reverse curves radii range from 300 to 400 feet.
- On the premise that the reverse curves radii should be maintained within the design speed limits, it is desirable to set the alignment of main lanes through the crossover to be tangent.

FHWA Displaced Left-Turn Intersection: Informational Guide (Hummer, J., and et.al. 2014)

- As shown in Figure 2-3, it recommended that the upstream crossover spacing to the main intersection be a distance ranging from 300-500 feet.

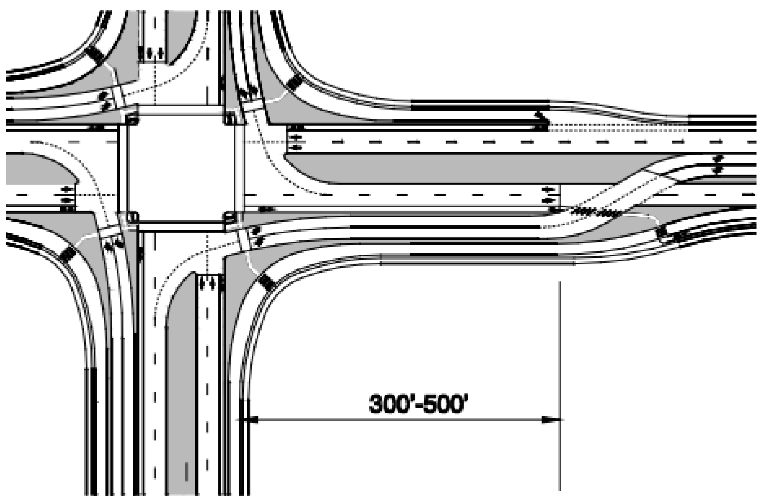


Figure 2-3: **Typical Intersection Spacing at DLT Intersection Designs**
Source: FHWA (2014)

Reid, 2004

- In a DLT design, the left-turn lane crosses the opposing traffic at a sub-intersection (crossover intersection) approximately 300 feet before the main intersection. This distance is a balance between the costs of a longer storage area and the spillback potential from the main intersection

Zhao, 2015

- Simulation results show that the maximum length of the displaced left turn lane tested in the paper produced the best performance, which was 150 m.

2.2.2 Median width

Median width is another important design element that needs to be carefully designed before implementation. Appropriate median width should provide pedestrian refuge and space for post-mounted signs to be installed while, at the same time, staying within the DLT footprint.

- Reference materials include the AASHTO Green Book, the Manual of Uniform Traffic Control Devices (MUTCD) and NCHRP Synthesis 225, "Left-Turn Treatments at Intersections—A Synthesis of Highway Practice," all of which are recommended to guide the DLT design features.

2.2.3 Right turn lane

In practice, there are two types of right turn lane (lanes) treatments, one is a channelized right turn lane and the other is a non-channelized right turn. Each treatment has its own advantages and disadvantages

FHWA Displaced Left-Turn Intersection: Informational guide (Hummer, J., and et.al. 2014)

- Auto-to-auto conflict points can be reduced if channelized right turns are applied, while more footprints may be needed to build it. Figure 2-4 below shows an example of a DLT intersection in Baton Rouge with channelized right turn lanes.

Figure 2-4: Four-legged DLT Intersection with Major Street Displaced Left Turns and Channelized Right Turns Located in Baton Rouge, LA
Source: FHWA (2014)

- Non-channelized right turns can reduce the required footprints by coinciding with single displaced left turns, and their turning paths can be defined to discourage wrong-way movements into the displaced left-turn lanes. No right-turn on red movement is allowed when there is no bypass right turn lane. Figure 2-5 below shows an example in West Valley City without right turn lanes.

Figure 2-5: Four-legged DLT Intersection with Four Displaced Left Turns and without Channelized Right Turns Located at West Valley City, UT
Source: FHWA (2014)

- Providing an add lane and leading it to merge with the crossing through lanes downstream of the crossover location is one way to accommodate the geometry, where the right-turn bypass lane joins the crossroad through lanes. This is illustrated in Figure 2-6 below. Using the crossover signal to coordinate the right turn movement is another way to accommodate the geometry issue as shown in Figure 2-7.

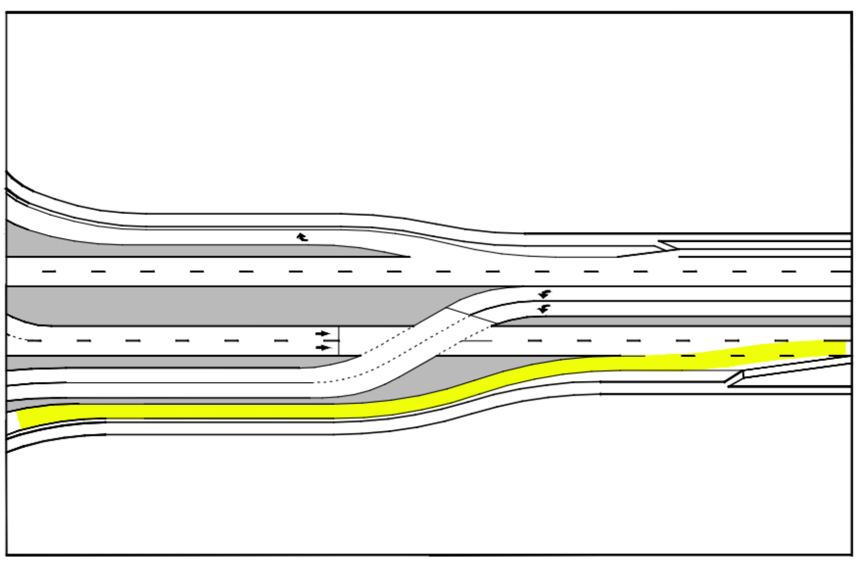


Figure 2-6: Add Lane with a Downstream Lane Merge

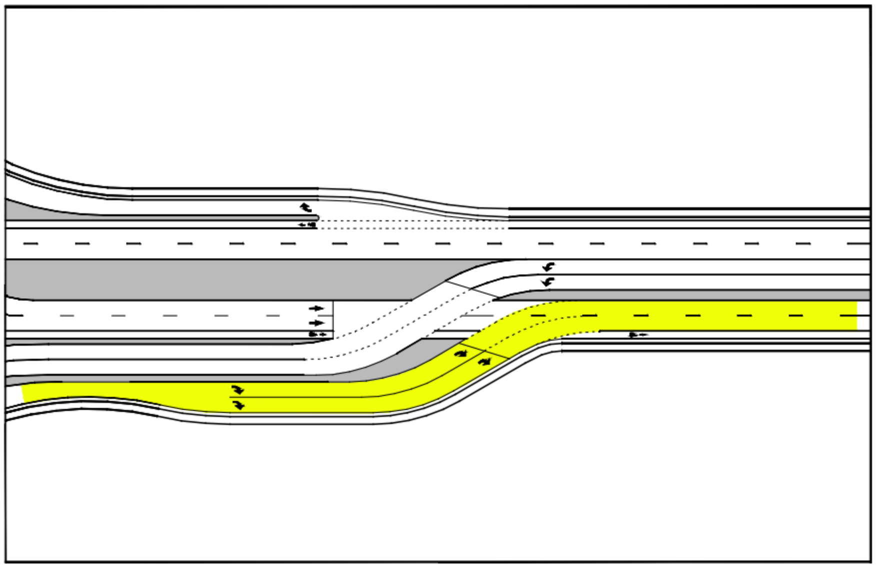


Figure 2-7: Signalized Right Turn

LaDOTD CFI Report (10-07-2007)

- The right turn lane should be wide enough to accommodate a stalled vehicle.
- A CFI right turn lane can be located adjacent to the displaced left turn lanes and can be channelized or unchanelized. The separation width is influenced by the required shoulder widths, the types of curbs and gutters, and the desired separator width. The CFI right turn lane should be wide enough to accommodate signs and signal supports and to shelter disabled vehicles. A flat slope curb near the outer through lane is suggested to accommodate the disabled vehicles.
- There are two ways to connect a right turn lane to the main lanes: one is to tie it directly into the main lanes and apply it under a signal control; the other way is to provide an acceleration lane to allow right turn vehicles to merge into the main lanes. Only if the angle of approach for right turning vehicles increases to 60 degrees is it necessary to use a stop or yield sign to control traffic between the right-turn lane and the main lanes.

2.3 Operational Performance

The major objective of the implementation of unconventional intersection treatments is to improve the operation of existing conventional intersections (Hughes et al., 2010). Numerous studies have been conducted to evaluate the operational performance of implementing DLT intersections. Most of those studies were based upon microsimulation-based analyses.

Claudia, L. O. (2011) compared the operational performance of three unconventional arterial intersection designs (UAID): a left-turn bypass, a diverging flow intersection and the DLT intersection. VISSIM v.5.10 was employed, and the measures of effectiveness were average delay time and total number of stops. Traffic demand data was generated hypothetically with the vehicles entering volume ranging from 500 to 6,000 to simulate peak and off-peak traffic. Results showed that, in the balanced conditions, the DLT intersections consistently performed better than the other two unconventional designs with 10% and 30% left turn movement when the average delay time was considered. The total number of stops results indicated that the DLT intersection performed better for a 10% left turn movement. For the 30% left turn movement, the DLT intersection and the diverging flow intersection had similar better results than the left-turn bypass up to 4,500 vph. Then the DLT intersection increased the number of stops consistently, but the diverging flow maintained constant values. In the unbalanced condition, the results indicated that, in the 60-40 split, the 70-30 split and the 80-20 split major and minor road distributions, the DLT intersection had an average delay of less than 20 sec/veh, which again was a better performance than the other two intersection designs.

Steve Chery (2010) compared the operational performance of the conventional intersection with four unconventional intersections, namely a signalized roundabout, an un-signalized roundabout, a continuous flow intersection, and a parallel flow intersection. Average delay time and number of stops were collected. Adopting two micro-simulation platforms, AIMSUN and VISSIM, the author tested 38 scenarios by using hypothetical traffic data with consideration of 3 critical issues: different volume levels, balanced and unbalanced flow conditions and increasing left-turn volume for the balanced scenarios. Results showed:

- In a balanced traffic condition, the CFI had the lowest average delays of all of the alternatives at higher flow levels. For example, when entering volume was 6,000 vph, the average delay time for the CFI was 26 seconds less than the conventional intersections. Comparatively, the conventional intersections did not perform well at volume levels close to saturation with an average delay of 50 seconds per vehicle. When the average number of stops was considered for 15% left turn movements, the vehicles followed the same trend with the average delay time in all intersection types. It was explained that, as the waiting queue at the intersection lengthened, the number of stops per cycle length also increased.
- In the unbalanced traffic condition, the results showed that the CFI had the lowest average delay among all of other intersections at traffic volumes higher than 2,000 vehicles per hour. Especially when the total approach volume was 5,000 vph, the CFI had an average delay of only 28 seconds.
- By analyzing the left turn movement, it was found that the left turn lane in the CFI could accommodate the increasing number of left turn vehicles and reduce delay time.

Vedagiri et al. (2012) evaluated the CFI under heterogeneous traffic flow conditions by using simulation. Average delay was employed to evaluate the performance of different intersections. The operational performance of the CFI was compared to a Normal Flow Intersection (NFI). The results showed that a CFI is more efficient than an NFI in that a CFI could successfully reduce the average delay by a considerable percentage. Two experiments were conducted by VISSIM to simulate the designs, because it is not practical to implement the research design in the field test. The traffic volume varying from 500 vehicles per hour to 3,500 per hour was set for the first experiment and 500 to 5,000 vehicles per hour for the second experiment. Different right turning proportion ranging from 10% to 50% of the total traffic volume was considered. The lane length was 3.5 m, and traffic behavior was set under heterogeneous traffic and random traffic in India. These settings may enable the study to simulate the real traffic accurately. It has been concluded that CFI is more efficient than NFI especially when traffic volume is more than 2,000 vehicles per hour.

Unlike the authors who use hypothetical volumes to compare the intersection delay and travel time, Reid (2001) conducted a travel time comparison of conventional and seven unconventional designs, namely the quadrant roadway intersection, the median U-turn, the superstreet median, the bowtie, the jug-handle, the split intersection, and CFI designs by using data from actual intersections. In the research, optimum cycle lengths were used in each intersection design, and a number of factors were held constant to make the comparison comparable and fair. Different scenarios, off-peak hour, peak hour and peak-plus-15-percent volume level were analyzed. The simulation results showed that the CFI had the largest number of trips completed and MOVE-TO –TOTAL-TIME ratio among all of the designs. In cases in which the tested intersection had the largest total volume (ADT was 74,300, 84,800 and 97,200 respectively) and high volume of turning movements were during the peak hour, the CFI outperformed the conventional intersections during peak hours with less travel time.

Goldblatt et al. (1994) evaluated the effectiveness of the CFI concept using the TRAF-NETSIM microscopic simulation model. The results indicated that the CFI has advantages over equivalent standard intersection designs especially when demand approaches or exceeds the capacity of conventional designs and when protected phases are required for large volume left-turn movements. In addition, it was also found that the mean speed of a CFI design nearly doubled that of the conventional design in the approach volume of 1,500, 2,000 and 3,000 vph. Signal efficiency increased by at least 80%. It can be concluded that the operational performance of traffic at the CFI is far superior to that at the conventional intersection.

To provide collective information on the unconventional arterial intersection design (UAID), Kim et al. (2007) conducted research on selected UAIDs in the state of Maryland. The researchers built a knowledge-base-web interface on their research to aid future engineers. The authors conducted 4 case studies on the superstreet design, the CFI design, the center turn overpass design, and the roundabout design. The study revealed that reductions in accident frequency, accident severity, stopped delay, and queue length can be achieved by the 4 intersection designs. By using average delay as the measure of effectiveness, results from the simulation showed that the CFI could significantly reduce delay for through and left turn movement on the arterial.

Jagannathan and Bared (2004) used VISSIM to compare the traffic performance of XDL and conventional intersections under different traffic flows. Cases A, B, and C were simulated to represent full DLT, partial DLT on major roads and one DLT on a T-intersection respectively. The simulation results indicated a great performance improvement in XDL design compared to conventional intersection designs. Total average delay results showed that the XDL intersection decreased significantly with a range of 48% to 85%, 58% to 71%, and 19 to 90% in each case. However, these results considered the pedestrian presence. Removing pedestrians caused a lower cycle length, which led to an average intersection delay that ranged from 14s/vehicle to 19s/vehicle for Case A under low to moderate traffic volumes. In the terms of the average number of stops, except for Case 3, in undersaturated traffic flow conditions, the XDL intersection will realize a 15% to 30% reduction and 85% to 95% for saturated traffic flow in each case. As for queue length, the compared reduction rate was 62% to 88%, 66% to 88%, and 34% to 82% for each of the three cases respectively. In addition, the simulation results indicated the capacity increase after the DLT intersection implementation at the rates of 30%, 30% and 15% for Case A, Case B, and Case C respectively.

Cheong et al. (2008), Dhatrak et al. (2010), El Esawey et al. (2007), Autey et al. (2013), Ladda et al. (2011), Park and Rakha (2010), Zhao et al. (2015), Hildebrand, T. E (2007) also conducted their research, which similarly revealed that the DLT intersection outperformed conventional intersections.

2.4 Safety Performance

Since DLT intersections are still very new, and very limited crash data are available, research focused on safety impacts of implementing DLT at a signalized intersection are very few.

Conflict points can be used to represent the safety of a roadway segment. The lower number of conflict points indicates a lower collision possibility (FHWA, DLT Information Guide, 2014). Table 2-1 compares the number of conflict points between varied forms of DLT designs and the conventional intersections. Comparison results show that the DLT intersection has fewer conflict points with a 6% to 12% reduction for four-leg intersections.

Table 2-1: Conflict Points Comparison between DLT and Conventional Intersections

	3 Intersection legs (1 crossover)	4 Intersection legs (2 crossover)	4 Intersection legs (4 crossovers)
DLT	9	30	28
Conventional intersection	9	32	32

Furthermore, 3 types of conflicts are caused by different vehicle paths: crossing, merging and diverging:

- A crossing conflict exists when two vehicles meet at right or nearly right angles
- A merging conflict exists when the paths of two vehicles coincide with each other.
- A diverging conflict point indicates a split or diverging path.

Figure 2-8 shows the conflict points in the conventional intersection, and Figures 2-9 and 2-10 show the conflict points for DLT intersections with 2 crossovers and 4 crossovers respectively. It can be seen that two DLT intersections have a smaller number of crossing conflicts, which are 13 and 12, compared to the conventional intersection, which has 16 crossing conflict points. Since a crossing conflict most likely results in the higher risk of a collision (Inman, 2009), the comparison results indicate that the DLT intersection has lower risk of collision.

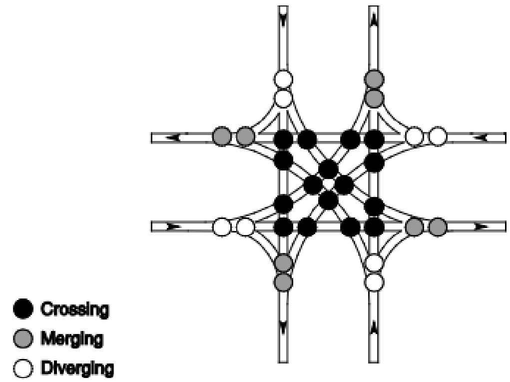


Figure 2-8: Conflict Point Diagram for a Conventional Intersection
Source: FHWA, Displaced Left Turn Intersection Informational Guide (2014)

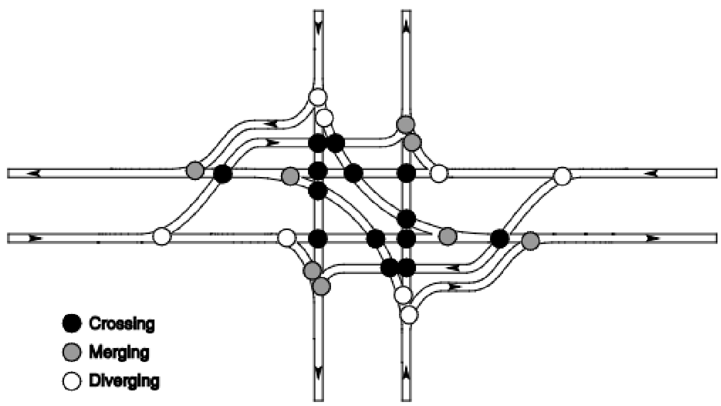


Figure 2-9: Conflict Point Diagram for a DLT Intersection with two DLT Crossovers
Source: FHWA, Displaced Left Turn Intersection Informational Guide (2014)

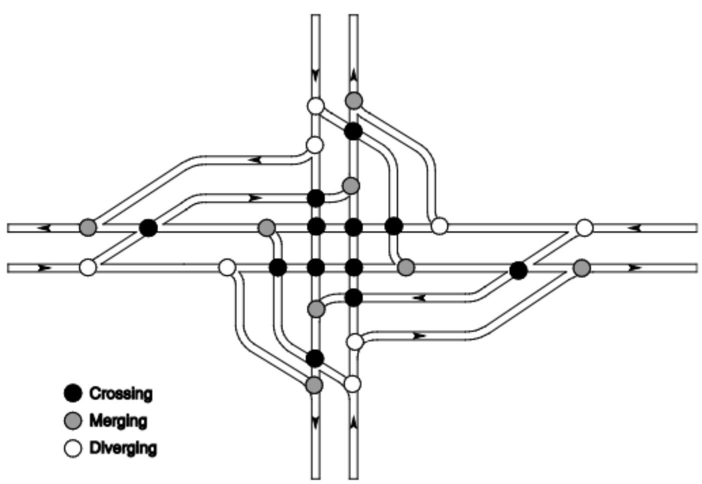


Figure 2-10: Conflict Point Diagram for a DLT Intersection with four DLT Crossovers
Source: FHWA, Displaced Left Turn Intersection Informational Guide (2014)

In addition, installing a DLT intersection with a channelized right turn bypass lane will reduce one conflict point on each approach, as shown in the figure below, and a layout without channelized right turns may cause right turn movement conflicts with vehicles coming from the displaced left turn lanes.

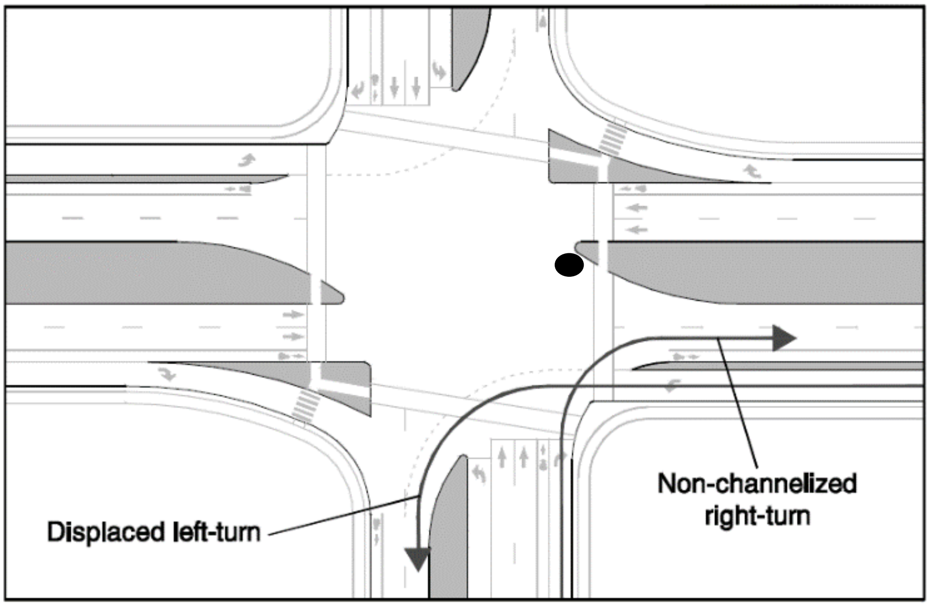


Figure 2-11: Conflict Point Diagram for DLT without channelized right turns
Source: FHWA, Displaced Left Turn Intersection Informational Guide (2014)

Moreover, the DLT design could not only reduce the number of conflict points and at the same time separate the conflict points of the left-turning traffic from the main intersection. Some research also indicates that increasing the space between the conflict points can also produce a safety benefit. (Reid, J., 2004.)

The Louisiana Department of Transportation (LaDOT, 2007) evaluated the safety performance of a pilot DLT intersection at Airline Highway/US 61 and Siegen Lane/Sherwood Forest Boulevard in Baton Rouge, LA by conducting a before and after analysis of crash data. This is a partial DLT design with two crossovers located on the 200-foot-wide Airline Highway. The LaDOT measured the crash data for two two-year periods (2002-2003 and 2004-2005) before the installation of the DLT intersection and measured the crash data for a 17-month period from March 21, 2006, through August 30, 2007, after the installation of the DLT intersection. The results showed that, after the implementation of the DLT design, the numbers of accidents were reduced from 185 and 200 to 146, which represents reductions of 21 and 27%, respectively. In addition, the rate of accidents involving significant injuries was reduced by 17%. The detailed results are provided in Table 1 below. However, LaDOT's Highway Safety Section recommended that at least a three-year period be used to collect post-crash data to conduct a proper evaluation of the safety performance of DLT intersections (2007). Therefore, additional study will be required to acquire adequate crash data after the installation of DLT at intersections.

Table 2-2: LaDOT CFI Report: Results of the Analysis of Before and After Crash Data

Type of collision	Four-Leg Signalized March 21-September 20 2002/2003			2004/2005			DLT Mar 21-Sep. 20 2006/2007		
	Serious Injuries	PDO	Total	Serious Injuries	PDO	Total	Serious Injuries	PDO	Total
Rear End	18	68	86	33	75	108	21	63	84
Merging/Diverging/Side Swiping	4	21	25	4	34	38	1	22	23
Crossing (Left Turn)	7	9	16	3	5	8	6	2	8
Crossing (Angle)	2	9	11	0	4	4	1	5	6
Right Angle	17	27	44	8	31	39	10	13	23
Right Turn	0	3	3	0	3	3	1	1	2
Total	48	137	185	48	152	200	40	106	146

Mary Eileen Yahl (2013) investigated the safety effects of a continuous flow intersection through observation before and after the study. By using a naïve method, a naïve with traffic factors method and a comparisons group method, the author selected five sites to investigate into the safety results of each individual site and then conducted an overall sites analysis. The naïve method can provide a base safety effect, which cannot be corrected for such changes as traffic volumes, historical trends, and seasonality. By using safety performance functions from the Highway Safety Manual and traffic volumes from before and after the installation of a CFI, the naïve method with traffic factors can adjust changing traffic volumes. The comparison group method can select comparison sites near the studied sites, which have similar crash trends to account for historical factors and seasonality. The results from the three methods varied. The Baton Rouge, LA site showed a decrease in the collision in all three types of methods but was the only individual site to do so outside of the margin of error. Generally, the other sites showed increasing collisions in the after period for all methods. In the overall site analysis, fatal and injury, rear end and sideswipe collisions increased while only angle and other collisions decreased.

The FHWA's Displaced Left Turn Intersection Informational Guide (2014) indicated several safety outcomes of implementing the displaced left-turn design: 1) The DLT intersection has successfully reduced the conflict points by 6 to 12% in four-leg intersections compared to conventional intersections. If left-turn crossovers are installed only on the main road, the total number of conflict points was 30 compared with 32 for traditional intersections. If left-turn crossovers are installed on all approaches, the total number of conflict points of a DLT intersection is 28, whereas a traditional intersection has 32; 2) the DLT design can reduce the delay time and the number of stops on the major road, which can reduce the rate of rear-end crashes; and 3) the DLT crossover layout increases the risk of wrong-way movements.

Zlatkovic (2015) assessed the safety performance of DLT intersections by developing crash modification factors (CMFs) using the Empirical Bayes (EB) methodology. Eight DLT intersections along Bangerter Highway in Utah were selected to acquire the available before and after crash data and annual average daily traffic (AADT) between 2008 and 2013. Crashes that occurred within 100 feet of each crossover and 250 feet of the main intersection were summed to provide the total crash data for the intersection. According to the EB analysis results, the crash modification factor for DLT intersection conversion was 0.877, which indicated that the DLT design had the potential to reduce crashes.

Park and Rakha (2010) assessed the safety impacts of the DLT intersection based on the analysis of traffic conflicts. They selected two DLT intersections in Louisiana to analyze the drivers' behaviors at these innovative intersections. Traffic videos were recorded at these intersections for two periods, i.e., immediately after the DLT intersection was opened and one year later. The traffic conflicts they identified included "Improper Lane Change", "Diverge", and "Red Light Violation". Their results indicated that drivers' lack of familiarity with the DLT design might cause unexpected driving maneuvers.

2.5 Accommodation of Pedestrians

The large footprint of a DLT intersection may result in a wider overall street at the intersection; thereby making it challenging to accommodate pedestrians as part of the traffic signal timing. In addition, the position of left-turn lanes between opposing through lanes and right-turn lanes presents pedestrians with an unfamiliar crossing scenario, especially for pedestrians with cognitive impairments.

Jagannathan, R. and Bared, J. G. (2005) analyzed the design and performance of pedestrian crossing facilities for CFIs. They also discussed the design methodologies to provide pedestrian access and the corresponding pedestrian signal timings. A simulation was conducted for CFIs designed by three typical geometries with base signal timings optimized for vehicular traffic performance. In the study, three cases were modeled:

- Case A: a four-legged intersection with four corresponding DLT lanes.
- Case B: a four-legged intersection with only two opposing DLT lanes on the major road.
- Case C: a T-intersection with one DLT lane.

Figure 2-12 to 2-14 illustrate the geometry design for the three cases.

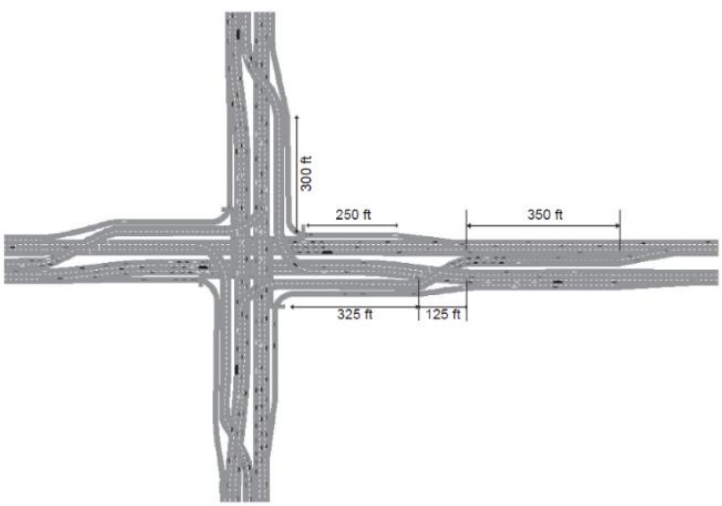


Figure 2-12: Typical geometry for CFI: Case A

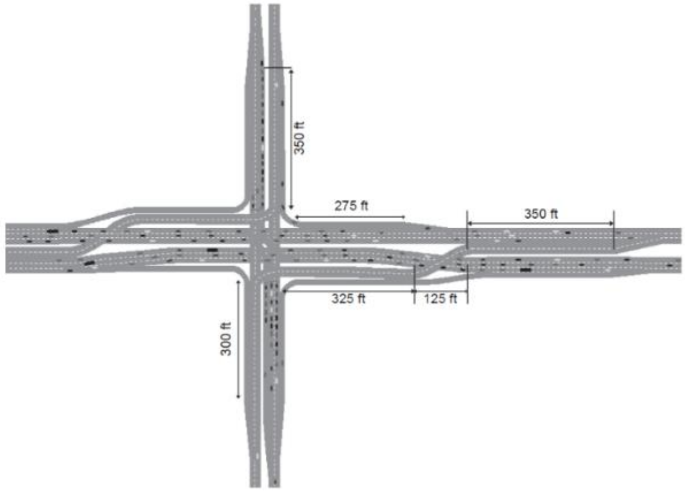


Figure 2-13: Typical geometry for CFI: Case B

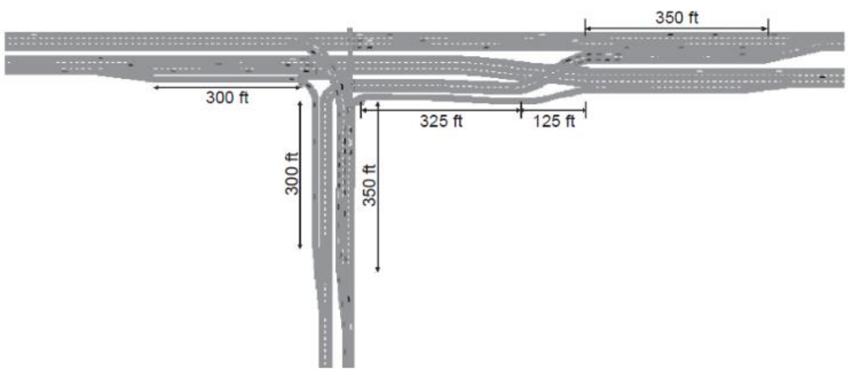


Figure 2-14: Typical geometry for CFI: Case C

Results showed that, on the basis of the average delay per stop experienced by any pedestrian for pedestrian crossings at the typical CFI geometries modeled, an acceptable pedestrian level of service of B or C is attained. All pedestrians served at the CFIs are accommodated within two cycles for a typical signal cycle length ranging from 60 to 100 seconds.

2.6 Signal Timing

Signal timing is a crucial component for DLT intersection design. An effective signal timing strategy can enhance the capacity, facilitate efficient traffic flow and achieve reduced control delay in the intersection.

The Federal Highway Administration (FHWA) introduced two signal timing schemes to account for whether the CFL is operated by a single controller or 5 five controllers in *Displaced Left Turn Intersection: Informational Guide* (2014).

Although the FHWA introduced the signal timing features for a CFI, very little about the green slits and offsets have been explained. The Louisiana Department of Transportation and Development emphasizes the principles of progression between the minor intersections to major intersections during signal design in its *Continuous Flow Intersection Report* (2007). Signals must be coordinated properly to ensure that traffic moves continuously through the CFI signalized intersections.

Utah's Department of Transportation (UDOT) proposed signal timing schemes for CFIs regarding both two-leg DLT intersection and four-leg DLT intersections (2013). Figure 2-15 provides examples of the UDOT's signal timing strategies for 2-leg CFIs using four rings, 2-leg CFIs using 2 rings, and 4-leg CFIs using 2 rings.

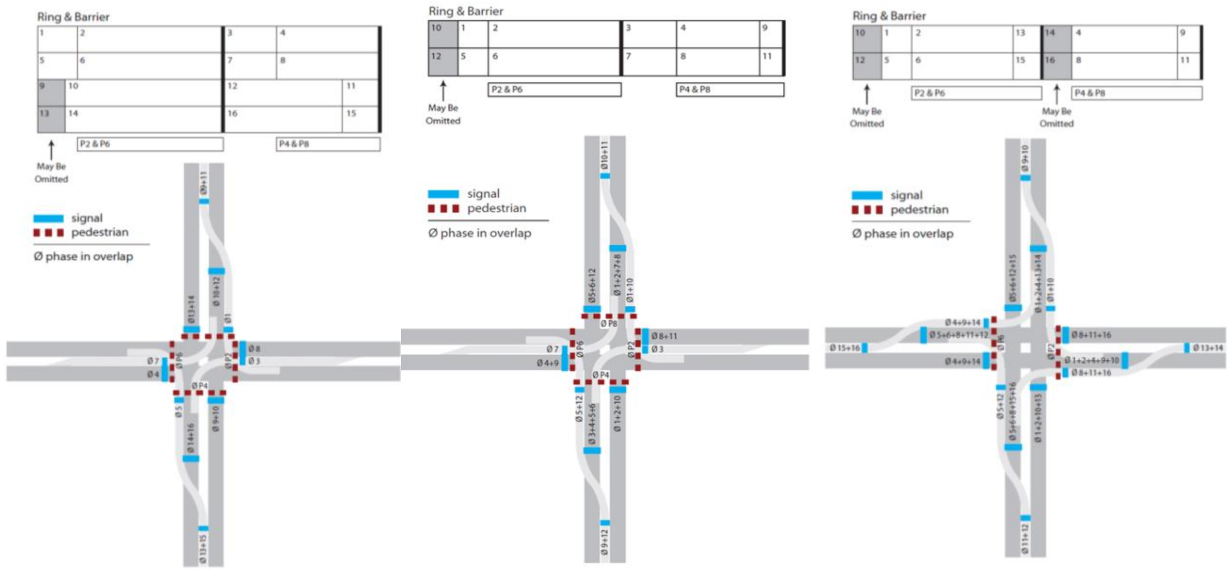


Figure 2-15: 2-Leg Signal Timing (Left, Middle) And 4- Leg Signal Timing (Right)

Mohamed Ei Esawey et al. (2007) compared DLT and upstream signalized crossover (USC) intersections using VisSim in terms of average delay. The results showed that the DLT intersection outperforms the conventional intersection under various volume scenarios. In contrast, the USC outperforms the conventional intersection under moderate and high-volume conditions or in the existence of extremely heavy left-turn movements. A brief introduction of the two-phase signal timing strategy was also given, while the process of determining the signal timings and offsets was not explained in detail. Figure 2-16 illustrates the two-phase signal scheme in a CFI. Figure shows five signal components, four of which correspond to the minor intersection traffic flows and one of which to the major intersection traffic flow.

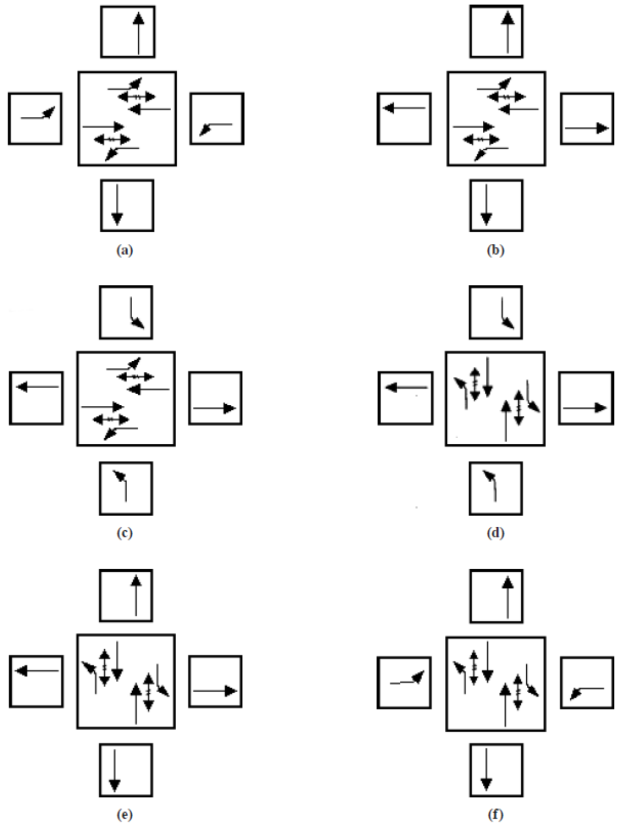


Figure 2-16: Two-Phase Signal Timing Strategy for Continuous Flow Intersection

Xiaoming You et al. (2013) developed a coordinated optimization model for signal timings of full CFLs under the three principles below:

- Both primary intersections and sub-intersections have the same cycle and operate under two-phase signal controls;
- The signals of sub-intersections and primary intersections are coordinated to minimize vehicle delay and the number of stops; and
- The queue length of each movement upstream of a primary intersection and sub-intersection should be no longer than the available space.

The optimization model utilized the shock wave theory to simulate the dynamic variables in the CFI. Then, he compared the control delay under the traffic signal timings generated from his model with the one from a conventional intersection with the same geometric characteristics. The results show that CFI outperforms the conventional intersection in high traffic demand scenarios. However, the model is overly complex and is not proper to be used as a guideline for transportation engineers to apply.

Since VISSIM and Transyt7f are not capable to generate signal timings and offsets for the CFI, Ramanujan et al. (2004) built an optimization model in his research to determine the signal timings for three types of DLT intersections respectively: 1) four-legged intersections with four corresponding DLT lanes; 2) four-legged intersections with only two opposing DLT lanes on the major road; and 3) T intersections with one DLT lane. Comparing the performance of the three types of CFIs with the conventional intersections proved that the CFI consistently outperforms the conventional intersection. But the paper provided only a list of constraints that the optimization model includes and did not include much more detail or instruction about this model.

Overall, although the signal timing schemes and optimization have been discussed in previous research, the basic guidelines for calculating the green splits and offsets have not.

2.7 Implement Barriers and Recommendations

In their study, Michelle L.S et.al. (2012) tried to inquire into the barriers to implementing unconventional intersections and to identify the corresponding solutions. 1,073 members of the Institute of Transportation Engineer (ITE) across the United States were asked to complete a 28-question survey. Most of the respondents (73%) were engaging in traffic operations. Survey results showed that public support was the biggest barrier. Other barriers included cost, right-of-way, access, and multimodal considerations. The survey also identified 6 public acceptance barriers, 8 professional barriers, and 8 political barriers. The following table 2-3 shows the ranking results of each dimension.

Table 2-3: Ranking and Response Distribution for Barriers

Part A: Public Acceptance Barriers	Average Rank	Number of Responses for Each Rank					
		1	2	3	4	5	6
Potential for driver confusion	1.96	111	72	16	16	14	3
Fear of the unknown	2.52	87	59	29	13	20	23
Concern about safety	3.21	19	50	76	46	32	9
Concern about property access	4.05	8	27	42	53	59	36
Concern about delay/travel time	4.41	3	15	37	55	66	51
Balancing vehicle traffic needs with others	4.76	5	10	31	46	35	102

Part B: Professional Barriers	Average Rank	Number of Responses for Each Rank							
		1	2	3	4	5	6	7	8
Lack of proof of design function	3.13	64	44	36	33	23	15	8	9
Concerns about safety	3.83	32	40	40	33	35	22	15	13
Professional indifference/ inertia to change	4.04	61	26	19	25	19	30	20	31
Lack of standards	4.06	21	34	43	36	44	23	22	8
Liability	4.61	26	33	23	27	30	29	39	26
Uncertainty in the design/ construction process	4.74	14	33	29	34	25	29	40	26
Balancing vehicle traffic needs with others	5.30	16	16	27	25	24	40	35	50
Lack of software to analyze the design	5.97	2	12	15	21	30	37	46	61

Part C: Political Barriers	Average Rank	Number of Responses for Each Rank							
		1	2	3	4	5	6	7	8
Public opinion	2.74	66	65	33	34	16	7	6	5
Lack of proof of design function	3.73	42	36	31	39	33	23	16	10
Cost/funding	3.83	52	22	39	34	24	28	13	20
Lack of political will	4.25	28	39	28	19	42	30	23	19
Concern about safety	4.42	17	22	34	40	41	41	20	10
Liability	4.70	20	33	24	29	33	29	34	30
Lack of cooperation between agencies	5.59	7	12	30	23	16	40	65	38
Balancing vehicle traffic needs with others	6.48	3	5	14	12	24	29	47	93

The results also showed that education was a key to the future use of unconventional intersections, and the state department of transportation was the key institution. The survey and interview result also showed that public opinion of the unconventional intersection will eventually improve after the opening of an intersection, and the public has some experience with it. Public opinion will cease to be a barrier after the intersection is put into use.

Moreover, the results of the interviews showed that the term "unconventional" has a negative connotation and may hurt public perception (G. Chlewicki, 2011). For example, the term "superstreet" sounds unfamiliar and scary to the public. In addition, some intersections have different names, and researchers may miss some important information about other uses of the design because of their lack of awareness of the alternative names.

For the factors influencing the use of unconventional intersection and interchange designs, respondents gave their choices as having a champion promote the design, educating engineers, politicians, or the public on the benefits of the designs, and proof of the benefits offered by the designs. The following figure part A shows the results that the proof of the benefits is the most important factor. Part B shows that the state department of transportation is the most required agency to support the implementation of unconventional intersections.

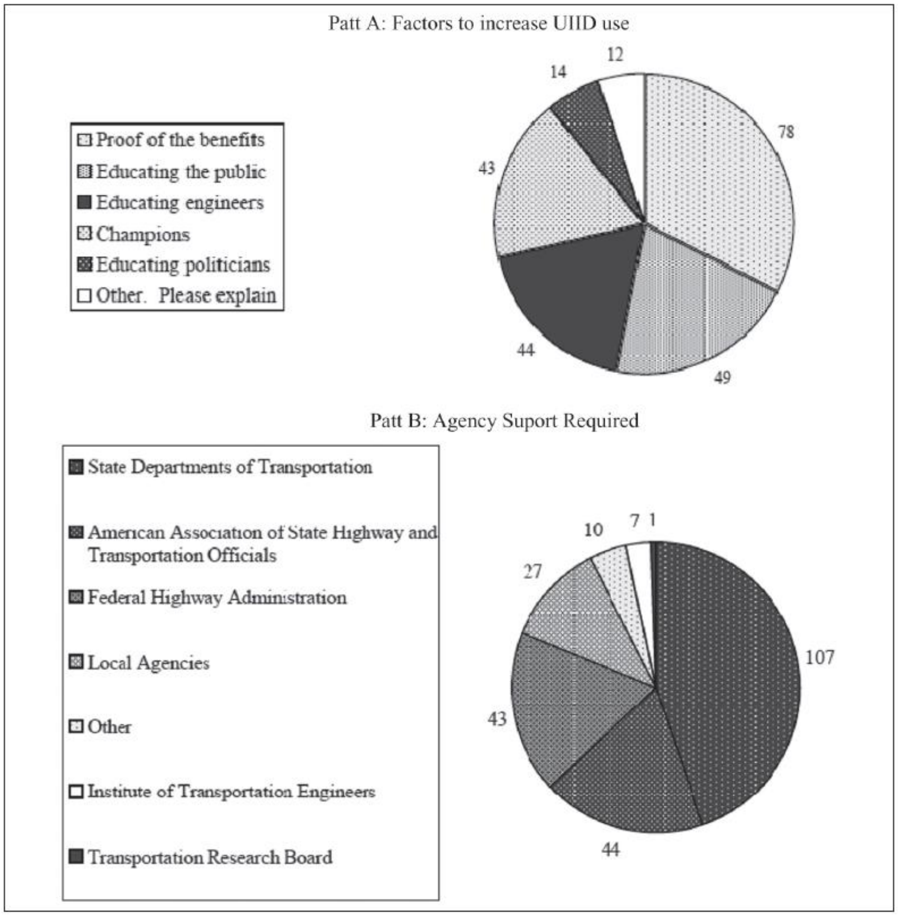


Figure 2-17: Factors Influencing Unconventional Design Use

2.8 Others

2.8.1 Comparison of Intersection Construction Costs

Construction costs also need to be considered when implementing an intersection design. Different researchers have estimated the cost of construction of a CFI intersection differently. Friedman believed the construction costs associated with CFI intersections might be 2 or 3 times the cost of standard intersection design because of the increased right-of-way requirements and the need for additional, coordinated signal controllers (1992). Similarly, a study conducted by KLD Associates and Francisco Mier concluded that the cost of a CFI intersection is 3 times the cost of a conventional intersection. In their research, Berkowitz et al. listed that the cost of a CFI intersection was \$0.638 million in Mexico, \$6 million based in Brooklyn, NY, and \$4.4 million in Baton Rouge, LA (1997). COMPASS of Southwest Idaho (2008) stated that the total cost of a CFI intersection in Salt Lake City was \$8.55 million, including construction costs of \$4 million, construction engineering costs of \$0.3 million, a preliminary engineering cost of \$1 million, and a right-of-way cost of \$3.25 million.

In his research, Hildebrand (2007) compared the construction cost of five innovative intersections with a conventional intersection as listed in the following table. As indicated in the table, the cost of building one CFI intersection is a 49.5% increase over the cost of building a conventional intersection and is the highest among all of the alternatives compared. The cost of the CFI intersection is significantly higher than the conventional solution because of the addition of eight ramps required to serve left and right turning vehicles.

Table 2-4: Comparison of Costs between Alternatives

Intersection Design	Cost Increase (%)
Bowtie	12.3
CFI	49.5
Jughandle	-7.3
Median U-turn	34.1
Superstreet	23.5

However, if traffic conditions are severe, or if there is consideration of such techniques as grade separation, then the CFI design might be the optimal solution and have the overwhelming cost advantage (Goldblatt, 1994).

2.8.2 Driver Acceptance

LaDOTA (2007) conducted a "Driver Acceptance Survey" for the CFI Improvement at Airline Highway and Siegen Lane/Sherwood Forest Boulevard in Baton Rouge, Louisiana. The survey was distributed to 3,300 drivers at the CFI intersection for one year after the opening. Results showed that most of the drivers were satisfied with the operation of the CFI intersection since its implementation. The major findings are listed as follows:

- 87% of drivers thought the traffic congestion was better;
- 68% of drivers felt the traffic safety was better;
- 74% of drivers proved a decreased travel time; and
- 92% of drivers were satisfied with the operation of the CFI.

A business survey was also conducted in this study, and more than 60 adjacent businesses were interviewed to determine if they had perceived any changes to their business and the positive or negative effects on their business. The results showed that the installation of the CFI intersection did not affect their business and that, for those businesses that did feel the changes, most perceived positive changes. The authors also got 11 positive feedbacks on the reduction of travel times, increased safety, and similar or better access to surrounding parcels.

2.9 Summary

The DLT intersection is a type of indirect left turn treatment that can allow left turn movement and oncoming through movement travel through the intersection at the same time. It reaches its best operational performance when there are a high left turn and total traffic volumes. A few federal or state agencies provide some suggestions on DLT design. However, comprehensive design guidelines are still lacking, and more research is needed to supplement the existing materials. Therefore, in this research, one critical design element, left turn crossover distance, was investigated and an appropriate distance was recommended.

From the literature reviewed, it is evident that most of the previous studies focused on the operational performance of DLT intersections. It can be no doubt that DLT intersections can improve intersection capacity and reduce delay and travel time when appropriately implemented. However, very few studies have evaluated the safety impacts of the DLT design. For the research on safety analysis, they were based on very-limited, historical crash data. To fill this gap, in this study, two DLT intersections in Texas were selected to conduct a comprehensive safety assessment. Eight-years of crash data, which included years before and after the implementation of these two DLT intersections, were collected for the TxDOT Crash Report Information System (CRIS).

Chapter 3. Existing Studies and Design Guidelines for Median U-Turn

3.1 Concepts, Definitions and Applicability

A Median U-turn (MUT) Intersection is also known as a Median U-turn Crossover and sometimes referred to as a boulevard turnaround, a Michigan loon, or a Thru-Turn Intersection. According to *Median U-turn Informational Guide* (FHWA, 2014), MUT refers to any intersection that replaces direct left turns at an intersection with indirect left turns using a U-turn movement in a wide median. The MUT design eliminates left turns on both of the intersecting streets and thus reduces the number of conflict points and the traffic signal phases at the main crossing intersection, thereby improving the intersection operations and safety. Figure 3-1 illustrates the footprint for a MUT intersection compared to a conventional intersection.

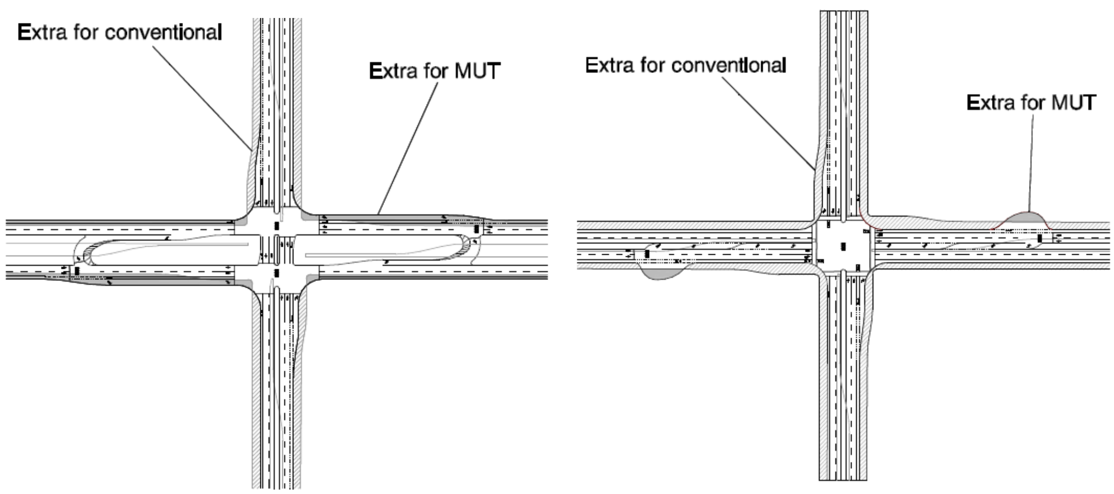


Figure 3-1: Footprint Comparison of A MUT Intersection (Left) Versus A Conventional Intersection (Right)
Source: Median U-turn Informational Guide, FHWA (2014)

The MUT design was first implemented by the Michigan Department of Transportation (MDOT) at the intersection of 8 Mile Road (M-102) and Livernois Avenue in Detroit in the early 1960s. There was a dramatic increase in traffic flow and a decrease in accidents after its installation. (*Klinefelter and Quinn, 2015*). Today, MUT intersections are widely used not only in Michigan but also in other states across the United States. Partial implementations or designs with similar concepts have appeared in Florida, Maryland, New Mexico, and New Orleans. Hummer and Reid (1999) recommended that agencies consider the median U-turn alternative for junctions on high design arterials where relatively high through volumes conflict with moderate or low left-turn volumes, regardless of the cross-street through volumes. As of 2017, more than 700 MUT intersections have been deployed throughout the state (*Sweeney and Kate,* 2017). Figure 3-2 marks all states implemented or planned MUT intersections.

Figure 3-2: Locations of MUT Intersections

Figure 3-3 shows the scheme of a MUT intersection. Although the MUT design is typically a corridor treatment, it can be used at isolated intersections to alleviate specific traffic operational and safety problems. For the best practice, it is recommended that the application of the MUT intersection along the corridor should not be mixed with other indirect left-turn treatments or conventional left-turn treatments to meet drivers' expectancy (Levinson et al., 2000).

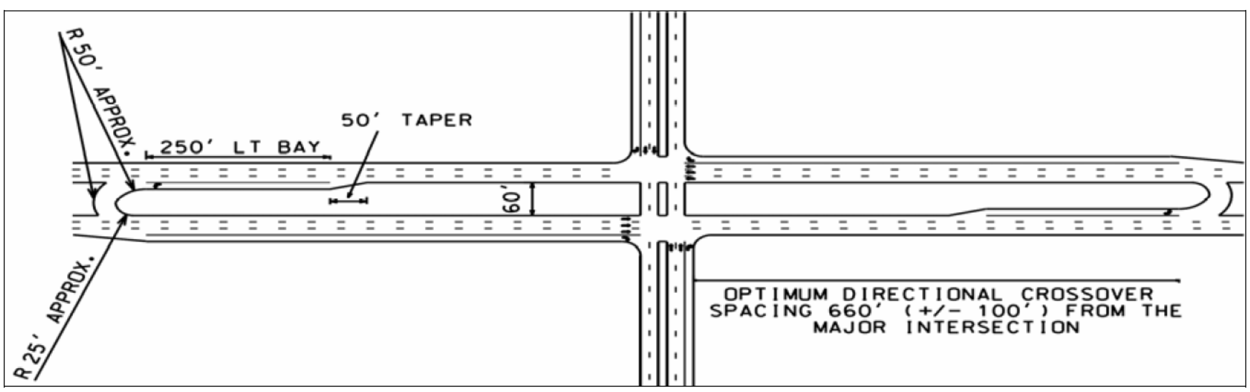


Figure 3-3: Typical Scheme of An MUT Intersection
Source: Synthesis of the Median U-Turn Intersection Treatment, FHWA-HRT-07-033

At a MUT intersection, the major street has the wide median, and the minor street does not. Vehicles on the major street that would typically turn left at a signalized intersection with the crossing street are directed through the main crossing intersection to make a U-turn movement at a downstream directional crossover and proceed back to the main crossing intersection, which is in the opposite direction from which the vehicle came. The vehicles then turn right onto the minor street. Directional crossovers are one-way median opening facilitating U-turns. Similarly, vehicles on the minor road that would typically turn left at a signalized intersection on the major street are directed to turn right to the major road and make a U-turn movement at the same directional crossover 500 to 600 feet downstream and then proceed through the main crossing street (FHWA-SA-14-069, 2014). Figure 3-4 illustrates the major street movements and minor street movements at an MUT intersection.

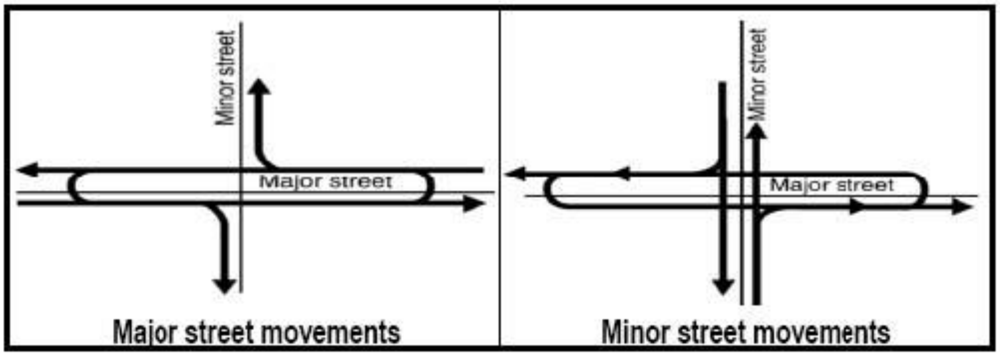


Figure 3-4: **Vehicular Movements at An MUT Intersection**
Source: Signalized Intersections Information Guide, FHWA-HRT-04-091

The signals at the main crossing intersection permit only through and right-turn movement from both the major and minor streets. The signal at the U-turn crossovers controls the through traffic on the major street and the U-turn crossovers. The two signals are coordinated to minimize stops and delays for both through and turning traffic. The following two figures are examples of an MUT intersection with two signals at the main intersection and one signal at the main intersection.

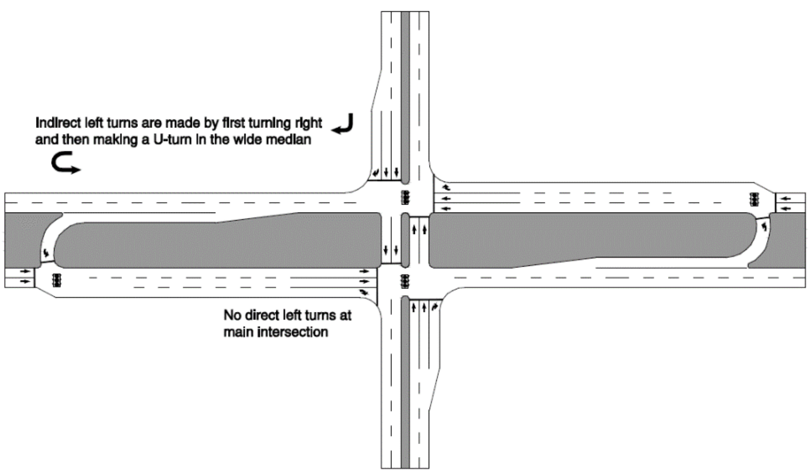


Figure 3-5: Example of An MUT Intersection with Two Signals in The Main Intersection

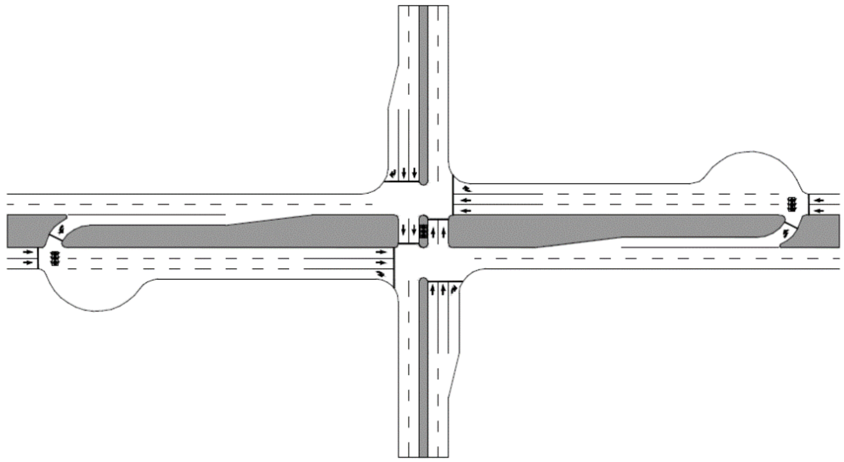


Figure 3-6: Example of An MUT Intersection with One Signal in The Main Intersection
Source: Median U-Turn Informational Guide, FHWA-SA-14-069

The MUT intersection design is applicable under only certain conditions. Compared with a conventional intersection, the MUT intersection can process higher volumes on the major road, especially through volumes. In addition, the MUT intersection is typically a corridor treatment. Candidate corridors for this design are high-speed, median-divided highways with some two-way crossovers that have moderate major road and minor road left-turn demands. Fewer conflicting travel streams, two-phase signals, short cycles, and the chance for good progression in both directions are all possible (FHWA-HRT-09-060 Report, 2010).

According to the **FHWA-HRT-09-060 Report (2010),** an MUT intersection may be applicable to the following situations:

- If there are heavy through volumes and moderate left-turn volumes on all approaches;
- If the left-turn approach volume/total approach volume is less than 0.2 on all intersection approaches;
- If the left-turn volume is less than 400 veh/lane, and opposing through volume is greater than 700 veh/lane on two opposing intersection approaches;
- If the v/c is greater than 0.8 on two opposing intersection approaches;
- If the cross product of the left-turn and the opposing through vehicles is greater than 150,000 on two opposing intersection approaches;or
- If the intersection is heavily congested with many signal phase failures for through traffic.

The following table 3-1 better explains an overview of the primary advantages and disadvantages of MUT intersections for users, policy makers, designers, and planners.

Table 3-1: Summary of MUT Advantages and Disadvantages

Advantages	Disadvantages
Non-Motorized Users	
• Pedestrians and bicyclists must cross only one direction of travel at a time • Pedestrians and bicyclists cross fewer lanes of travel (shorter distance, less exposure) • Because of the two-phase signal operations, greater service time can be given to pedestrians and bicyclists • Bicyclists have center refuge (room for bicycle box) in making two-stage left turns	• Pedestrians crossing the major street may have to cross in two stages, potentially increasing crossing time • Because all left turns must also turn right, greater right-turn/pedestrian exposure • Bicyclists turning left must use crosswalks as a pedestrian or mix with vehicle traffic to access MUT as a vehicle would
Safety	
• Fewer overall conflict points and no left-turn conflicts • Lower delay and fewer stops on major street could reduce rear-end crash rates	• Drivers may be less familiar with intersection • Potential for driver disregard of the left-turn prohibitions
Operations	
• Reduced delay and fewer stops for through movements on the major street • Shorter cycle lengths and increased green time for through movements decreases intersection delay, congestion, and queuing	• Potential increase in delay, travel distance, and stops for left-turning traffic • Slightly longer clearances phases needed to clear main crossing intersection
Access Management	
• Eliminates left turns out of driveways along corridor • Consolidates access to U-turn crossover intersections	• Some drivers must pass through intersections twice • Access may be restricted between main crossing and U-turn intersections
Right of Way	
• If planned properly, establishes final limits of ROW as future lanes can be added in the median without outside widening	• Requires substantially more ROW along major street • Required right of way not typically available in urban and suburban areas or at great cost
Aesthetics	
• Median provides opportunity for landscaping and other aesthetic treatments	• Wide distances between sides of road make urban feel difficult

Source: Median U-Turn Informational Guide, FHWA-SA-14-069

3.2 Existing Design Guidelines

At an MUT intersection, the design of the main intersection is similar to the design of a conventional intersection. The main intersection is designed for larger volumes of right-turn movements than a conventional intersection serving the same total volumes, since the left-turning vehicles become right-turning vehicles. Thus, the right-turn bays of the intersection must have sufficient width and length to accommodate the volume of turning vehicles. Depending on the right-turn volume, dual right-turn lanes or an exclusive right-turn lane and an adjacent shared-use through and right-turn lane may be considered.

With regard to the MUT design, there are a series of design elements to be determined based on the geometric, environmental, and traffic conditions.

3.2.1 Spacing between the main intersection and the U-turn crossover

The spacing refers to the distance between the main intersection and the U-turn crossover. This distance is critical for the efficient operation of the roadway. An appropriate distance from the main intersection to the U-turn crossover is a trade-off between providing a sufficient U-turn storage bay length (to minimize spillback potential) and keeping the left-turning path length short (to minimize travel time) (Reid, 2004). The following is a list of the guidelines for designing appropriate spacing.

<u>*AASHTO Green Book* (2011)</u>

- The crossover should be located downstream of the intersection, preferably midblock between adjacent crossroad intersections at locations where the U-turn crossovers were designed specifically to eliminate direct left turns at a major intersection.
- Recommends a distance 400 to 600 ft for the minimum spacing between the median crossover and the MUT intersection.
- Where the minimum required distance to the U-turn crossover plus the distance required for the next downstream left-turn lane are greater than the distance between the two adjacent intersections, the *AASHTO Green Book* recommends that the U-turn crossover be located 50 to 100 ft in advance on the next downstream left-turn lane.

<u>*Geometric Design Guide 670 (Michigan Department of Transportation, 1993)*</u>

- Recommends a distance of 660 ft (201 m) (+/-100 ft (30.5 m)) for the median crossover from the MUT intersection. The distances recommended by the MDOT were established to accommodate drivers desiring to turn left from the crossroad. The longer distance facilitates the completion of the U-turn maneuver at the median crossover and subsequent right turn maneuver at the intersection of the major road and cross street for a 45 mph (72 km/hour) posted speed limit on the major road.

<u>*The Access Management Manual (TxDOT, 2011)*</u>

- Recommends an access spacing of 660 ft (201 m) on minor arterials and 1,320 ft (402.3 m) on principal arterials between consecutive directional median openings on divided highways.

<u>*Median U-Turn Informational Guide (FHWA-SA-14-069, 2014)*</u>

- Recommends a distance of 500 to 600 feet for the median crossover from the MUT intersection.

The report also describes each key distance that should be considered:

- The distance for left turning vehicles (both from the major and minor road) passing through the main intersection to the U-turn crossover. The distance between the main intersection and the U-turn crossover should include the distance required for deceleration and storage for the left turning vehicles both from the major crossroad and from the minor road that are about to make a right turn onto the major crossroad.

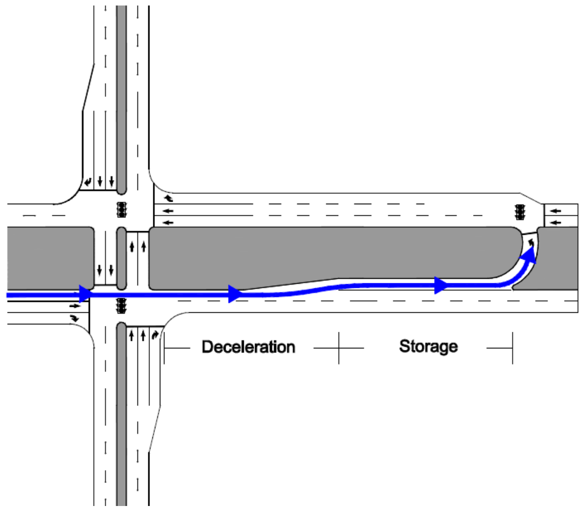


Figure 3-7: Spacing Consideration for A Major Street Left Turn Movement

- The distance for right-turning vehicles (with a destination to the left on the major street) from the minor crossroad to move from the right side of the major crossroad after completing their right turn to the left side prior to the deceleration lane. While traffic laws vary among states, in some states right-turning vehicles are mandated to enter the rightmost lane available on the crossroad onto which they are turning.

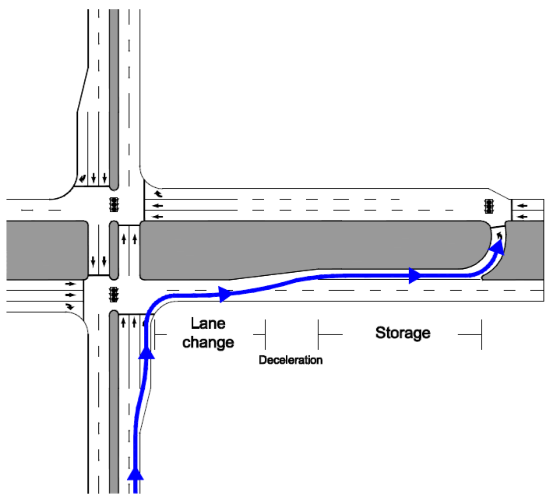


Figure 3-8: Spacing Consideration for Minor Street Left Turn Movement

- The distance for vehicles to decelerate on the major crossroad plus storage for right turning vehicles from the major crossroad and for those from the opposing left-turning vehicles on the major crossroad that used the U-turn crossover.

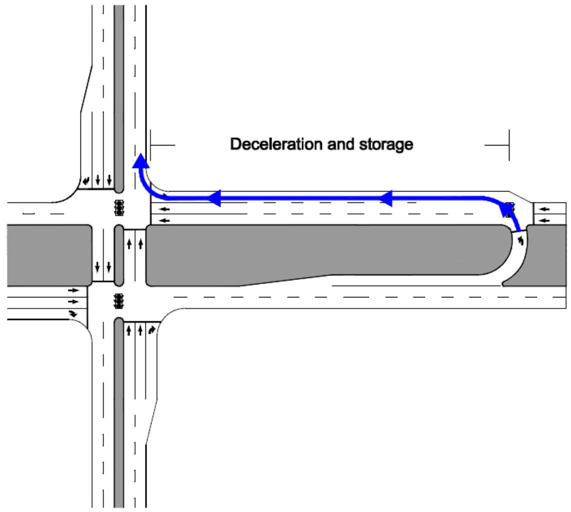


Figure 3-9: Spacing Consideration for A Right Turn

3.2.2 Median Width

Desired median width depends on the design vehicle (specifically the vehicle U-turn radii requirements) and the number of lanes on the arterial (Reid, 2004). A wide median is often needed to facilitate the median U-turn movement.

AASHTO Green Book (2011)

- The *AASHTO Green Book* provides guidance on minimum median widths for various design vehicles when designing for U-turns. Table 3-2 shows the minimum median width required for seven different types of design vehicles turning from the inside lane of a four-lane divided street to either the inside lane in the opposing direction, the outside lane in the opposing direction, or the outside shoulder in the opposing direction.

Table 3-2: AASHTO- Minimum Median Widths for U-Turn Crossovers

U.S. Customary							
	M—Minimum Width of Median (m) for Design Vehicle						
	P	WB-40	SU-30	BUS	SU-40	WB-62	WB-67
	Length of Design Vehicle (ft)						
Type of Maneuver	19	50	30	40	40	63	68
Inner Lane to Inner Lane	30	61	63	63	76	69	69
Inner Lane to Outer Lane	18	49	51	51	64	57	57
Inner Lane to Shoulder	8	39	41	41	54	47	47

It can be concluded from the above table that, depending on the design vehicle and the resultant turning location when the U-turn is completed, median widths can range from a minimum of 8 feet (passenger car) to 69 feet (WB-67). If the median width is not wide enough to accommodate the various design vehicles, sometimes loons can be designed to provide additional width to complete the U-turn. Since most of the U-turning vehicles will make a right turn at the main crossing intersection after completing the U-turn, most of the U-turning traffic will need to be in the rightmost lane before the main crossing intersection. As a result, the optimal U-turn design will use the rightmost lane of the opposing through traffic as the receiving lane for U-turns where possible.

Geometric Design Guide 670 (MDOT, 1993)

The table gives the minimum median widths required for U-turns from the major road as suggested by the MDOT.

Table 3-3: Minimum Median Widths M for U-Turn Maneuvers Suggested by the MDOT

Type of Maneuver	P	SU	BUS	WB-50	WB-60
	Length of Design Vehicle, m (ft)				
	5.8 (19)	9.1 (30)	12.2 (40)	16.8 (55)	21.3 (70)
Left Lane to Inner Lane	13.4 (44)	23.2 (76)	24.4 (80)	25 (82)	25 (82)
Left Lane to 2nd Lane	9.8 (32)	19.5 (64)	20.7 (68)	21.3 (70)	21.3 (70)
Left Lane to 3rd Lane	6.7 (22)	16.5 (54)	17.7 (58)	18.3 (60)	18.3 (60)

Where:
P = passenger car
SU = Single-unit truck
WB-50 = Semitruck medium size
WB-60 = Semitruck large size

Signalized Intersections: Informational Guide (FHWA-HRT-04-091, 2004)

The median on a four-lane arterial should have a width of 60 ft. to accommodate a tractor-semitrailer combination of trucks as the design vehicle.

3.2.3 U-turn Crossovers

Median U-turn crossovers are designed as the secondary intersections in MUT intersections. U-turn crossovers allow a vehicle to make a U-turn and do not allow for through movement from a side street or driveway. The placement of the crossover is critical for the efficient operation of the roadway. A U-turn crossover is usually located on the major crossroad to accommodate indirect left turns from the major and minor crossroads.

There are two types of median crossovers, the bidirectional crossover, and the directional crossover, as shown in the following figure.

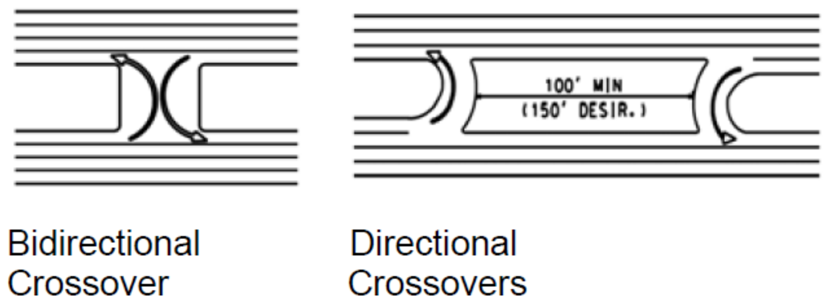


Figure 3-10: Directional and Bidirectional Crossovers

Bidirectional crossover

A bidirectional crossover is an opening in the median only for vehicles to make U-turns, and vehicles may enter from either direction. Usually, deceleration or storage lanes are not installed in bidirectional crossovers. If no deceleration/storage lanes are installed in a bidirectional median crossover, only one or two vehicles can be stored. When the turning volumes increase, an interlocking effect is created. The vehicles have to queue to enter the crossover and make U-turns until the vehicles in the crossover move out of the opening and merge into the travel lanes.

Directional crossover

In contrast, a directional crossover is a one-way crossover with a deceleration/storage lane. The directional crossover allows vehicles traveling in one direction of the road to enter the crossover, and thus vehicles should never experience the interlocking effect at medians with a bidirectional crossover at a properly designed directional crossover.

Studies show that one-way (directional) median crossovers provide better traffic operation and safety performance than two-way (bidirectional) crossovers (Scheuer and Kunde, 1996; Castronovo et al., 1995; Taylor et al., 2001).

The MDOT has developed design guidelines for directional median crossovers. Figure 3-11 illustrates the dimensions used for directional crossovers on a highway.

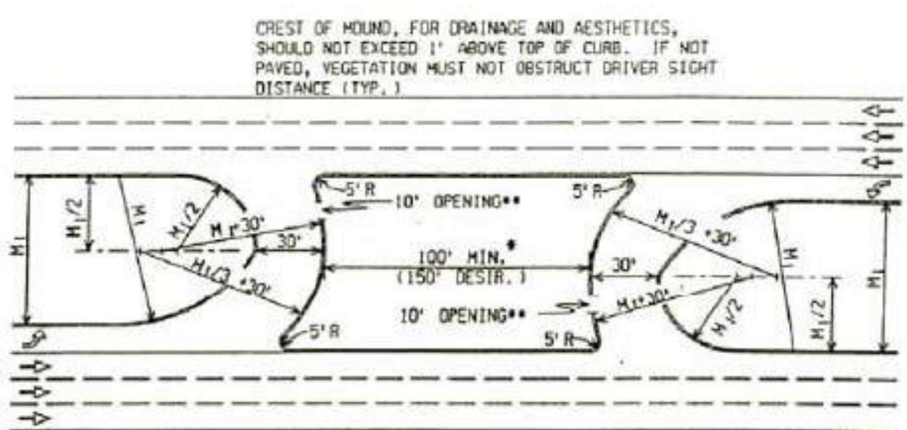


Figure 3-11: Directional Crossover Design on Highway
Source: Geometric Design Guide 670 by the MDOT (1993)

As indicated in Figure 3-11, if a typical road with three lanes for both inbound and outbound directions is considered, the median opening length is 30 ft for each direction. If, for example, the median width is M1, then the outer radius of the median opening is $M_1/3$ plus 30 ft. The inner radius of the median opening is $M_1/2$. The minimum length for the median refuge island is 100 ft with 10 ft openings on the upper left corner and lower right corner. The radius for the four corners of the median refuge island is 5 ft each.

In Michigan, drivers of passenger vehicles get used to queuing side-by-side in a 30-ft wide crossover and treat it as if it had two lanes. For large trucks and other heavy vehicles, the entire width of the crossover might be used. The MDOT uses striped two-lane crossovers (with two lanes of storage leading up to the crossover) in some places. These crossovers are typically 36 ft wide.

3.3 Operational Performance

In an MUT intersection, left-turn movements are made indirectly. The MUT intersection increases traffic operational benefits by reducing the number of intersection signal phases and shortening overall signal cycle lengths. Extensive research has been conducted to examine the operational performance of the MUT design. The representative research will be introduced.

Ibrahim H. Hashim et. al (2017)

This study evaluated the operational performance of the median U-turn design by comparing it with conventional three-leg and signalized three-leg intersections. The environmental performance was also analyzed. The measure of effectiveness used was average delay, fuel consumption and air emissions. Microscopic simulation model VISSIM was used to analyze the three designs under balanced and unbalanced flow conditions. Traffic demand data was generated hypothetically to intimate traffic volumes from low to high for peak and off-peak traffic. The percentage of right-turn traffic was designed as 10% for all scenarios, and two different levels of left turn volume were simulated with 20% and 30% of the approaching volumes. The results showed that, under balanced flow conditions, the conventional signalized three-leg intersection had higher delays than median U-turn and conventional three-leg intersections. The median U-turn had a slightly lower delay than a conventional three-leg intersection up to a traffic volume of 1,250 veh/hour but exhibited higher delays than the three-leg intersection. It can be concluded that, in most cases, the conventional three-leg intersection performed better than or the same as the median U-turn design.

In terms of the impact of left-turn percentage on the performance of the median U-turn design, the author analyzed the impact of left-turn percentage on the average delay of all vehicles at all movements for median U-turn design under balanced scenarios. The results showed that the higher left-turn traffic volumes had higher average delays. Increasing the left-turn percentage has the minor impact on average delay at low traffic volumes below 1,100 veh/hr. The impact became more significant above this volume.

To determine the impact of the percentage of heavy vehicles on the performance of median U–turn design, the authors analyzed the relationship between approach volume and average delay of all vehicles for different balanced volumes with a 20% left-turn. The results showed that, at low volumes, the increasing percentage of the heavy vehicles had a minor impact on average delay at low traffic volumes below 800 veh/hr. Above 800 veh/hr, the 5% heavy vehicle has a slightly higher average delay.

In unbalanced flow conditions, the authors analyzed the average delay of all vehicles on three-legs with a median U-turn intersection with unbalanced volumes. It can be concluded that the intersection delay increased with the increase of main and/or crossroad volumes.

Joe G. Bared and Evangelos I. Kaisar (2002)

This paper conducted a comparison study of the MUT intersection design and the conventional intersection with single and dual left-turn lanes. CORSIM was employed to simulate the geometric designs with different traffic volumes. The results indicated:

- Median U-turn had considerable savings on the network travel time at high volumes compared with a direct single left turn lane at 10% or 20% left-turn volumes;
- The average proportion of vehicles that stops at the network studied is consistently lower for the U-turn design;
- The derived average travel times for the U-turning traffic is about 20 to 30 s/veh higher than the direct left-turn;
- Derived stopping time is also higher for the U-turn intersection by about 10 to 18 s/veh;
- Vehicles traveling at the main intersection and in the left-turn bay downstream of a U-turn tend to stop more than in the other intersection designed.

Liu, P. et. al. (2007)

This paper evaluated the operational effects of using the right turn/U-turn maneuver to replace a direct left turn from a driveway. In the research, direct left turn, right turn followed by U-turns (RTUT) at median openings, and right-turns followed by U-turns at signalized intersections are studied. Field data were collected from 34 roadway segments in central Florida. The measures of effectiveness used were delay and travel time. Different left-turn alternatives were evaluated under different traffic volumes and through traffic volumes on the major road. A binary logit model was developed to estimate how many drivers would like to make a RTUT instead of a DLT under different traffic and roadway geometric conditions. Detailed results are as follows:

- Compared with the vehicles that are making direct left-turns, less delay is found for the vehicles that make right-turns followed by median U-turns before the signalized main intersection. However, when U-turns are made by right-turns followed by U-turns at the downstream signalized intersection, longer delay time was found than those that were making direct left-turns.
- When making right-turns followed by U-turns, the distance between a driveway and the downstream U-turn location significantly impacted the running time drivers spent at a weaving section. The running time increased with the separation distance and decreases with the major street speed limit.

- The percentage of drivers selecting RTUT increased with the upstream through traffic volume, left-turn volume from the major road into the driveway, and the total left-turn traffic demand at a driveway. More drivers preferred RTUT at the median opening rather than at signalized intersections.
- The vehicles making RTUT have a similar travel time with those making direct left-turns at a driveway, if the separation distance between the driveway and the downstream U-turn location is reasonable.

Yang and Zhou (2004)

This paper evaluated the operational performance of the direct left turn and right run plus U-turn (RT+UT) from driveways under different levels of traffic volumes by using CORSIM software. Six sites were selected to do the field data collection, and the medians at those sites were all full openings, which allow vehicles at the driveway to make a direct left turn maneuver. Then site-specific simulation models were developed by CORSIM, and, finally, each model was calibrated based on the field data. Simulation results indicated that, at a lower level of through traffic, the direct left-turn has a lower travel time and delay than the RT+UT on the major road. However, with the increase of the through-traffic volume on the major road, both delay and the travel time of the direct left turn were higher than those of the Right Turn plus U-Turn (RTUT).

Elesawey M. and Sayed T (2011)

This study compared the operational performance of the unconventional median U-Turn to the baseline conventional four-legged and conventional MUT intersections. VISSIM was used to simulate the three designs under a wide range of balanced and unbalanced volume scenarios. The results showed that the capacity of conventional MUT intersections with signalized and unsignalized crossovers was about 10% and 8% higher than that of the conventional intersection, respectively. In addition, the performance of the unconventional MUT intersection was shown to be poor in comparison to the other two designs. The overall capacity of the unconventional MUT intersection was lower than that of a conventional four-leg intersection by about 27%.

Taha M. A. and Abdelfatah A.S (2015)

This study evaluated the impact of replacing a direct left-turn with a right-turn followed by a U-turn (RTUT) or a U-turn followed by a right-turn (UTRT). Traffic signal evaluation and simulation tools, Synchro and VISSIM, were employed to calculate the optimized signal timings and to evaluate intersection performance for each left-turn control type. The results indicated that unconventional left-turn control types have less delay compared to the direct left-turn. In addition, the U-turn followed by a right-turn (UTRT) control type has the lowest travel time among all left-turn control types. Finally, unconventional left-turn control types have higher vehicle kilometers traveled (VKT) compared to the direct left-turn control types.

3.4 Safety Performance

Compared with the conventional four-leg signalized intersection, the MUT intersection reduces vehicular intersection conflict points from 32 to 16 by restricting direct left turns at the main crossing intersection. The following two figures show the conflict points at a conventional intersection and at a MUT intersection, respectively.

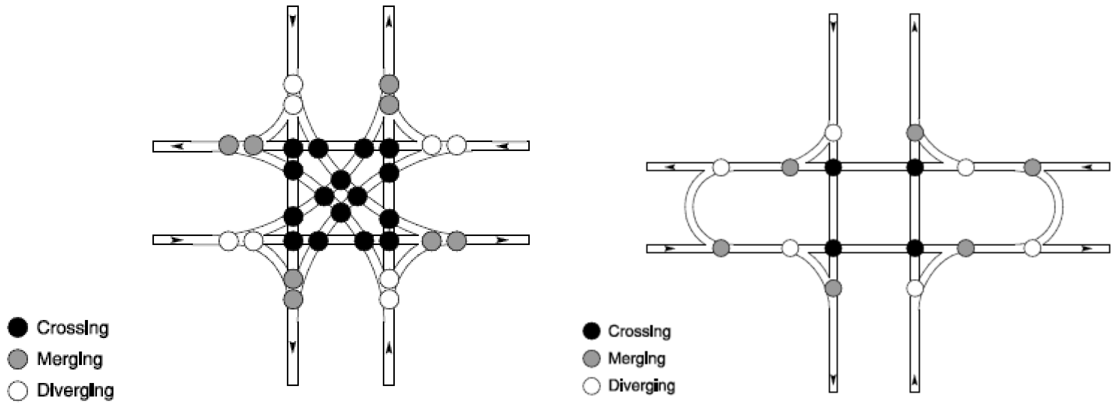


Figure 3-12: Vehicle-Vehicle Conflict Points at A Conventional Intersection (Left) and A MUT Intersection (Right)

Removing direct left turns also reduces some of the conflict points that can cause the severe type of crashes, namely the left-through angle ("T-bone") collision. This type of collision ranks second behind head-on collisions for the risk of causing severe injury. Compared to a conventional intersection, the MUT intersection reduces crossing conflict points by 75%. In addition, merging conflict points are reduced from 8 to 6, and diverging conflict points are reduced from 8 to 6.

Table 3-4: Comparison of Conflict Points for MUT and Conventional Four-Legged Intersections

Conflict Type	Four-Legged Signalized Intersection	MUT Intersection
Merging/diverging	16	12
Crossing (left turn)	12	0
Crossing (angle)	4	4
Total	32	16

As displayed on the official website of the Michigan Department of Transportation, on roadways where crossovers and Michigan Lefts (refers to MUT intersections) have been added, crashes have been reduced 30% to 60% overall. The greatest reductions are in rear-end and head-on crashes during left-turns (60% to 90% reduction) and right-angle crashes (60% reduction). Slight increases were noted for two other crash types: non-left-turn rear-end crashes increased by approximately 25%, and fixed-object crashes increased by approximately 20%.

Jian John Lu and Sunanda Dissanayake (2002)

The safety performance of two left turning alternatives, direct left turns and Right Turns Followed by U-turns (RTUT) were evaluated by conducting traffic conflict analysis using field data collected at seven sites by video cameras. Two types of conflict rates, conflicts per hour and conflicts per thousand involved vehicles, were used for the safety comparison.

In this paper, the investigation of conflicts per hour considered three-time periods: non-peak, peak, and total time. The analysis results indicated that direct left turns experienced 29%, 76%, and 51% more traffic conflicts as compared to RTUT during non-peak, peak, and total time periods respectively. Moreover, the research group calculated conflicts per thousand involved vehicles to identify the effects of volume on the conflicts rates. The data for conflicts per thousand involved vehicles indicated that most of the sites observed had experienced lower conflict rates for RTUT movements. The average rate of conflict per thousand of direct left turns was 64% more than the RTUT.

Maki, R.E. (1996)

To evaluate the safety benefits of the MUT intersection, Maki conducted a before-after study from 1990 to 1995 at locations where replacing conventional signalized intersections with the MUT intersection for a total length of 0.43 miles of Grand River Avenue in Detroit, Michigan. Results showed that the average number of accidents experienced a 61% reduction from 32 to 13 accidents per year. Angle accidents and injury accidents were prominently reduced by 96% and 75% respectively. Moreover, sideswipes decreased by 61%, while rear-end accidents decreased by 17%.

Gluck. et. al. (1999)

In the NCHRP report 420, the safety impacts were discussed for implementing the U-turn as an alternative to direct left turns. Accident rates data in Florida and Michigan were collected. The comparison results are shown in Table 3-5. It can be seen that the accident rate reduced 22% when direct left turns were eliminated from driveways. The accident rate reduced 50% when Two-Way Left-Turn Lanes (TWLTL) were replaced by directional crossovers and wide medians. The directional MUT intersection has a 14% higher accident rate in comparison to the bidirectional crossovers at locations where there were no traffic signals. However, the researchers point out that, as the density of traffic signals increases, divided highways with exclusive directional crossovers had a 50% lower accident rate compared with sections with bidirectional crossovers.

Table 3-5: Accident Rate Differences- U-Turns as Alternate to Direct Left Turns

Location	Change	Difference in Accident Rate
1. US-1, Florida	Driveway Left-Turns Replaced by Right –turn/U-turn	-22%
2. Michigan U	Directional Crossover Versus Bi-Directional Crossover (Unsignalized with Opposing Traffic)	+14%
3. Michigan U	Directional Crossover Versus Bi-Directional Crossover (Signalized with Opposing Traffic)	-35% to 50%
4. Michigan U	Directional Crossover Versus TWLTL	-50%

NCHRP Report 524 (2005)

In this report, the safety performance of typical median opening designs was documented, and guidelines for the use, location, and design of un-signalized median openings were developed. The research results indicated that access management strategies that increase U-turn volumes at un-signalized median openings can be used safely and effectively. Analysis of accident data found that accidents related to U-turn and left-turn maneuvers at un-signalized median openings do not occur frequently. In urban arterial corridors, un-signalized median openings had an average of 0.41 U-turn-plus-left-turn accidents per median opening per year. In rural arterial corridors, un-signalized median openings experienced an average of 0.20 U-turn-plus-left-turn accidents per median opening per year. On the basis of these limited collision frequencies, the authors concluded that there is no indication that U turns at un-signalized median openings are a general safety concern.

Castronovo et al. (1998)

This study analyzed the MUT intersection's safety benefits versus conventional intersections as a function of traffic signal density using data from 123 segments of boulevards totaling 226 miles. The results indicated that, as traffic signal density increased, the MUT intersections had increasingly lower crash rates (measured in crashes per 100 million vehicle miles). For typical suburban conditions, with signal densities of one or more signals per 1 mi, the crash rate for MUT intersections was about one half the rate for conventional intersections. For typical rural conditions, with signal densities of one or less signal per 1 mi, the reduction in crashes for MUT intersections was 36% when compared to conventional intersections.

3.5 Driver Confusion and Perception

Esawey and Sayed (2012) attached importance to driver confusion and perception analysis that functions as a critical indication of the safety level associated with a specific intersection design. The authors gathered information about driver feedback and signing/marking schemes at one of the unconventional arterial intersection designs (UAIDS) for further illustration. The authors also concluded that the unusual layout of UAIDS might have some operational impacts due to the expected changes in driver behavior.

Jagannathan (2007) summarized the importance of driver confusion and expectancy in MUT design. He emphasized that positive guidance communicated through additional signs and pavement markings at MUT sites may be beneficial in reducing driver confusion and enhancing traffic safety; and with respect to driver expectancy, the MUT intersections should not be mixed with other indirect and direct left-turn strategies on corridor level implementations.

3.6 Pedestrian Accommodations

As the FHWA report (Hughes, et. Al, 2010) suggests, in general, pedestrians should benefit from the simpler two-phase signal timing and the fewer conflicting traffic streams than at a conventional intersection. The crosswalks, as displayed in the figure below, indicate a possible one-stage crossing, if the distance is not too long, and if the necessary green time does not adversely affect traffic flow on the major road. A two-stage crossing of the major street will be provided, if these conditions are not met. In this case, a pedestrian may cross one direction of the major street during one signal phase and the other direction during a second signal phase. An expected delay exists between the two phases. To accommodate pedestrians better, if pedestrian signals and push-button controllers are provided, the devices need to be installed in the median and on the sides of the road.

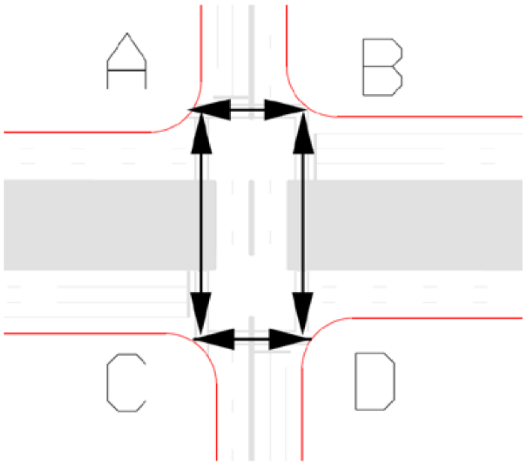


Figure 3-13: Pedestrian Movements at An MUT Intersection

The report further states that the amount of delay to a pedestrian due to the two-stage crossing is relatively small, since there are only two signal phases, and the cycle lengths are short. As it is claimed in another FHWA report (Rodegerdts, et. Al, 2004), median width as a critical factor contributes to pedestrian accommodation in the MUT design. The authors summarize issues for providing median treatments for intersection designs, including:

- Overly wide medians may require all pedestrians to cross in two stages, significantly increasing pedestrian delay; and
- Narrow medians may require long one-stage crossings.

3.7 Summary

The Median U-turn (MUT) intersection, also known as the Michigan U-turn intersection, is a design replacing direct left turns at an intersection with indirect left turns using a U-turn movement in a wide median. The MUT design eliminates left turns on both of the intersecting streets, thereby reduces the number of conflict points and the traffic signal phases at the main crossing intersection, and thus improves the intersection operations and safety. The MUT intersection has a relatively long history in the United States compared to two other selected innovative intersections. Therefore, many researches have been conducted to understand fully the performance of the MUT intersection. It has been proved that the MUT intersection can improve intersection capacity, reduce traffic delay and the number of crashes.

Chapter 4. Existing Studies and Design Guidelines for Restricted Crossing U-Turn

4.1 Concepts, Definitions and Applicability

The restricted crossing U-turn (RCUT) intersection is also known as a superstreet intersection, the initial design concepts of which were concentrated in suburban arterials in the 1980s as proposed by Richard Kramer (Kramer, 1987). Different from the DLT and the MUT intersections, RCUT intersections are applied mainly on corridors where the traffic volumes between the major and minor roads obviously differ. According to the RCUT Information Guide (FHWA 2014), the RCUT minor roads have a demand limit of about 25,000 cars per day. RCUT intersections eliminate minor street movements at the main intersection by rerouting the minor street through and left turn traffic moving together into the major road through traffic streams and then proceeding along the arterials with a few hundred meters distance until they reach the U-turn crossover to complete their maneuvers. Therefore, the major road through movements will achieve larger green time, save travel time and decrease the number of stops. RCUT intersections can be classified into signalized and unsignalized types, which can be further defined to stop-controlled and merge or yield-controlled.

The basic design layout of a signalized RCUT is shown in Figure 4-1. It is applicable to urban and suburban arterial roads and will generate great performance when installing many along a corridor rather than at an isolated intersection (FHWA, 2014).

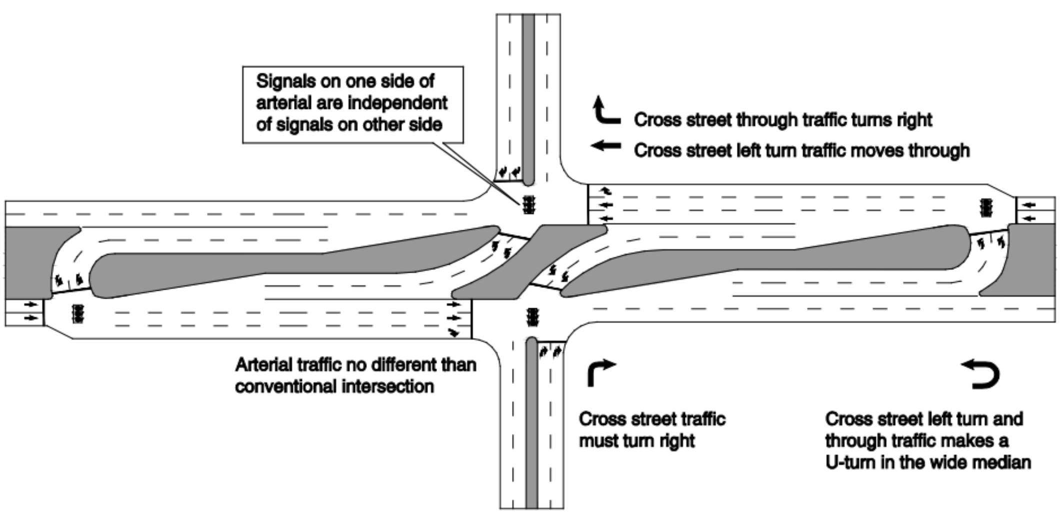


Figure 4-1: An RCUT Intersection with Signals
Source: FHWA (2014)

Unsignalized RCUT intersections are commonly applied on rural arterials because of their safety benefits. The stop-controlled RCUT design is suitable for an isolated intersection on a four–lane divided arterial. The yield controlled RCUT intersection is usually applied on a high-speed divided four-lane corridor to serve as an interim when the interchange conversion is constrained for budgetary reasons. Figures 4-2 and 4-3 illustrate a stop-controlled RCUT and a merge or yield-controlled intersection respectively.

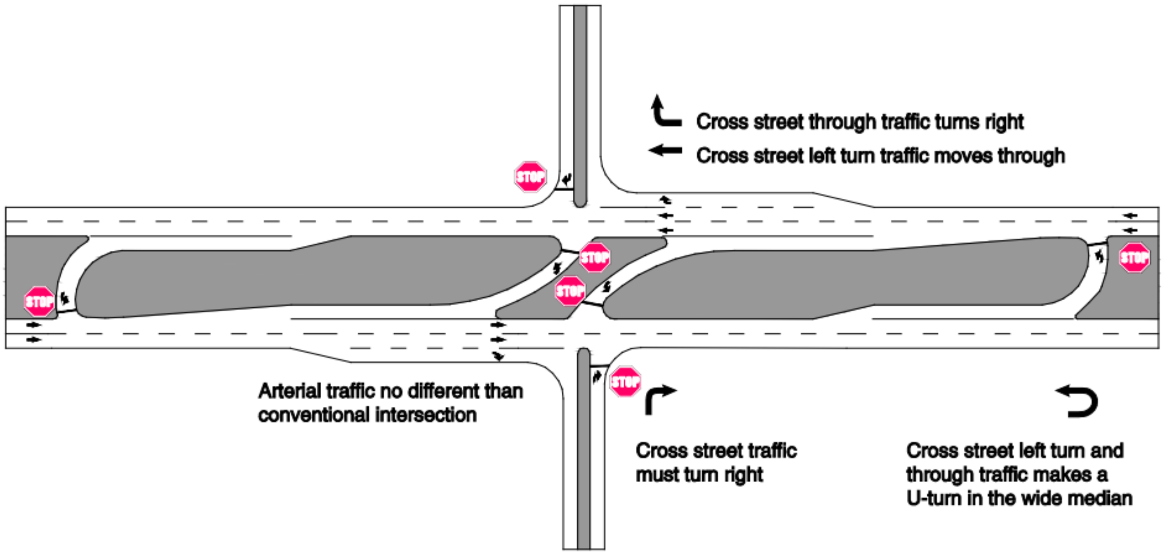


Figure 4-2: An RCUT Intersection with A Stop Control
Source: FHWA (2014)

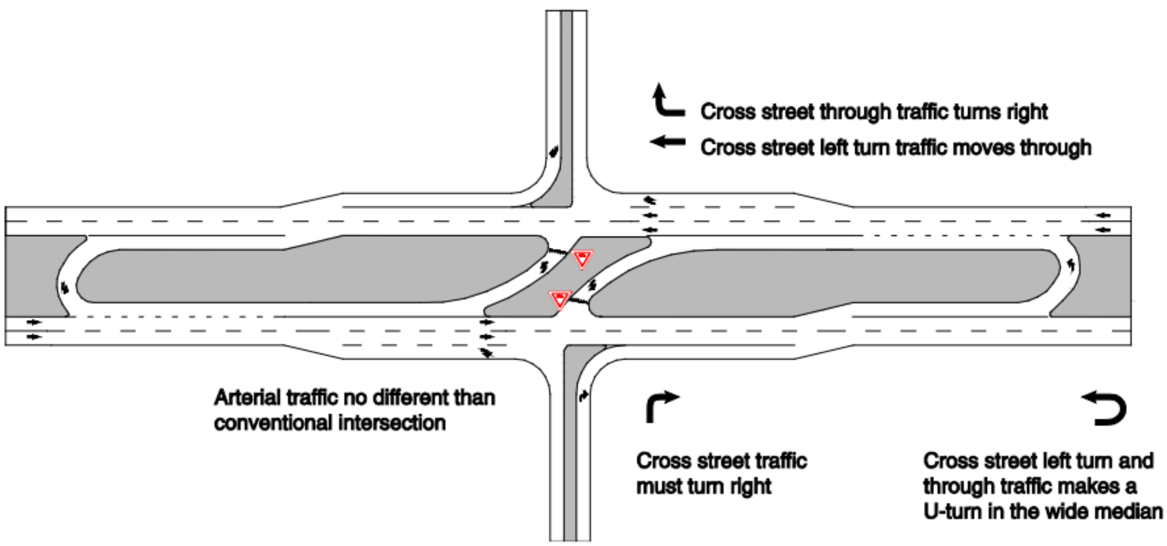


Figure 4-3: An RCUT Intersection with a Yield Control
Source: FHWA (2014)

These different types of RCUT intersections can be used in combination and can be converted into each other under certain conditions, such as traffic volume changes. So far, 10 states have installed RCUT intersections in the United States. Their general design features are introduced in the following section.

4.2 Existing Design Guidelines

The restricted crossing U-Turn intersection has similar geometric features similar to Medium U-turn designs, for which current guidelines do not apply to RCUT intersection designs explicitly. Therefore, it is necessary to draw on and compile state DOT experience to guide the RCUT construction or retrofit to RCUT intersections. Further, the reviewed geometric criteria are concentrated mainly on signalized RCUT intersections or RCUT intersections with stop signs covering various RCUT design features.

4.2.1 Crossover

There are two types of crossovers on an RCUT intersection: one is a left turn crossover, and the other one is a U-turn crossover. The left turn crossover accommodates left turning vehicles from the main road. The U-turn crossover is located on each approach of the main road and serves mainly to accommodate left turning vehicles from minor roads.

FHWA Restricted Crossing U-Turn: Informational guide (by Hummer, J., and et.al. 2014)

- The left-turn crossover on the major intersection is usually a directional median with one lane on each approach. The design speed for vehicles to proceed through this area is 15 to 20 mph.
- For an RCUT intersection with stop signs or signals, the common distance between the main intersections to the U-turn crossover is 400 to 800 feet with 15 mph design speed limits.
- Access points are not allowed to open at the place near the signal and near the entrance to a U-turn crossover. As shown in the picture below, the suggested avoidance distance is 100 feet on each side of a U-turn crossover. It is allowable to align the driveways or side streets with the exit of a U-turn crossover.

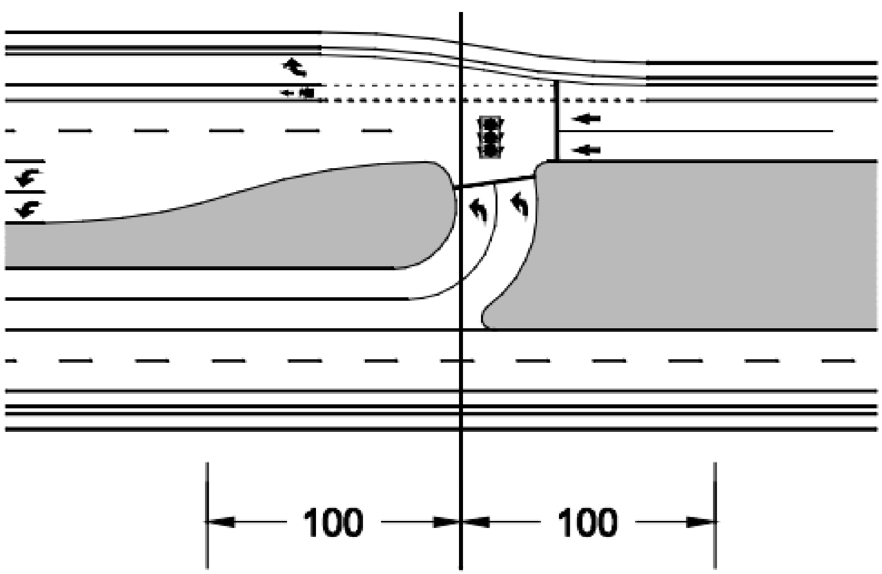


Figure 4-4: Suggested Distance for Access Points to Avoid Locating Along RCUT Crossovers
Source: FHWA (2014)

MDOT

- Considering the required deceleration length, with a posted speed limit of 45 mph, the distance between the main intersection and the U-turn crossover is suggested to be 660 feet ±100 feet for an RCUT intersection.
- For consecutive U-turn crossovers, the experience of MUT corridors could be applied to RCUT intersections. The distance between two U-turn crossovers is suggested to be 100 feet at least and 150 feet as a favorable separation. If consecutive U-turn crossovers are placed close together, traffic signals should be introduced to this area and 'left turn on red' (LTOR) maneuvers should be prohibited.

NCDOT

- It is suggested that 800 feet is an appropriate spacing from the main intersection to a U-turn crossover.
- It is suggested that 100 feet is an appropriate outside turning radius for the left-turn crossover on major roads, shown in the figure below.

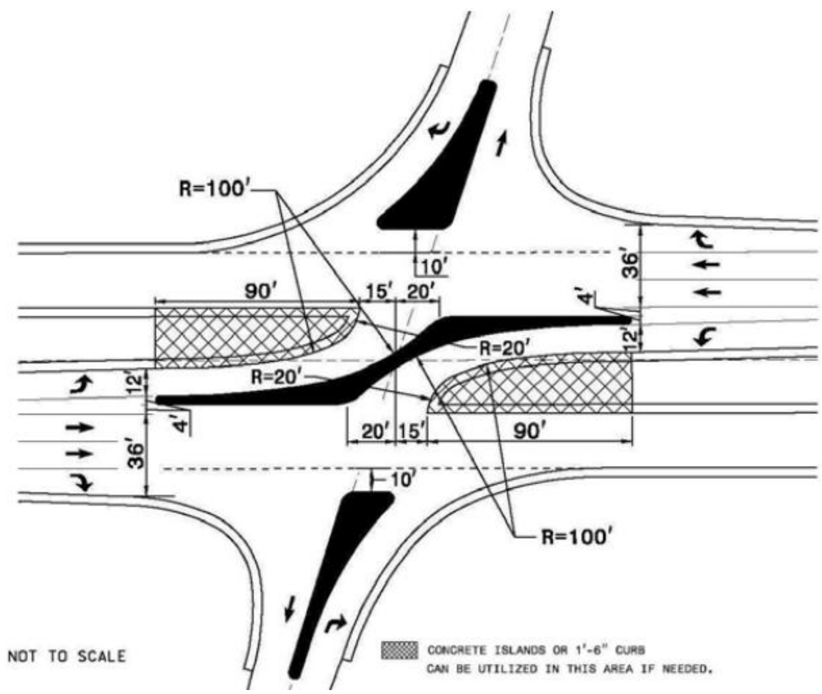


Figure 4-5: Left-turn Crossovers Design Layout
Source: NCDOT Roadway Design Manual

The AASHTO Green Book

- The AASHTO Green Book proposed the distance between the main intersection and the U-turn crossover distance ranging from 400 to 600 feet.
- Provided that the distance between the two adjacent RCUT intersections is less than the total of the minimum required distance to the U-turn crossover plus the distance

required for the next downstream left-turn lane, the U-turn crossover should be placed 50 to 100 feet ahead of the next downstream left-turn lane.

4.2.2 Median Width

Median width is an important factor to accommodate vehicles' turn maneuvers.

AIIR (Hughes, W., and et.al. 2010)

- The desirable median width is indicated to be 42 to 66 feet to accommodate large truck vehicles. In addition, the median width can be minimized by using a combination of median, lane, and shoulder. When doing so, the median width can be no wider than 16 feet, which includes at least a 4-ft-wide median and a 12-ft-wide turn bay. Correspondingly, the right-of-way is 84 feet for four-lane arterials and 132 feet for eight-lane arterials in this situation.
- To not encroach on curbs or shoulders, it is suggested that approximately 140 feet be used for four-lane arterials to approximately 165 feet for eight-lane arterials to accommodate large truck U-turn maneuvers, where 12-foot-wide lanes and 10 feet of the shoulder are assumed. In this case, ideal minimum median widths between 47 and 71 feet are commonly applied.
- RCUT designs will affect surrounding businesses, especially those that are not located at the median opening whereas invited left-turn pass-by trips.

FHWA Restricted Crossing U-Turn: Informational Guide (by Hummer, J., and et.al. 2014)

- A crossover combined with a loon at the area with a sufficient right of way is one way to allow designed vehicles to make a safe U-turn. A "loon" or "bump out" refers to a semi-circle paved lane outside of the original dive lanes alongside which it is preferred that no parking signs are posted. In this case, the median may be as narrow as 18-foot-wide (12 left turn lane width plus 6 feet median separation width).
- At a crossover without sufficient right of way or with a low volume of trucks, a 69-foot-wide median on a four-lane major street will be wide enough to accommodate the U-turn traffic. Commonly, U-turn drivers can also be led to use an existing or widened shoulder to complete their maneuvers. Engineers can also design the U-turn to align into a right-turn lane to accommodate the U-turn traffic. The referral values of median width without loons are presented in the AASHTO Green Book and will be shown in section 4.2.4 later in this chapter.
- Back-to-back storage bays are suggested to minimize the median width. The median width is 30 feet for an RCUT intersection with back-to-back two-lane storage bays.

MDOT

- The MDOT applied the striped two-lane crossovers in some places with the width of 36 feet.
- For U-turn crossovers at MUT intersections, the MDOT uses median widths ranging between 47 and 71 feet to accommodate design vehicles, which can also be applied to RCUT intersections.

The AASHTO Green Book

- The different types of vehicles that can be accommodated and their associated ranges of minimum median width without loons are shown below for reference.

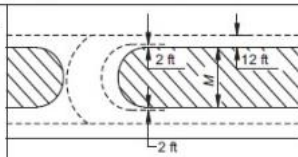
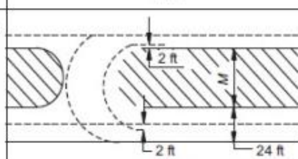
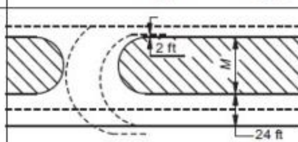
U.S. Customary								
		M—Minimum Width of Median (m) for Design Vehicle						
		P	WB-40	SU-30	BUS	SU-40	WB-62	WB-67
		Length of Design Vehicle (ft)						
Type of Maneuver		19	50	30	40	40	63	68
Inner Lane to Inner Lane		30	61	63	63	76	69	69
Inner Lane to Outer Lane		18	49	51	51	64	57	57
Inner Lane to Shoulder		8	39	41	41	54	47	47

Figure 4-6: Recommendation of Minimum Median Widths for U-Turn Crossovers
Source: AASHTO (2014)

4.2.3 Peer Studies Related to Geometric Design Impacts

One study conducted by Lu et al. (2005) evaluated the effects of offset distances between driveway exits and downstream median openings or signalized intersections on the safety and operational performance of vehicles making right-turns followed by U-turns (RTUTs). The critical offset distance for vehicles making RTUTs under different scenarios was determined based on the 50th percentile value of crash rate and conflict rate using the regression models developed in this study. The suggested minimum offset distance is 122 m for unsignalized U-turn openings on 4-lane roadways and 152 m for openings on 6-or-more-lane roadways. In addition, the suggested minimum offset distance for signalized intersections on 4-lane roadways is 168 m and 229 m on 6-or-more-lane roadways.

The other study conducted by Xu et al. (2017) developed a tool to help traffic professionals to determine the minimum required offset length required for an unsignalized superstreet. The model was developed on the basis of traffic dynamics and driver gap acceptance behavior. VISSIM and SSAM were employed to evaluate the safety impact of the different U-turn offset lengths. Three scenarios were designed and simulated, which were: 1) 700 ft southern U-turn offset (shortened U-turn offset); 2) 1,100 ft southern U-turn offset (mean of the model output) and 1,500 ft southern U-turn offset (field implementation). The results showed that there is little difference between scenarios 2 and 3, which indicated that the safety performance for U-turn segments will not be reduced if the U-turn offset is reduced from 1,500 ft to 1,100 ft. However, the scenario with a 700 ft U-turn offset significantly increased the potential for lane-changing conflicts and the severity of collisions compared with the other two scenarios. The simulation results showed that the proposed model can generate a reasonably shortened U-turn offset length without sacrificing the expected safety performance.

4.3 Operational Performance

Microsimulation analysis is a powerful tool used to conduct studies that contain various users and intersection types. Therefore, in this section, only peer studies on microsimulation-based operational analysis were reviewed.

Reid and Hummer (1999) used CORSIM to conduct a comparison study that focused on total system travel time impacts on conventional intersections with two-way left-turn lane and RCUT median crossovers. To make an equitable comparison, a 2.5 mi suburban arterial corridor with 5 signalized intersections near Detroit, Michigan was modeled in CORSIM. The basic intersection has four lanes except on the eastern end of the corridor, which has 6 lanes. By that time, this corridor was applying a MUT design, the median width of which was 80 feet with a 180 feet right-of-way. The arterial speed limit was 50 mph, and the minor street speed limit ranged from 35 to 45 mph. They obtained the traffic counts data from an operational study for this corridor in 1995 by the MDOT. The CORSIM simulation model for the superstreet assumed the same basic roadway geometrics, as did the MUT model intersection with high through volumes. Three intersections used the superstreet layout without a left-turn crossover opening on the major intersections (Figure 4-7. B), and one used the offset minor streets geometry (Figure 4-7. A), as shown in the figure below:

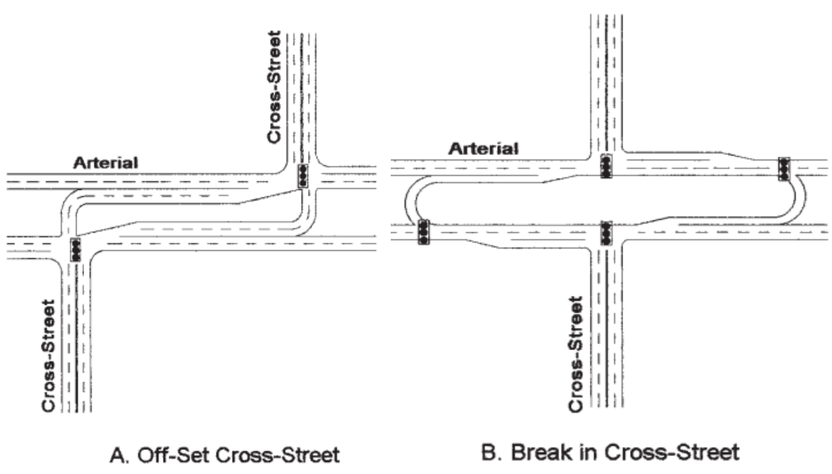


Figure 4-7: RCUT Intersection Layouts for Comparison
Source: Reid and Hummer (1999)

The analysis used a combination model of a fixed external-node coordinated system and a fixed origin-destination volume model and Traffic Assignment feature of CORSIM to determine intersection volumes for 4 time periods: morning peak-hour period (8:00 to 9:00 a.m.), noon-hour period (12:00 to 1:00 p.m.), midday period (2:00 to 3:00 p.m.), and afternoon peak-hour period (5:00 to 6:00 p.m.). In addition, to correspond with the time period, they changed the driveway volumes and through-trip percentages to employ four different volumes ranging from low to high. They went to the location to collect driveway volume information and to generate the trip rates. Further, they converted the problem that CORSIM prohibits the analysis of left turns on red by using the “right-turn-on-red” capabilities in CORSIM. Synchro was used to optimize each arterial network cycle length. The results showed that, by using RCUT crossovers, the travel time decreased by 10%, and travel speed increased by 15% compared with the same conditions using TWLTLs.

Reid and Hummer (2001) used CORSIM to conduct a comparison study focusing on operational impacts of the conventional intersections with a two-way left-turn lane (except for two-way collector roads) and RCUT median crossovers. To make an equitable comparison, a series of roadway factors were held constant. In addition, the researchers used 2-year-old turning movement data of existing intersections form Virginia and North Carolina. The simulation experiment was tested using optimum cycle lengths with 4 s yellow time and 2 s red time. Three different traffic volumes were set to represent off-peak, peak, and peak-plus- 15% volume respectively, with 3% truck on arterials and 2% on collectors. The travel speeds were set to 50 mph for arterial and 40 mph for collector roads. The results showed that RCUT crossovers saved more travel time on intersections where multi-lane arterials intersect with 2 lane collector roads compared with the same conditions using TWLTLs. For the scenario of a 4-lane by 2-lane intersection, the average travel time was reduced from 68 to 54 vehicles per hours. During the peak-plus-15% volume, the RCUT intersection gained most travel time benefits. For the scenario of a 6-lane by 2-lane intersection, the travel time benefits stayed at nearly the same level with 2 or 3 vehicle hours saved.

Hughes et al. (2010) used VISSIM simulations to conduct an operational performance analysis of RCUT intersections. Based on different geometric design features of RCUT intersections, 5 intersection cases were designed and analyzed on a 1 mi long network. Three sets of directional splits (50:50, 60:40, and 75:25, respectively) of major road volumes were applied for these five cases. The simulation volumes were ranged from low to high with the assumption of 5% heavy vehicles on each leg. They used Synchro to optimize the signal timing, and ITE policy was referenced to determine the yellow and all-red times. As for the geometric parameters, the major roads median width was 40 feet, and the U-turn crossovers were located 450 feet away from the main intersection. Loons may be needed to accommodate large truck movements on U-Turn crossovers. Each crossover was installed with a signal. Major roads had single right-turn bays, and right-turn on red was allowed at each signal. However, no left-turn on red was allowed. The desired speed on major roads was 45 mph and 25 mph on minor roads. In total, 90 unique VISSIM® simulations were generated for both the RCUT intersection and the comparable conventional intersections. The simulation seeding time was 30 minutes, and the running period was 60 minutes.

The authors used the ratio of minor road total volume/total intersection volume (MRTV/TIV) to represent the corresponding turning volumes and to find the functional relationship in the difference of travel time between the RCUT intersection and conventional intersections. In general, simulation results showed that the RCUT intersection had the highest overall capacity under all of the cases in which the minor road volumes were lower. Specifically, for the high-volume scenarios, when the MRTV/TIV ratio was in the range of 0.1 to 0.2, the RCUT throughput was 15% to 30% higher than that of the conventional intersections. When the ratio improved, the capacities of the two tended to be the same, and the RCUT showed 5% to 7% lower capacity when the MRTV/TIV ratio was beyond 0.25. In the aspect of travel time, for the high-volume scenarios, when the MRTV/TIV ratio was in the range of 0.1 to 0.15, the travel time of the RCUT intersection decreased 25% to 40%. When the ratio improved, the travel time of the two tended to be the same, and the RCUT intersection showed 15% to 25% lower capacity when the MRTV/TIV ratio was beyond 0.25. Similar results were found for medium and low volume scenarios.

Hana & Prof Wakeel (2014) used CORSIM to conduct a simulation-based comparison study of superstreet and traditional intersections to analyze their operational performance. Delay time and the queue length experienced by the vehicle users are the main evaluation parameters in this measurement. 36 scenarios were created for each intersection design with variances in approach volumes and left turning percentages (10%, 15% and 20% for arterials and 30%, 20% and 15% for minor roads). The percentage of the right-turn volume was fixed with 15% for major roads and 20% for minor roads. All of the modeled intersections were designed with the form of four-lane divided arterials intersecting three-lane undivided collector roads, and each intersection stretched 1,000 feet. Lane width was set at 12 feet, and shoulder width was 4 feet. The design speed was 45 mph. To set the signal timing, a saturation flow of 1,800 vehicles per hour (vph), and a cycle length of 120 seconds was used in this simulation when the intersection critical (v/c) ratio was equal to or greater than 1.

The simulation result showed that the superstreet intersection performed better than the traditional intersection in the aspects of delay time and queue length. With the extra green available time, even under high traffic volumes, the superstreet network experienced decreasing delays that ranged from 27.39% to 82.26% and about a 97.5% reduction in average network queue length on the major road’s through lanes. The authors also noted that the left-turn traffic flow from the minor roads was essential to the efficiency of the entire intersection. When the left-turn volume on the minor road reached 30% and entered into the main intersection, the volume amount it summed up with major road left-turners would cause serious delay.

4.4 Safety Performance

Until now, the evaluation of safety performance has been conducted only toward unsignalized RCUT intersections, because signalized RCUT intersections are usually designed to improve the operation of the traffic volumes. Nevertheless, the whole RCUT intersection’s safety performance has been improved by the decreased conflict points. Figure 4-8 and Figure 4-9 below show two conflict points diagrams for a four-leg RCUT intersection and a conventional intersection.

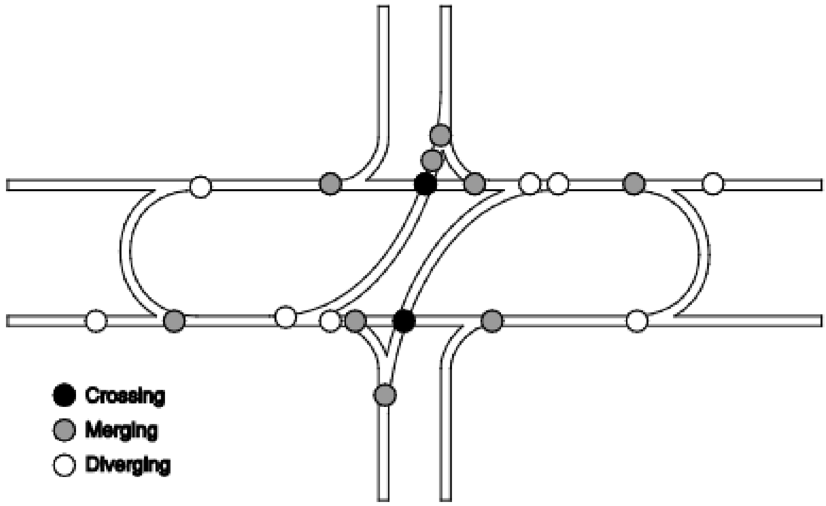


Figure 4-8: Vehicle-Vehicle Conflict Points at A Four-Leg RCUT Intersection
Source: FHWA (2014)

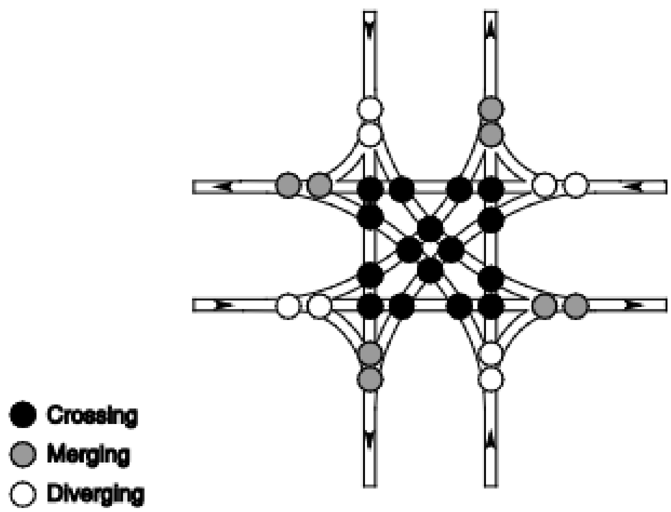


Figure 4-9: Vehicle-Vehicle Conflict Points at A Four-Leg Conventional Intersection
Source: FHWA (2014)

The diagrams show that, for a four-leg intersection, the RCUT form can reduce totally 18 conflict points, in which the crossing conflicts represent a higher potential to result in more severe crashes like angle crashes. Because the traffic on the minor road is rerouted to conduct a right turn first, the exposure of pedestrians to left-turning vehicles may decrease, but it may increase to right-turning vehicles. Figure 4-10 and Figure 4-11 compare pedestrian to vehicle conflict points for a four-leg RCUT intersection and a conventional intersection.

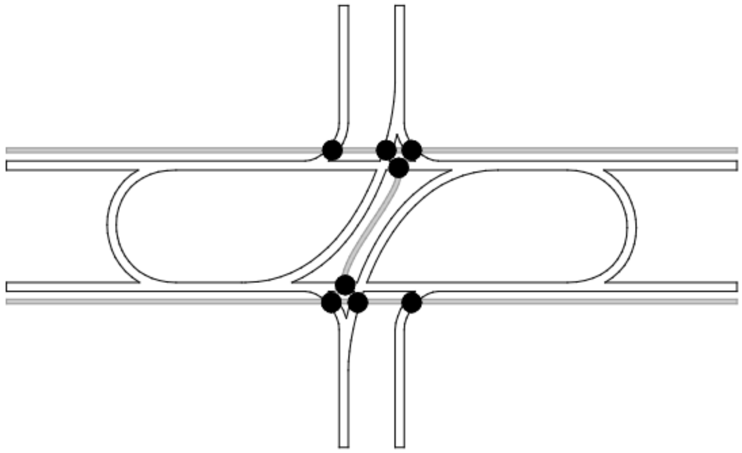


Figure 4-10: Pedestrian-Vehicle Conflict Points at A Four-Leg Conventional Intersection
Source: FHWA (2014)

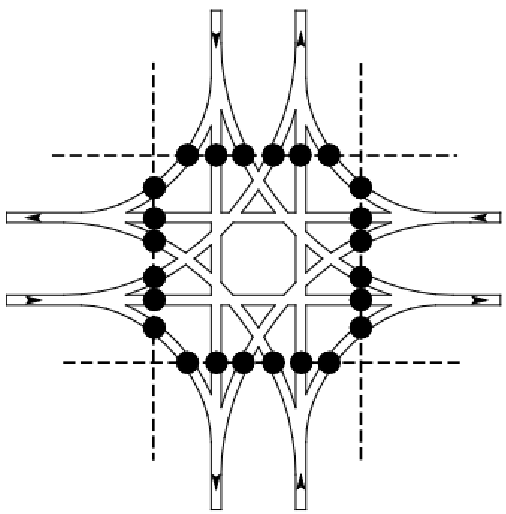


Figure 4-11: Pedestrian-Vehicle Conflict Points at A Four-Leg Conventional Intersection
Source: FHWA (2014)

Several studies have been conducted to evaluate the safety performance of signalized RCUT intersections.

PBS & J. (2005) conducted a highway corridor study of US 17, which has strategic meaning for the states through which it lies. Their research found that, compared with crash rates predicted for a four-legged conventional intersection based on the Highway Capacity Manual (HCM) method, RCUT intersections with similar average daily traffic (ADT) volumes have lower crash rates. In addition, compared with the 10-year average crash rates obtained from 25 conventional intersections with similar ADT volumes in the same area, the total intersection crash rates reduced after RCUT intersections were installed.

Sarah et.al. (2012) evaluated the safety performance of 13 unsignalized superstreet sites in North Carolina by conducting traffic flow adjustment, comparison-group, and Empirical Bayes analyses. All results showed that the total crash rates, fatal and injury crashes and turning crashes were reduced at most tested unsignalized superstreet intersections. However, traffic flow adjustment results also indicated the increased occurrence of rear-end, sideswipe, and other crash types mainly on minor streets.

Inman et.al. (2013) used three methods (Empirical Bayes, a simple before and after analysis and a before and after analysis with control intersections) to analyze the safety performance of 9 rural RCUT intersections in the state of Maryland with time periods ranging from 1988 to 2003. 6 were on U.S. 15 and 3 were on U.S. 301; all of them were four-lane divided highways. All of the crash data were gained from the Maryland State Highway Administration. Specifically, crash data covered a period from January 1, 1980 through December 31, 1999 for U.S. 15. The time period for U.S. 301 was from January 1, 1996 through December 31, 2008. In 2009, the AADT for chosen intersections along U.S. 15 ranged variously from 20,000 to 45,000 vehicles per day, while the AADT ranged from 10,000 to 26,000 vehicles per day for chosen intersections on U.S. 301 from northern to southern parts.

The results of the Empirical Bayes test showed that the crash rate was reduced by 62% in total, including an approximate 14% crash rate decrease achieved from the main intersection through the U-turn crossing. In addition, injury or fatality crashes dropped from 55% to 46% after the implementation of the RCUT intersection, and fatal crashes were reduced by 70%. In the simple before and after crash analysis, they analyzed crashes that happened within 60 days before or after the RCUT opening date. The results indicated that crash counts dropped 61% at the main intersection compared with 18% at adjacent segments. Consistently, the before and after with control intersection analysis observed a shorter time period with 3 years of crashes for each of the before and after deployments and a longer time period with coverage of all available crash data for the before and after deployment. Thus, the observation time periods varied among intersections. The results showed a total of 12% reduction in crashes at RCUT intersections, with a 49% decrease in crashes at the main intersection and a slight increase on the adjacent segments. In contrast, for the control intersections groups, crashes on the main intersections increased by 25% and decreased on the comparable adjacent segments, which contributed to an overall 21% increase in crashes.

4.5 Pedestrian Considerations

Compared to conventional intersections, pedestrian crossing routes and time will change at an RCUT intersection. However, appropriate signal timing and operation at an RCUT design will enhance the pedestrian travel experience.

Hummer, J., and et.al. (2014) recommended using “Z” crossing routes at an RCUT intersection, because they will reduce the pedestrian-to-vehicle conflict points compared to a conventional intersection. As shown in the figure below, pedestrians crossing minor road paths will be the same as conventional intersections. Unlike directly crossing the entire street width during the vehicle phase of the major road at a conventional intersection, pedestrians who want to cross the major road, such as A to C and B to D, shall experience two-stage crossings. They should cross the minor street first and then go to the left turn crossover (E shown in the figure) as a halfway break to wait for next appropriate time to finish their crossing. Since pedestrians are accustomed to perpendicular crossing routes, way-finding techniques, such as audible devices, channelization, and separation and detectable delineation of the pedestrian crossing routes, can be used to guide the pedestrian crossing behavior. For RCUT intersections installed where streets do not exist, engineers can use the layout of offset minor streets to accommodate these crossing habits. In addition, persons with disabilities should be considered. It is highly suggested that audible pedestrian signals be installed at RCUT intersections and that the push-buttons shall be reachable for wheelchair users and adjacent to the crossing at a minimum separation of 10 feet, that medians accommodate wheelchair passing, and that landscaping, curbing, or fencing be used to delineate the walkway better for visual impaired persons to find their way.

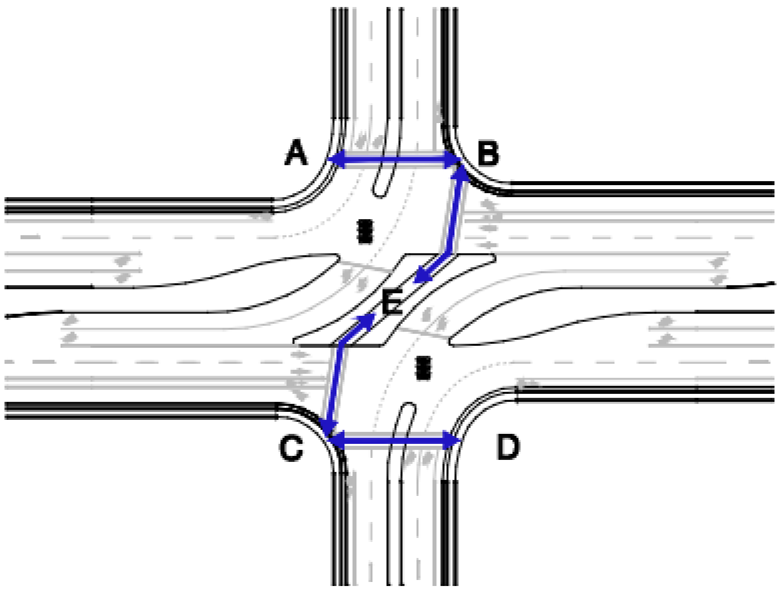


Figure 4-12: "Z" Crossing Path for Pedestrian to Cross an RCUT Intersection
Source: FHWA (2014)

Anne M. et.al. (2015) focused on evaluating different crossing options for pedestrians and bicyclists using two methods: LOS analysis for signalized intersection in HCM and microsimulation based on VISSIM. In addition, the group analyzed traffic signal and midblock distance related crossing configuration parameters to further assist users in adopting crossing routes. In the results of the LOS method, pedestrians experienced the least delay (95.3 s/person) with LOS C in the midblock cross routes. For bicyclists, direct cross indicated lower travel times. (58.1 s/person) with LOS C. Pedestrian analysis by VISSIM showed that two-stage Barnes Dance generated the lowest total delays (102 s/person) and 1.2 stops per pedestrian, while the median cross had the highest total delay (160 s/person) and 1.8 stops. In contrast, the fewest stops (4.8/bicycle) and the shortest travel time (210 s/bicycle) for bicyclists were achieved by bicyclists using the direct cross, whereas bicycles adopting the Vehicle U-turn had the lowest stopped delay (98s). When considering crossing configurations, a suggested approximate 90s cycle length, a signal split closer to 60/40 and two directional platoons coming from the major streets that did not arrive at the intersection simultaneously would help reduce pedestrian travel time. Similarly, bicycle users would experience a shorter travel time by applying a 90s cycle length and by having the two directional platoons arrive at a staggered time period.

Hughes et al. (2010), in their VISSIM simulation analysis introduced previously in section 4.3 of operational performance, stated the results of their evaluation of the impacts of heavy pedestrian volumes on the intersection. The results showed that, for the high-volume scenarios, both the RCUT and the conventional intersections can accommodate the pedestrian volume well. For the medium and low volume scenarios, the pedestrians resulted in less delay at RCUT intersections compared with conventional intersections. In detail, for the medium-volume scenarios, the pedestrian volumes caused a 7% additional delay for RCUT intersections and a 12% delay for conventional intersections. For the low-volume scenarios, the pedestrian volumes caused a 10% additional delay for RCUT intersections and a 15% delay for conventional intersections.

4.6 Signal

The RCUT intersection design has unique operational features that are similar to a one-way street which allows each side of the arterial to have its own cycle length and signal space. This flexibility of traffic signal placement is one advantage over many other intersection design forms. It indicates that the placement of signals on crossovers will have little effect on travel time experienced by the through movements at major roads. In addition, because of the two-phase signal resulting in a shorter cycle length, the pedestrian can also gain benefits with less delay experienced when making a two-stage crossing path compared to a conventional intersection.

4.7 Access Management

The RCUT intersection is a type of alternative design form that has fewer restrictions to locate adjacent parcels. It does not need frontage roads along the corridor and allows multiple driveways or side streets alongside. The signals installed for the driveways and side streets will bring slight delay effects on the arterial through movements. However, the access points should avoid the signals and exits of the U-turn crossovers. In addition, the MDOT suggested adding a third signal phase, if there are obviously higher right-turning vehicles coming out of the driveway or side-street to reduce the potential collision between the right-turning vehicles and U-turning vehicles.

Sarah et.al. (2015) carried out a corresponding questionnaire survey on different affected groups in the intersection of North Carolina's improved superstreet. They found that the residents living near the superstreet gave a positive evaluation of the safety performance improvement of the superstreet. However, 45% of the residents living near a signalized intersection noticed a slight increase in the number of stopped vehicles at the intersection. The residents of the minor road complained about the increase in travel time and the inconvenience of assessment. As the driving activity for residents living near the superstreet is mainly coming in and out of the superstreet and not includes long distance usage of the superstreet, the commuting drivers were also investigated. Similar to the opinions of the residents, they recognized the improvement of safety performance. Among them, 33% of the drivers stated that their travel time was shortened after the opening of superstreet, and 48% experienced fewer vehicle stops. As for the business assessment evaluation, most business agents felt that the converted superstreet intersection contributes to traffic safety and traffic flow improvement. However, 58% of the owners put forward the customer's inconvenience and confusion in their assessment. 47% of them mentioned their added problem in delivery, and 16% of the owners thought that the superstreet had a negative impact on their business.

4.8 Summary

RCUT is an alternative intersection treatment that is more suitable to apply along a corridor where arterial roads intersect with minor roads, and there is a significant traffic volume difference between the crossing roads. Since the restricted crossing U-turn shares many similarities with the Median U-turn intersections' geometric features, it is possible to learn from the experience with MUT designs. Meanwhile, the RCUT intersection has its unique signal timing features that can operate independently on each direction of the arterials. This feature accommodates the surrounding driveways and allows the installation of signals on crossovers without affecting the whole arterial's operational performance. However, the traffic on minor roads and the residents and businesses alongside may experience increased travel time and more inconvenience.

Studies have been conducted to investigate the operational and safety impacts Of RCUT intersection. It was proved by many researchers that RCUT could benefit the intersection when implemented properly.

Chapter 5. Operational Analysis of Displaced Left Turn Design

In this chapter, a VISSIM simulation-based study was conducted to compare the operational performance of the displaced left turn intersection with the conventional intersection. In addition, as mentioned in Chapter 2, the distance between a left turn crossover and the main intersection is a crucial element in DLT design. Therefore, the operational impacts of various crossover distances on DLT intersections were also investigated. The results are presented in this chapter.

5.1 Operational Performance of DLT Intersections Compared with Conventional Intersections

5.1.1 Base Model Develop

DLT Intersection

The simulation model for the DLT intersection was developed based on a roadway segment located in West Valley City, Utah. Minor changes were made to ensure the comparability between the DLT and conventional intersections. Figure 5-1 shows the Google map screenshot for this location.

Figure 5-1: Bangerter HWY (UT-154) at 4100 S Rd., West Valley City, Utah

The following are the basic roadway and traffic conditions:

- It was designed and operated by the UDOT in 2011.
- It is a full DLT design with displaced left turn lanes operated on each approach, which made it the first 4-leg DLT in the U.S. (http://www.quadrantintersections.org). Among the 4 legs, the southbound approach has two displaced left turn lanes, and the other three approaches have one displaced left turn lane.

- Rd 4100 S has two through lanes and one through and right turn shared lane for each side.
- Bangerter HWY has three through lanes and one right turn lane for each side.
- The posted speed limit is 40 mph for traffic on Rd 4100 S and 55 mph for traffic going through the Bangerter HWY.
- The crossover distance was set at 325 ft.

Figure 5-2 is the VISSIM screen shot of the base model developed for the DLT intersection.

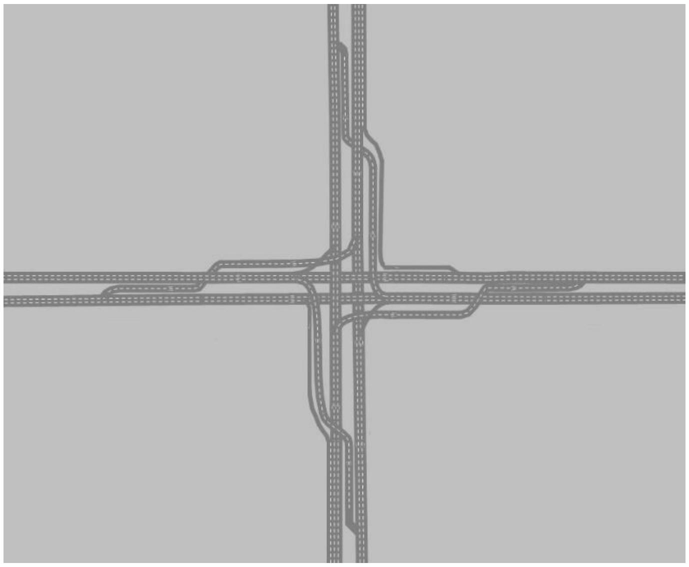


Figure 5-2: VISSIM Screen Shot of the Displaced Left Turn

Conventional Intersection

The hypothesized conventional intersection was deployed here to conduct the comparison study with the DLT intersection. To be consistent, as with the DLT model, the simulated conventional intersection has 4 legs, and each has three through lanes and two left turn lanes. Figure 5-3 shows the base model developed for the conventional intersection.

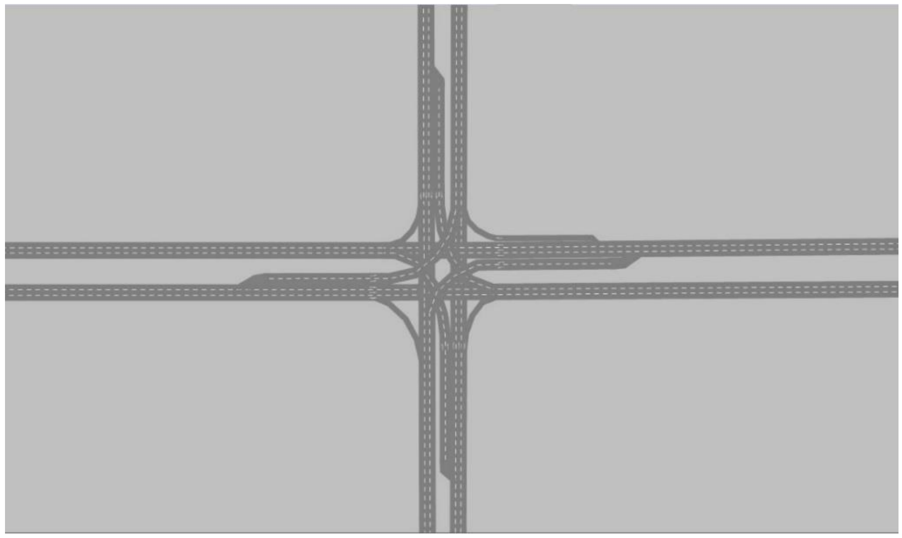


Figure 5-3: VISSIM Screen Shot of the Conventional Intersection

5.1.2 Scenario Design

To compare the operational performance of the DLT and conventional intersections, 18 simulation scenarios were created from the base models with various combinations of traffic volume, and left turn percentage.

- Volume: 1,000, 2,000, 3,000, 4,000, 5,000, and 6,000 vehicles per hour
- Left turn percentage: 15%, 20%, and 25%

To exclude the impacts of signal timing, Synchro, in conjunction with SimTraffi, optimized the signal timing in terms of cycle, split and the offset for the conventional intersection. For the DLT intersection, the signal plan used by the UDOT and provided by Synchro was adopted and adjusted based on the left turn percentage.

5.1.3 Results Analysis

VISSIM Version 9-10 was used to model and analyze the experimental scenarios. Since VISSIM uses stochastic (random) models, there may be minor differences in the results depending on the random number seed. To address this issue, multiple runs were used. For each run, the simulation time was set to 4,800 seconds, and the warm-up time was 1,200 seconds for each scenario and repeated for 7,200 seconds. 10 runs with different random seeds were performed for each volume of scenarios. The results presented in later sections are the averages for the ten runs. Measures of performance, average delay and travel time, were collected for further evaluation.

5.1.3.1 Average Delay

Table 5-1 to Table 5-3 show the simulated average delay results. By analyzing the results, it can be seen that the DLT intersection produced less delay than the conventional intersection for all scenarios when compared with conventional intersections. To be more specific:

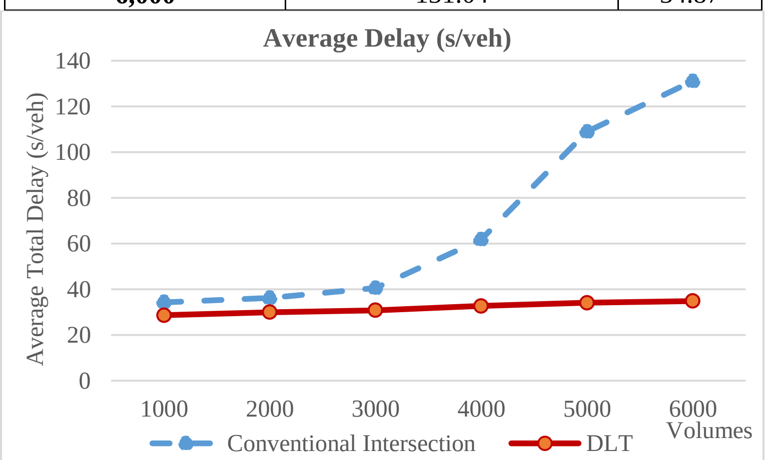
- When traffic volume was low at 1,000 or 2,000 veh/hr, the conventional intersection and DLT intersection produced similar delay;
- The average delays of the DLT intersection increased slightly when traffic volume increased or when the left turn percentage increased;
- For the conventional intersection, the average delay rose when traffic volume increased and jumped dramatically when the traffic volume reached 3,000 vph and above;
- With the increase in left turn percentage, the difference of average delay between the two intersections increased.

From all findings listed above, it can be seen clearly that the DLT intersection performed better than the conventional intersection, especially when traffic volume was moderate to high or the left turn percentage was high.

15% left turn percentage

Table 5-1: Simulated Average Delay for 15% Left Turns

Traffic volumes (veh/hr)	Average Delay (s/veh)	
	Conventional Intersection	DLT
1,000	34.35	28.70
2,000	36.21	29.63
3,000	40.56	30.88
4,000	61.82	32.74
5,000	108.92	34.15
6,000	131.04	34.87

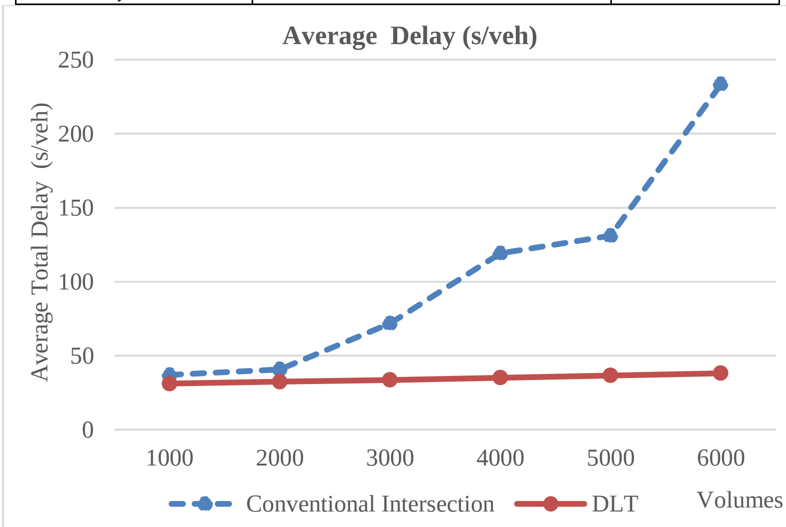


20% left turn percentage

Table 5-2: Simulated Average Delay for 20% Left Turns

Traffic volumes (veh/hr)	Average Delay (s/veh)	
	Conventional Intersection	DLT
1,000	36.96	31.08
2,000	40.72	32.45
3,000	71.82	33.64
4,000	119.15	35.13
5,000	131.01	36.57

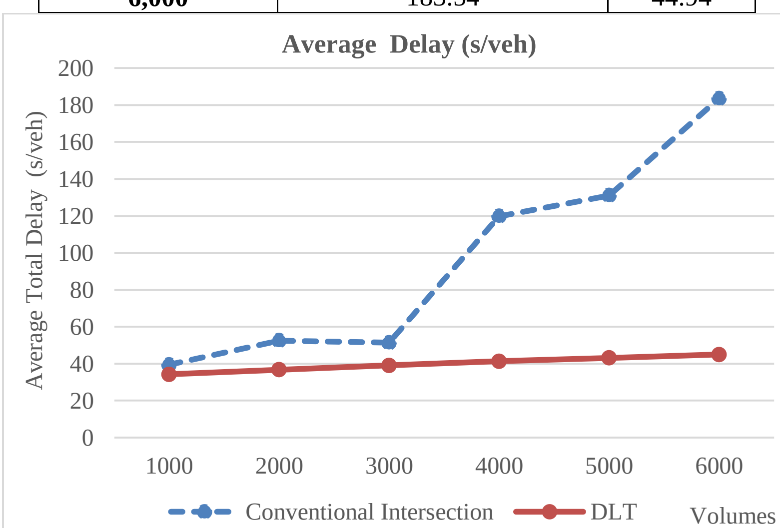
6,000	233.44	38.10



25% left turn percentage

Table 5-3: Simulated Average Delay for 25% Left Turns

Traffic volumes (veh/hr)	Average Delay (s/veh)	
	Conventional Intersection	DLT
1,000	39.46	34.22
2,000	52.51	36.74
3,000	51.33	39.06
4,000	119.80	41.30
5,000	131.01	43.10
6,000	183.54	44.94



5.1.3.2 Travel Time

Travel times were also collected. Since the tested scenarios were all balanced conditions, eastbound through (EBT) and left turn (EBL) travel times were selected for analysis. Figure 5-4 shows the start and end points for these two routes. A is the start point, B is the end point of the EBT movement, and C is the end point of the EBL movement.

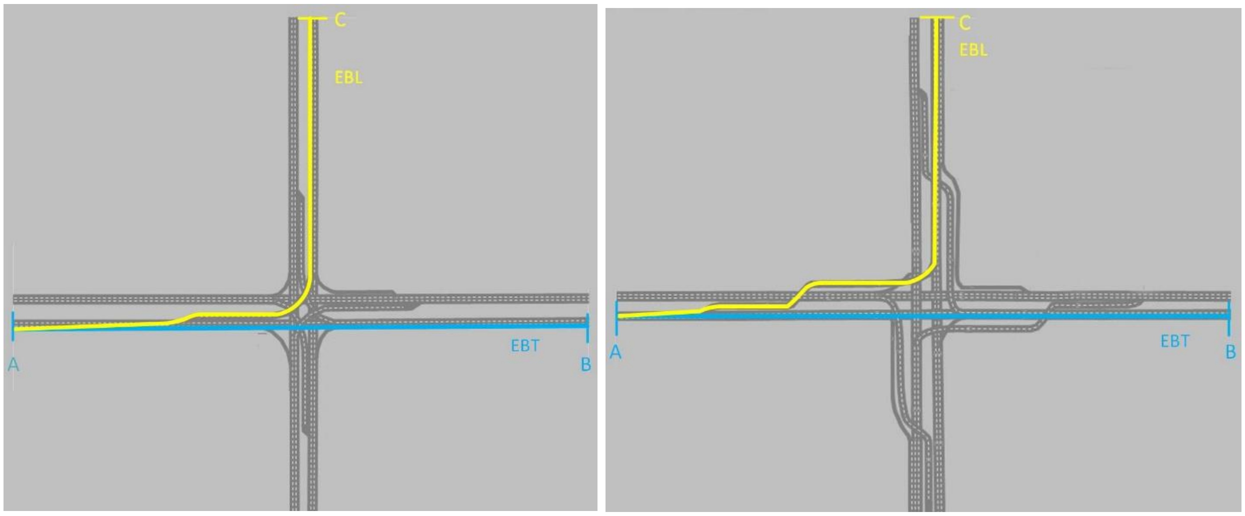


Figure 5-4: Illustration of Eastbound Through Movement and Left Turn Movement for a Conventional Intersection (left) and a DLT Intersection (right)

Travel times for each scenario were listed in Tables 5-4 to 5-6. Table 5-4 presents the simulated travel time when left turn volume accounted for 15% of the total volume. The results indicated that the conventional intersection produced less EBT travel time than the DLT intersection when traffic volume was less. When traffic volume reached 6,000 vph, the DLT intersection started to show its advantage and had less travel time. For EBL travel time, the DLT intersection always performed better than the conventional intersection, especially with higher traffic volume.

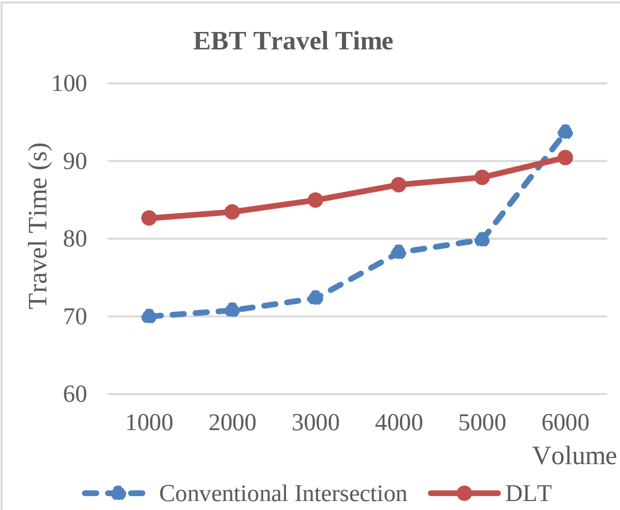
Similar trends were also presented for 20% and 25% left turns. When the left turn volume was 20% and 25% of the total volume, the DLT intersection had less eastbound through travel time when traffic volume was more than 5,000 vph and 4,000 vph respectively.

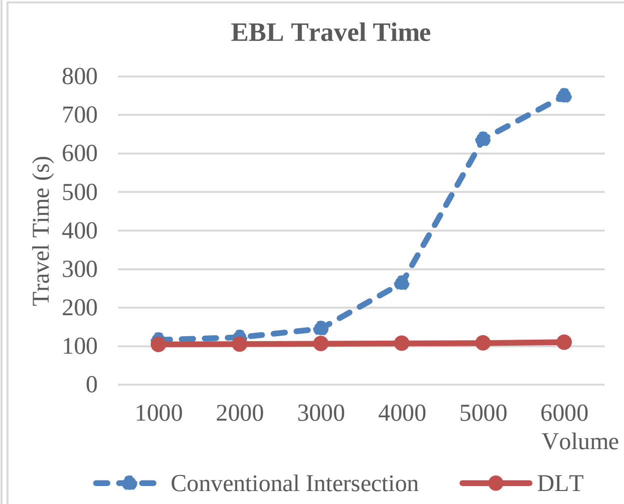
The conclusion can be drawn that the DLT intersection design works better when there is a large traffic volume or a high percentage of left turn vehicles.

15% left turn percentage

Table 5-4: Simulated Travel Time for 15% Left Turns (s)

Traffic volumes (veh/hr)	EBT (A to B)		EBL (A to C)	
	Conventional Intersection	DLT	Conventional Intersection	DLT
1,000	69.99	82.65	115.93	104.31
2,000	70.79	83.46	122.77	105.38
3,000	72.36	84.97	145.62	106.62
4,000	78.24	86.95	263.63	107.50
5,000	79.88	87.90	636.99	108.37
6,000	93.72	90.45	749.26	110.24

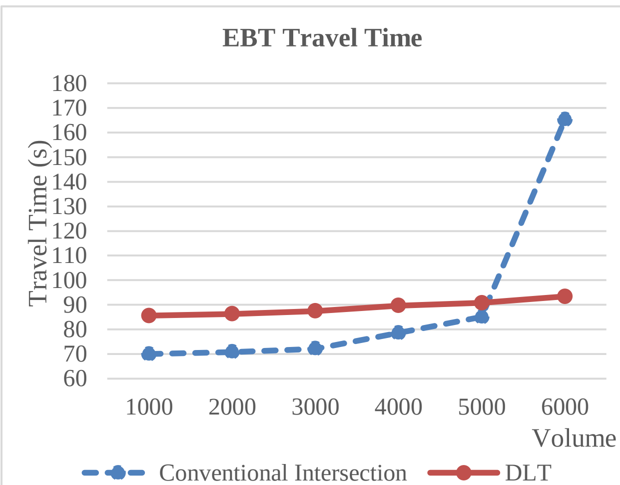


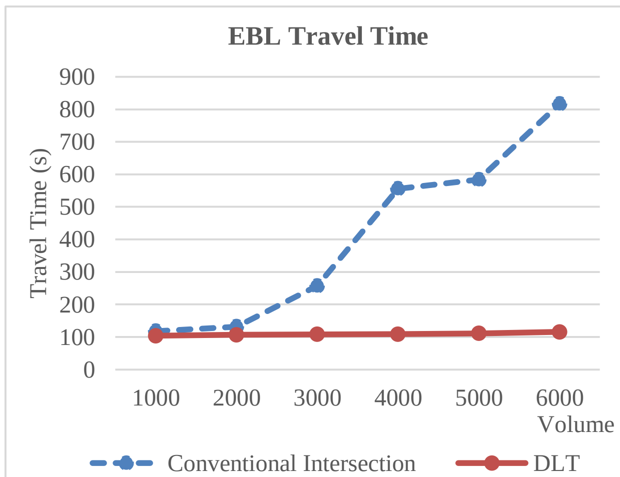


20% left turn percentage

Table 5-5: Simulated Travel Time for 20% Left Turns (s)

Traffic volumes (veh/hr)	EBT (A to B)		EBL (A to C)	
	Conventional Intersection	DLT	Conventional Intersection	DLT
1,000	69.99	85.58	117.91	103.95
2,000	70.83	86.28	131.60	106.73
3,000	72.10	87.44	257.38	108.05
4,000	78.55	89.67	555.86	108.82
5,000	85.02	90.76	584.02	110.90
6,000	165.27	93.40	816.61	115.32

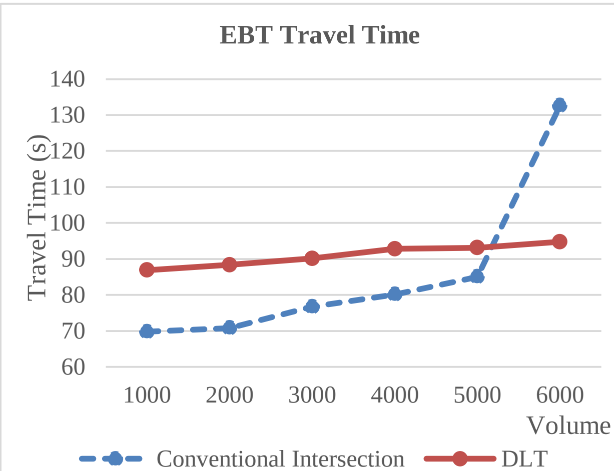


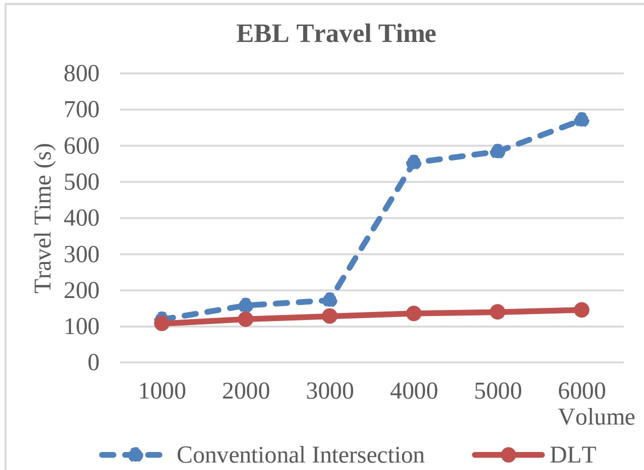


25% left turn percentage

Table 5-6: Simulated Travel Time for 25% left Turns (s)

Traffic volumes (veh/hr)	EBT (A to B)		EBL (A to C)	
	Conventional Intersection	DLT	Conventional Intersection	DLT
1,000	69.77	86.91	119.23	107.77
2,000	70.80	88.36	157.92	119.89
3,000	76.72	90.15	172.55	128.19
4,000	80.14	92.80	553.31	135.57
5,000	85.02	93.11	584.02	139.53
6,000	132.61	94.75	671.11	145.37





5.2 Operational Impacts of DLT Crossover Distance

As mentioned previously, left-turn crossover distance is a critical geometric design element in affecting the storage of left-turn volumes and thus will also influence the capacity of the whole intersection. Short crossover spacing will not able to store the left turn vehicles and can easily cause left-turn queue spillback to the through lanes; whereas, longer crossover spacing will occupy a larger space to build the displaced left turn lanes, which will increase DLT footprint and investment. As shown in Figure 5-5, crossover distance refers to a distance from the secondary intersection to the main intersection. To be specific, in this research, the distance starts from the signal head of the crossover traffic to the signal head controlling the displaced left-turn volumes at the main intersections.

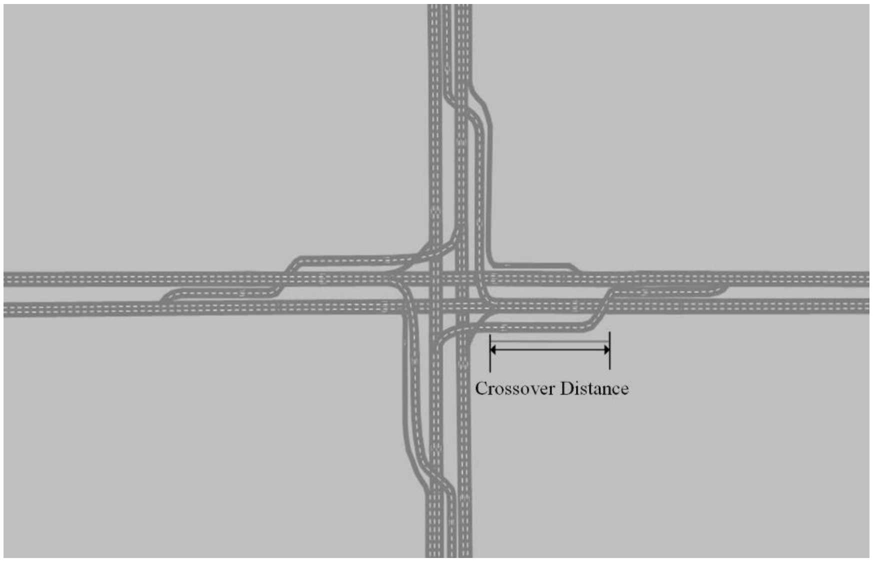


Figure 5-5: Illustration of Left Turn Crossover Distance at a DLT Intersection

5.2.1 Base Model Development

The base model here is still the same one developed in the last section. For the base case, the left turn crossover distance was set at 325 ft, which represented the real geometric design. In addition, the right-turning pockets were set to be 250 ft, and the acceleration lanes are set to be 325 ft.

5.2.2 Scenario Design

To investigate the operational impacts of crossover distance, various scenarios were designed with different left turn crossover distances, different traffic volumes and different left turn percentages.

- Crossover distance (ft): 75, 100, 175, 250, 325, 400, 475, and 550
- Volume (vph): 1,000, 2,000, 3,000, 4,000, 5,000, and 6,000
- Left turn percentage: 15%, 20%, and 25%

In total, 144 scenarios were generated.

5.2.3 Results Analysis

The VISSIM Version 9-10 was used to model and analyze the experimental scenarios. For each run, the simulation time was set to 4,800 seconds, and the warm-up time was 1,200 seconds for each scenario and repeated for 7200 seconds. 10 runs with different random seeds were performed for each scenario. Average delay and travel times were then collected for analysis.

5.2.3.1 Average Delay

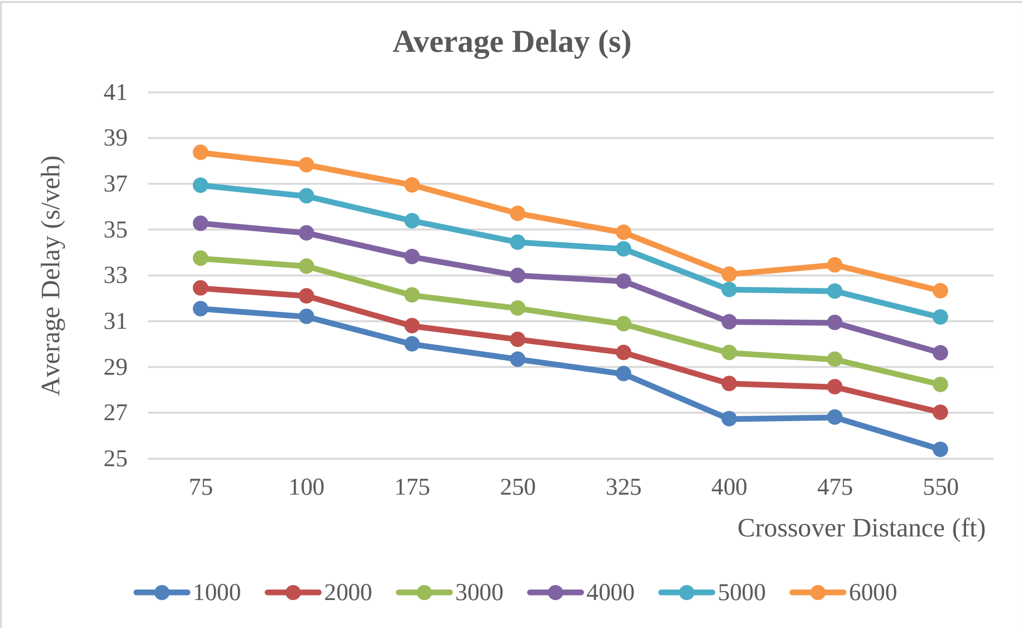
Table 5-7 to Table 5-9 present the simulated average delay for all scenarios. By analyzing results, the following findings were discovered:

- For a given left turn crossover distance, the average delay increased with the increase of traffic volume;
- For most of the cases, the average delay reduced with the increase of crossover distance;
- When left turn crossover distance increased to 400ft and above, there was slightly decrease with the increase of the crossover distance.

15% left turn percentage

Table 5-7: Simulated Delay for 15% Left Turns

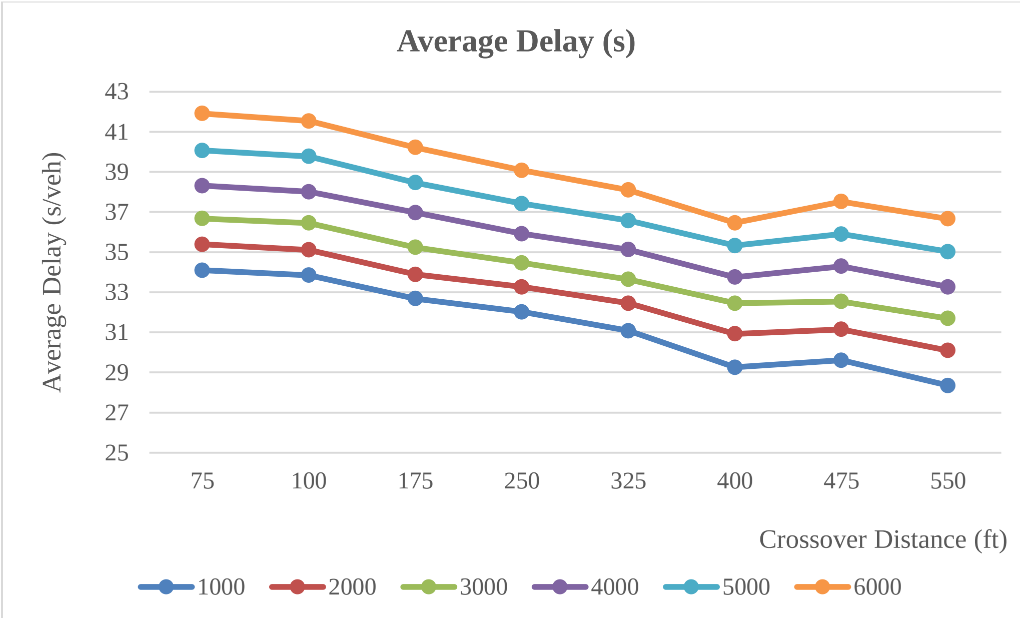
Traffic volume (veh/hr)	DLT Crossover Distance (ft)							
	75	**100**	**175**	**250**	**325**	**400**	**475**	**550**
1,000	31.54	31.20	30.00	29.33	28.70	26.73	26.80	25.40
2,000	32.44	32.10	30.79	30.20	29.63	28.27	28.13	27.02
3,000	33.74	33.40	32.13	31.56	30.88	29.62	29.33	28.23
4,000	35.27	34.85	33.81	32.99	32.74	30.97	30.93	29.61
5,000	36.93	36.46	35.38	34.44	34.15	32.38	32.31	31.17
6,000	38.36	37.82	36.94	35.70	34.87	33.05	33.45	32.32



20% left turn percentage

Table 5-8: Delay Results for 20% Left Turn Volumes for All of the Scenarios

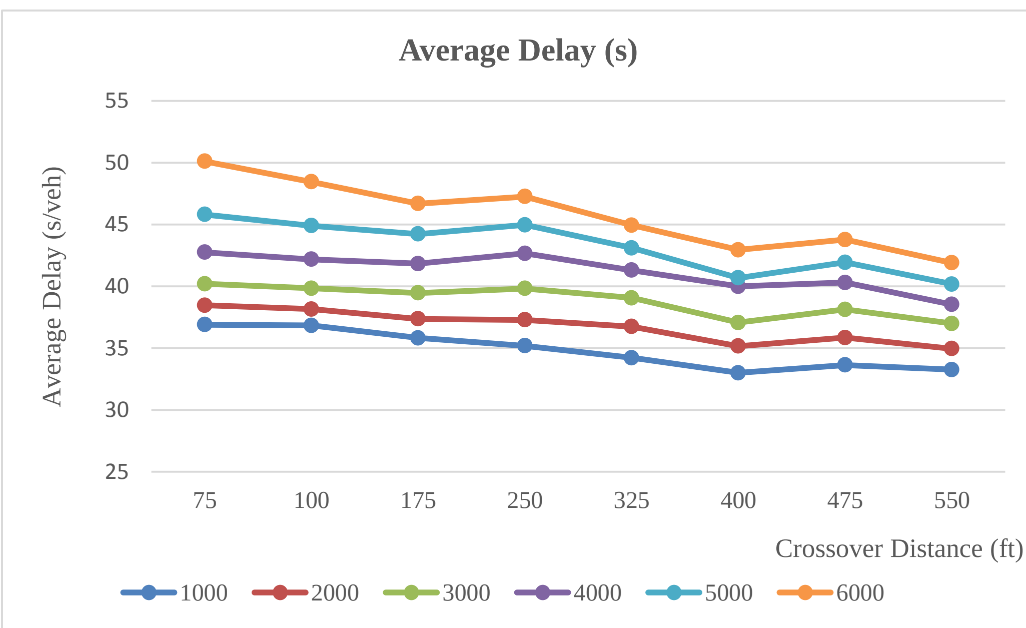
Traffic volume (veh/hr)	DLT Crossover Distance (ft)							
	75	**100**	**175**	**250**	**325**	**400**	**475**	**550**
1,000	34.10	33.85	32.68	32.02	31.08	29.26	29.61	28.35
2,000	35.39	35.11	33.89	33.27	32.45	30.93	31.15	30.10
3,000	36.67	36.45	35.24	34.46	33.64	32.45	32.54	31.69
4,000	38.31	38.01	36.97	35.92	35.13	33.75	34.30	33.27
5,000	40.07	39.77	38.46	37.42	36.57	35.33	35.90	35.02
6,000	41.91	41.54	40.22	39.08	38.10	36.46	37.52	36.66



25% left turn percentage

Table 5-9: Delay Results for 25% Left Turn Volumes for all of the Scenarios

Traffic volume (veh/hr)	DLT Crossover Distance (ft)							
	75	**100**	**175**	**250**	**325**	**400**	**475**	**550**
1,000	36.90	36.83	35.82	35.19	34.22	32.99	33.63	33.26
2,000	38.46	38.15	37.37	37.29	36.74	35.16	35.85	34.96
3,000	40.20	39.84	39.46	39.83	39.06	37.06	38.12	36.99
4,000	42.75	42.17	41.84	42.65	41.30	39.99	40.31	38.53
5,000	45.80	44.90	44.23	44.96	43.10	40.68	41.94	40.18
6,000	50.11	48.45	46.69	47.26	44.94	42.95	43.77	41.89



5.2.3.2 Travel time

Eastbound through (EBT) and eastbound left turn (EBL) travel times were selected for analysis. Figure 5-6 shows the start and end points for these two routes. A is the start point, B is the end point of the eastbound through movement, and C is the end point of the eastbound left turn movement.

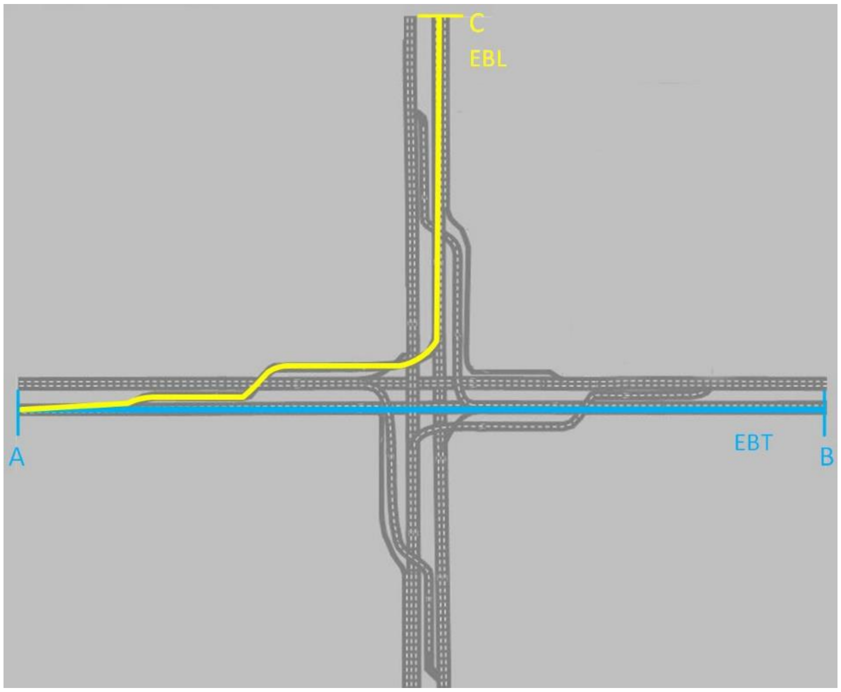
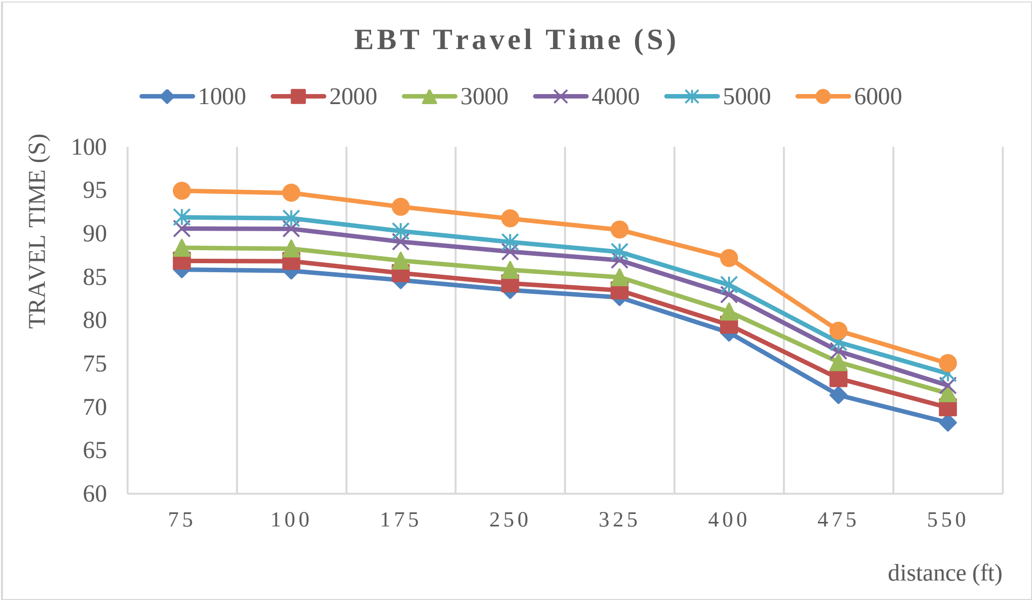


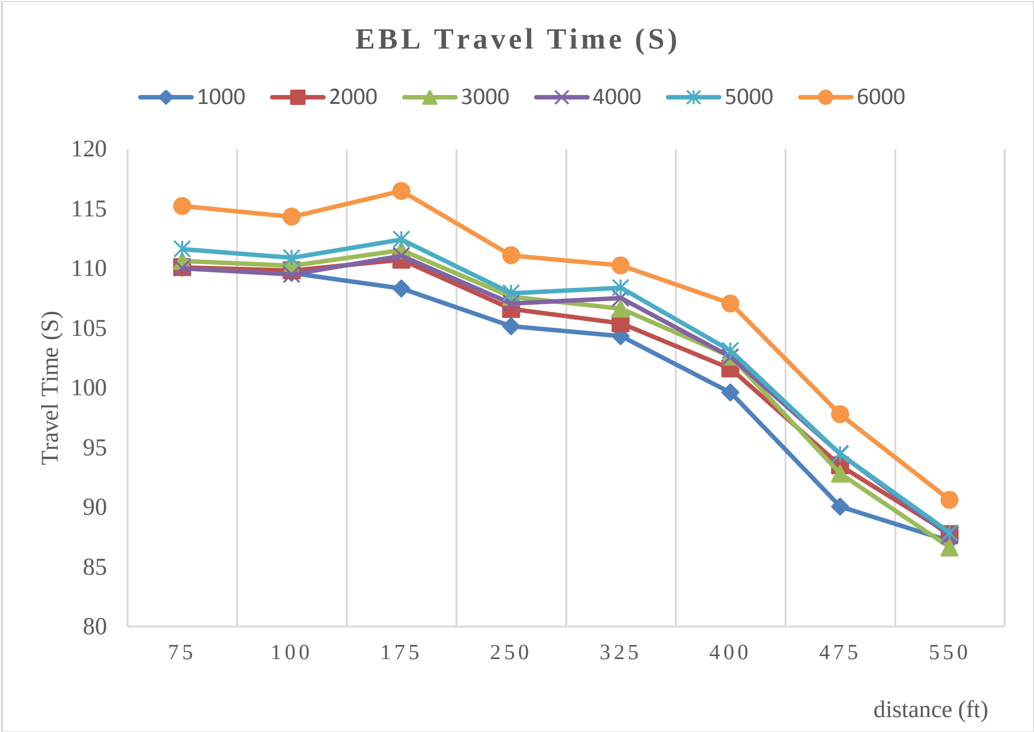
Figure 5-6: Start and End Points for Travel Time Collection

15% left turn percentage

Table 5-10 Simulated Travel Time for 15% Left Turns (s)

	Traffic volumes (veh/hr)	Crossover Distance (ft)							
		75	100	175	250	325	400	475	550
EBT	1,000	85.87	85.72	84.63	83.48	82.65	78.58	71.36	68.19
	2,000	86.86	86.83	85.44	84.26	83.46	79.48	73.31	69.95
	3,000	88.37	88.27	86.88	85.81	84.97	81.00	75.18	71.57
	4,000	90.58	90.56	89.06	87.93	86.95	82.98	76.44	72.49
	5,000	91.89	91.77	90.28	89.02	87.90	84.10	77.47	73.87
	6,000	94.94	94.70	93.10	91.75	90.45	87.18	78.80	75.06
EBL	1,000	110.04	109.60	108.31	105.15	104.31	99.59	90.03	87.14
	2,000	110.08	109.82	110.71	106.59	105.38	101.59	93.48	87.73
	3,000	110.61	110.20	111.52	107.61	106.62	102.60	92.79	86.60
	4,000	110.00	109.48	111.05	107.06	107.50	102.57	94.47	87.57
	5,000	111.61	110.88	112.41	107.92	108.37	103.10	94.43	87.83
	6,000	115.21	114.32	116.47	111.08	110.24	107.05	97.76	90.58



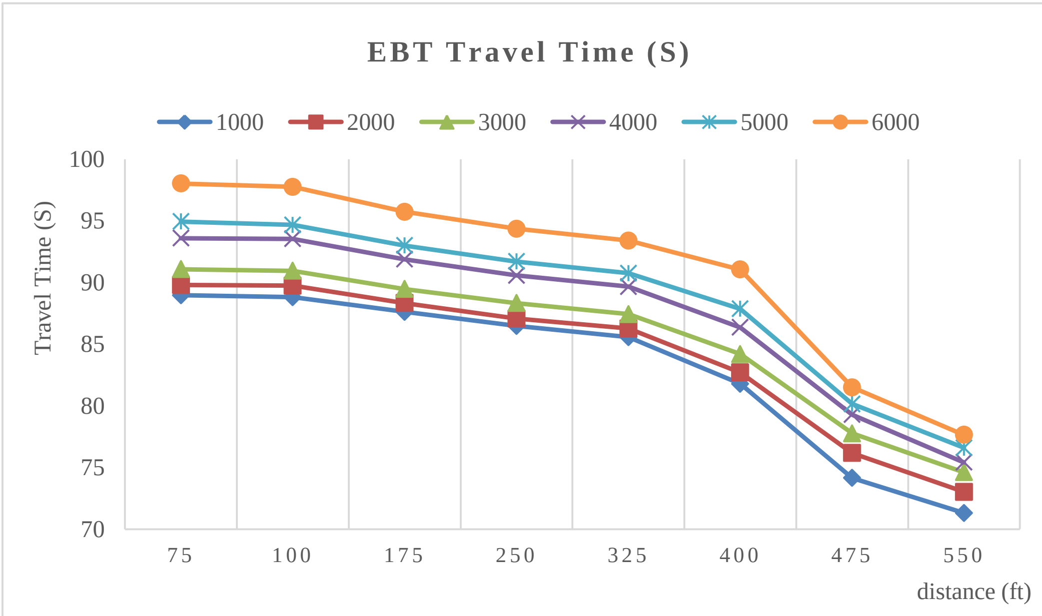


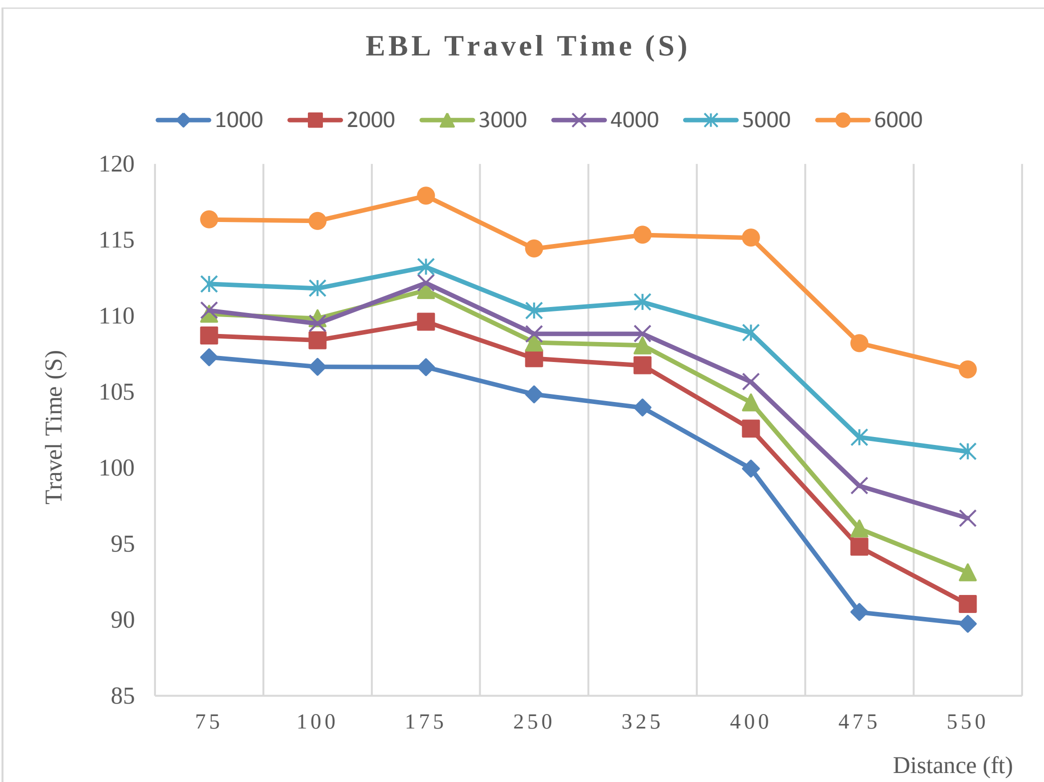
<u>*20% left turn percentage*</u>

Table 5-11: Simulated Travel Time for 20% Left Turns (s)

	Traffic volumes (veh/hr)	**DLT Crossover Distance (ft)**							
		75	**100**	**175**	**250**	**325**	**400**	**475**	**550**
EBT	**1,000**	88.97	88.81	87.62	86.49	85.58	81.79	74.17	71.33
	2,000	89.80	89.75	88.33	87.08	86.28	82.71	76.18	73.04
	3,000	91.09	90.95	89.47	88.34	87.44	84.20	77.77	74.63
	4,000	93.60	93.55	91.89	90.58	89.67	86.37	79.30	75.43

	5,000	94.94	94.67	93.00	91.71	90.76	87.87	80.16	76.61
	6,000	98.03	97.76	95.73	94.36	93.40	91.06	81.51	77.66
EBL	**1,000**	107.27	106.64	106.61	104.83	103.95	99.94	90.49	89.73
	2,000	108.69	108.38	109.60	107.19	106.73	102.56	94.79	91.02
	3,000	110.12	109.83	111.68	108.24	108.05	104.30	95.99	93.12
	4,000	110.35	109.49	112.16	108.80	108.82	105.66	98.81	96.67
	5,000	112.09	111.81	113.22	110.34	110.90	108.88	102.00	101.06
	6,000	116.33	116.24	117.89	114.42	115.32	115.13	108.20	106.47

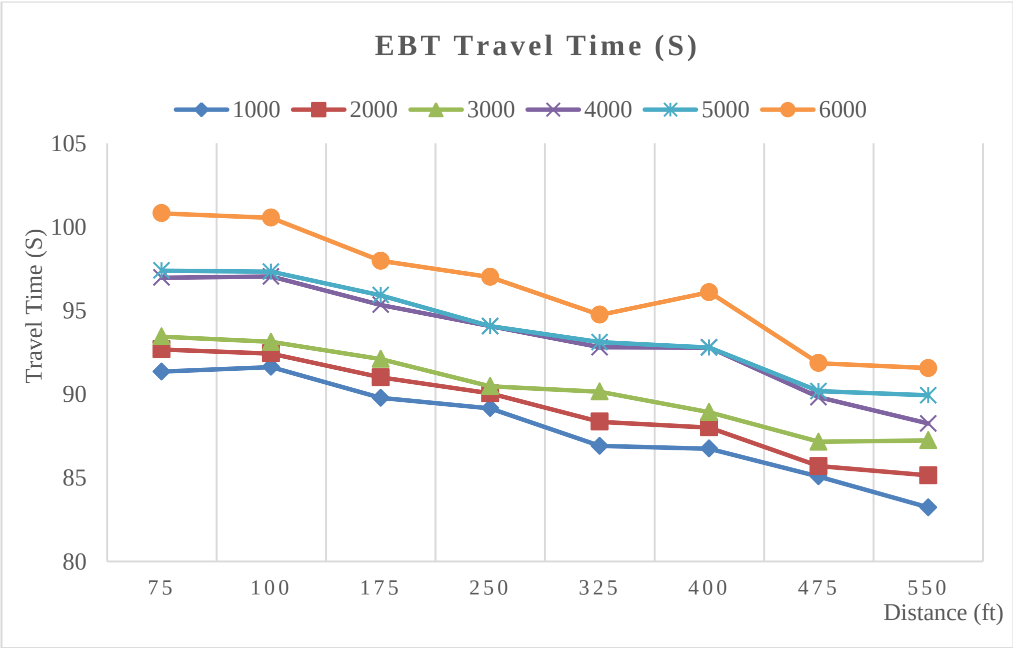


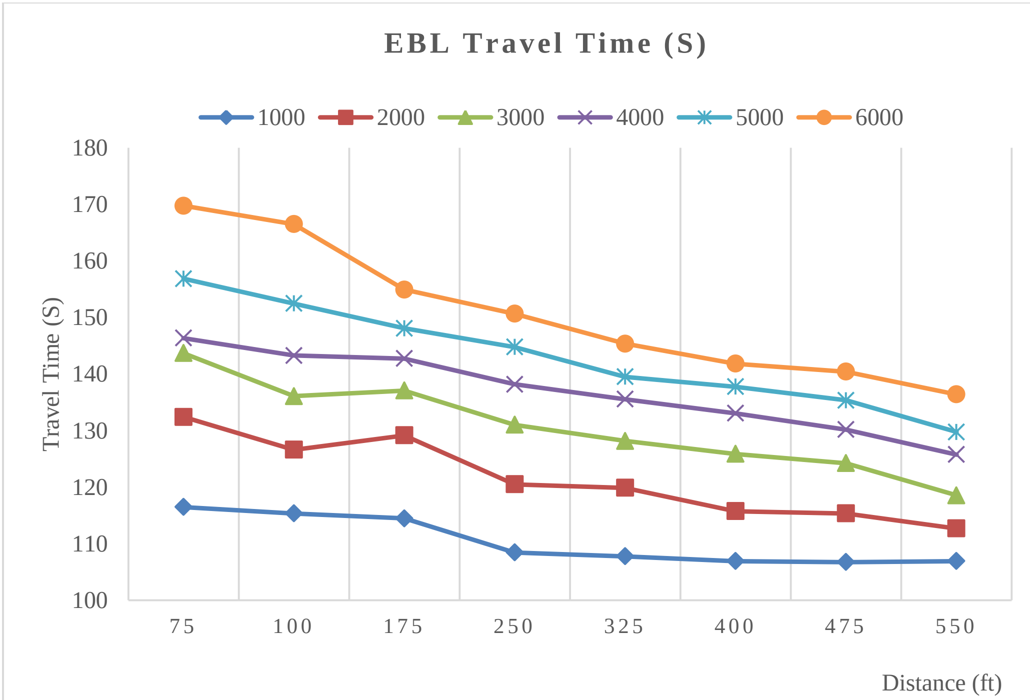


25% left turn percentage

Table 5-12: Simulated Travel Time for 25% Left Turns (s)

	Traffic volumes (veh/hr)	DLT Crossover Distance (ft)							
		75	**100**	**175**	**250**	**325**	**400**	**475**	**550**
EBT	**1,000**	91.35	91.63	89.78	89.16	86.91	86.75	85.08	83.23
	2,000	92.68	92.43	91.01	90.05	88.36	88.01	85.70	85.15
	3,000	93.45	93.13	92.11	90.48	90.15	88.93	87.16	87.24
	4,000	96.97	97.04	95.34	94.07	92.80	92.80	89.82	88.25
	5,000	97.39	97.32	95.92	94.07	93.11	92.78	90.18	89.93
	6,000	100.82	100.55	97.97	97.00	94.75	96.10	91.85	91.57
EBL	**1,000**	116.50	115.35	114.50	108.45	107.77	106.94	106.75	106.94
	2,000	132.43	126.63	129.17	120.51	119.89	115.77	115.37	112.70
	3,000	143.72	136.09	137.10	131.05	128.19	125.88	124.26	118.56
	4,000	146.38	143.29	142.75	138.18	135.57	133.06	130.19	125.76
	5,000	156.87	152.49	148.08	144.79	139.53	137.77	135.36	129.75
	6,000	169.77	166.51	154.94	150.68	145.37	141.84	140.42	136.41





Tables 5-10 to 5-12 are simulated travel time results for different left turn percentages (15%, 20% and 25%). It can be seen that with the increase of crossover distance, the EBT and EBL travel times both decreased.

5.3 Summary

The objective of this chapter is to evaluate the operational performance of the DLT intersection and the operational impact on left turn crossover distance. To achieve the research goals, a simulation-based analysis was conducted. VISSIM was utilized to build simulation models for both the conventional intersection and the DLT intersection. Various traffic volumes and left turn percentages were considered to design different scenarios. Average delay and travel time were collected. By analyzing results, it can be seen that the DLT intersection produced less delay for all scenarios compared with conventional intersections, especially when traffic volume was moderate to high or left turn percentage was high. For the travel time, the results indicated that the conventional intersection produced less EBT travel time than the DLT intersection when traffic volume was less. When traffic volume reached 6,000 vph, the DLT intersection started to show its advantage and had less travel time. For EBL travel time, the DLT intersection always performed better than the conventional intersection, especially with higher traffic volume.

In addition, operational performance of different left turn crossover distances was tested for a same DLT intersection. The simulation results show that intersection average delay reduced with the increase of crossover distance. In addition, when left turn crossover distance increased to 400ft and above, there was slightly decrease with the increase of the crossover distance. For the travel time, both EBT and EBL travel times decreased with the increase of crossover distance. Therefore, when considering the construction cost and the accessibility to make a left turn for vehicles from drives nearby, around 400 ft is recommended to place the left turn crossover.

Chapter 6. Safety Analysis of the Displaced Left Turn Design

6.1 Introduction

This chapter investigated the safety impacts of implementing two DLT intersections. Case studies were conducted at both DLT intersections in in San Marcos, Texas.

6.2 Study Locations

Two DLT intersections were selected as study locations for this research, which are Loop 82 @ IH 35 and SH 80 @ IH 35 in San Marcos, Texas.

Figure 6-1 is the first study location, Loop 82 @ IH 35 To analyze the safety impacts of DLT design at these two intersections, crash data in the past 8 years (Jan. 2011-Apr. 2018) were obtained from TxDOT's Crash Records Information System (CRIS) for conducting before and after studies.

For this location, a total of 40 months before data (from Jan.2011 to Apr.2014) with 167 crashes and 48 months' after data (from May.2014 to Apr.2018) with 169 crashes were studied.

Figure 6-1: Loop 82 @ IH 35, San Marcos, Texas.

Following are the basic roadway and traffic conditions at Loop 82 @ IH 35:

- It is designed and opened by TxDOT on May 1st, 2014.
- It is a partial DLT design with a two-lane displaced left turn lane operated for the eastbound traffic on the Loop 82.
- Loop 82 has one through lane and one right turn lane for eastbound traffic. It has one through lane and one through and right turn shared lane for the opposite direction.

- IH 35 Frontage Rd has one through lane, one right turn lane and two left turn lanes and one U-turn lane for northbound traffic. It has one through lane, one through and left turn shared lane, one right turn lane and one U-turn lane for the southbound traffic.
- Posted speed limit is 35 mph for traffics on Loop 82, 45 mph for traffics go through IH 35 Frontage Rd.

Figure 6-2 is the second study location at SH 80 @ IH 35, a total of 45 months before data (from Jan.2011 to Oct 12.2014) with 246 crashes and 43 months' after data (from Oct 12.2014 to Apr.2017) with 267 crashes were studied.

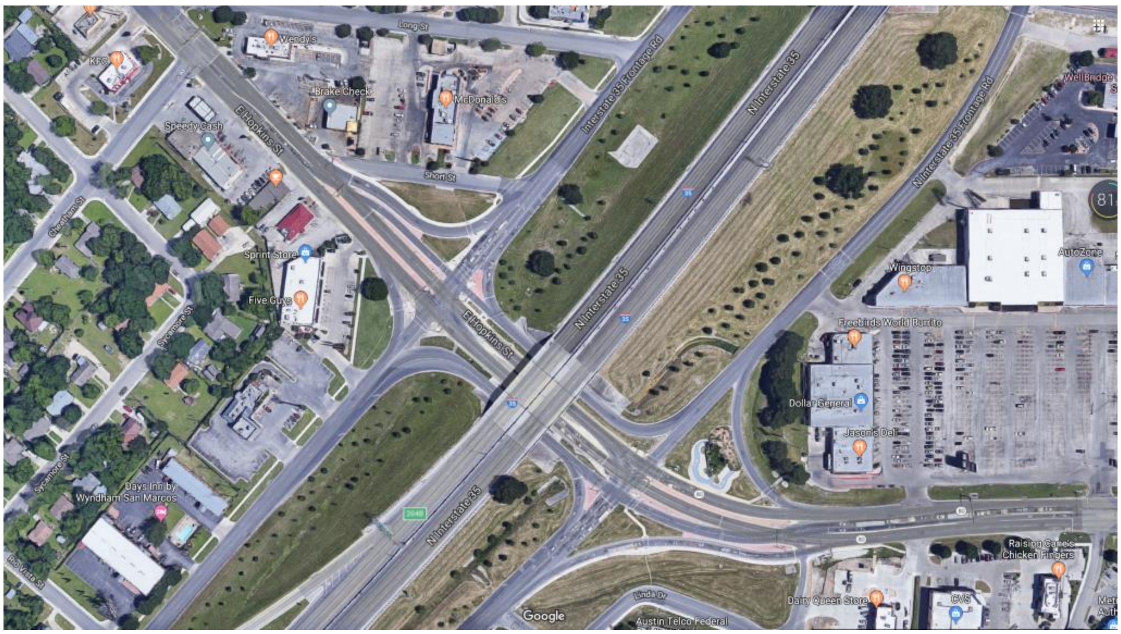


Figure 6-2: SH 80 (Hopkins Street) @ IH 35, San Marcos, Texas

Following are the basic roadway and traffic conditions at SH 80 @ IH 35:

- It is designed and opened by TxDOT on October 12st, 2014.
- It is a partial DLT design with two displaced left turn crossover intersection installed at SH 80 (Hopkins Street). Among them, a one-lane displaced left turn lane operated for the eastbound traffic, and a two-lane displaced left turn lane operated for the westbound traffic.
- SH 80 has two through lanes and one right turn lane for each side.
- IH 35 Frontage Rd has one through lane, one right-turn lane, one left-turn lane, one through and left-turn shared lane and one U-turn lane for both directions.
- Posted speed limit is 35 mph for traffics on SH 80, 45 mph for traffics go through IH 35 Frontage Rd.

6.3 Data Collection

To analyze the safety impacts of the DLT design at these two intersections, crash data and police reports for the past eight years (January 2011-April 2018) were obtained from TxDOT's Crash Records Information System (CRIS) for use in conducting the before and after studies.

For Loop 82 @ IH 35, we studied a total of 40 months of data (from January 2011 to April 2014) before DLT was installed, which included 167 crashes, and a total of 48 months of data (from May 2014 to April 2018) after DLT was installed, which included 169 crashes.

For SH 80 @ IH 35, we studied a total of 45 months of before data (from January 2011 to October 12, 2014) with 246 crashes and 43 months of after data (from October 12, 2014 to April 2017) with 267 crashes.

6.4 Collision Diagram Based Safety Analysis

6.4.1 Methodology

In this study, two approaches were used to analyze the safety impacts of converting a conventional intersection to a displaced left turn intersection, i.e., we used statistical analysis and collision diagram-based analysis.

Approaches 1: Statistical analysis

First, we compared the monthly crash rates before and after implementing the DLT. However, for both study locations, crashes that occurred during the construction period were excluded from the data to eliminate crashes caused by construction. In addition, the change point analysis was used to determine the critical value of the number of crashes. We used Change-Point Analyzer, which is a shareware software package for analyzing time-ordered data to determine whether a change has occurred. The software can detect multiple changes, and it provides both confidence levels and confidence intervals for each change.

Approaches 2: Collision diagram-based analysis

For the collision diagram-based analysis, for each of the two selected study intersections, one diagram before a collision and one diagram after a collision were developed to identify the patterns and locations where certain types of crashes occurred frequently. There are four steps to develop collision diagrams:

- Draw base maps of before and after conditions for both locations
- Extract police reports for crashes occurred at the selected intersections
- Review detailed police reports of these crashes carefully
- Finally, based on the locations and types of the crashes, the crashes were marked on the base maps to develop the collision diagrams.

Figure 6-3 is one of the developed collision diagrams.

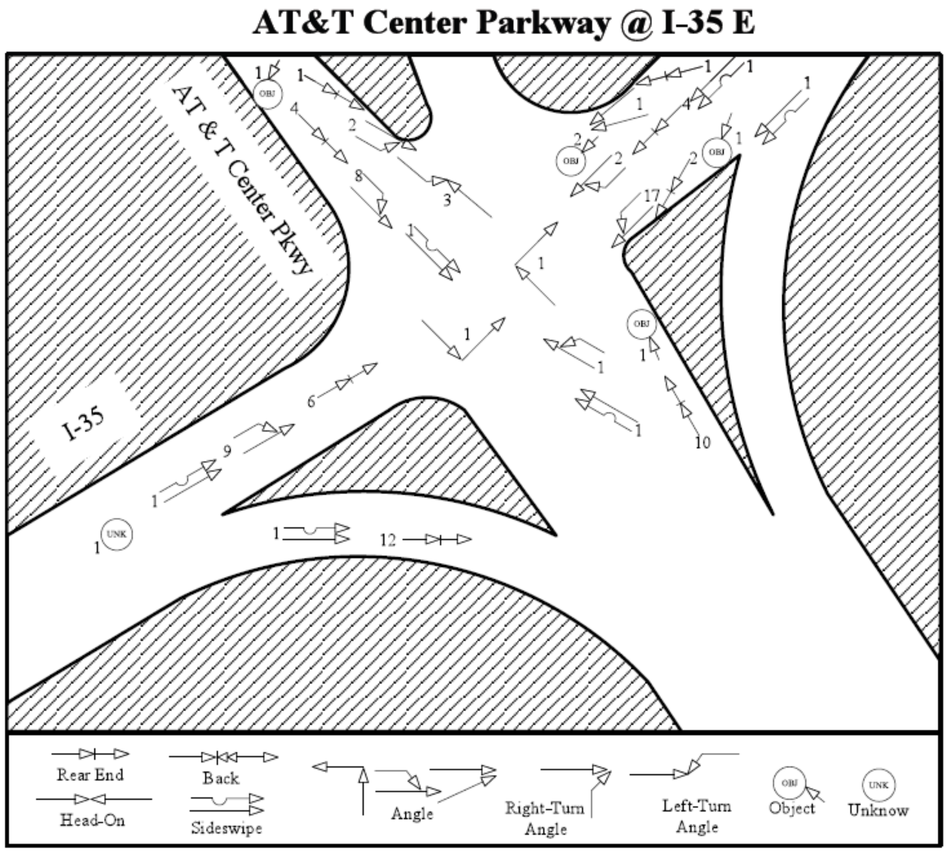
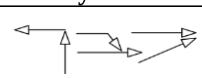
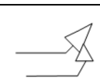
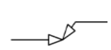
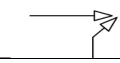
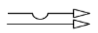
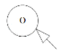
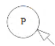


Figure 6-3: Sample Collision Diagram the Team Developed for TXDOT Project 0-6112: Development of Guidelines for Triple Left and Dual Right-Turn Lanes

In this figure, different symbols indicate different types of crashes, and the numbers beside the symbols are the numbers of the same type of crashes that occurred at the same location. There is a total of 11 different types of crashes marked in the collision diagrams, i.e., angle, dual left turn angle, intersect, left-turn angle, rear-end, right-turn angle, head on, U-turn, Out of control, sideswipe, object, and pedestrian-related crashes. The definitions of these types of crashes along with their symbols are provided in Table 6-1.

Table 6-1: Symbols and Definitions of Crash Types in the Collision Diagrams

Type	Symbol	Definition
Angle		One through vehicle collides with another through vehicle in the crossing direction, or two vehicles collide while traveling in the same direction during lane change.
Dual left turn		An accident involving two vehicles traveling same direction making a left turn while either one fails to maintain in their own lane and collides the other vehicle.
Left-turn angle		An accident involving two opposing vehicles when one of them is turning left.
Rear-end		The front of one vehicle collides with the rear of another vehicle while both vehicles are traveling in the same direction.

Right-turn angle		One right-turning vehicle collides with another vehicle on the cross street.
Head on		One vehicle hit another opposing vehicle's front end.
U- turn		Crash happened when one vehicle performs a 180-degree rotation to reverse of their travel and hit with others.
Out of control		The vehicle started to act of spinning or twirling because of vehicle mechanical problems or driver related affects, e.g. intoxicant.
Sideswipe		One vehicle impacts another traveling in the same direction by "swiping" along the surface with the direction of travel.
Object		One vehicle hits a roadside object, e.g., the curb.
Pedestrian		An accident in which a vehicle and a pedestrian collide.

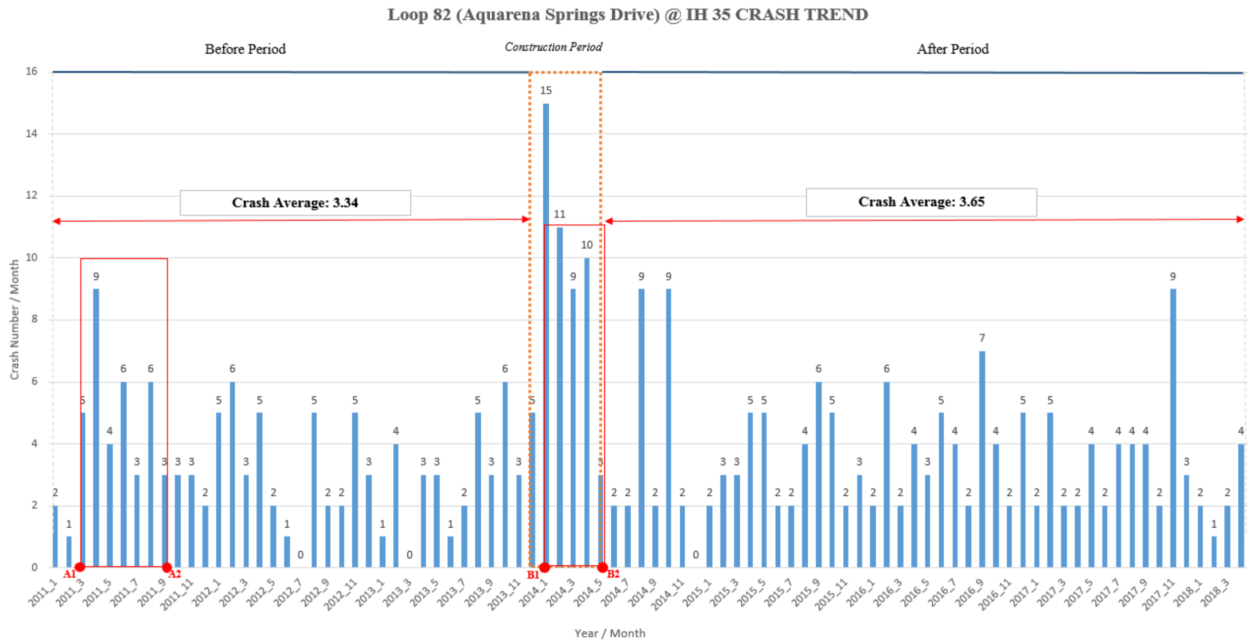
In the following sections, the developed collision diagrams at both study locations and the key findings are discussed.

6.4.2 RESULTS ANALYSIS

6.4.2.1 Statistical analysis

Location 1. Loop 82 (Aquarena Springs Drive) @ IH 35

Intersection 1 is the first phase of the displaced left-turn intersection project in San Marcos, Texas. It stretches 0.32 miles and has two at-grade intersections, where IH 35 frontage roads meet with Loop 82 (Aquarena Springs Drive). This location was converted to one displaced left turn lane for the northbound traffic, which opened on May 1, 2014. Figure 2 presents the monthly crash frequency during the study period. It can be seen that a relatively high number of crashes occurred during the construction periods. The before-construction average crash frequency was 3.34 per month, and, after the construction was completed, the average crash frequency is 3.65 per month. This suggests a slight increase of 9% in the crash frequency, but it is not a statistically significant difference, i.e., the p-value of the T-test statistic is 47% > 5%. The analysis of the change point showed that there were four significant change points, i.e., A1: March 2011; A2: September 2011; B1: January 2014; and B2: May 2014. These four change points form two change periods, i.e., Period A and Period B. Period A (from March 2011 to September 2011) was about three years before the implementation of the DLT design and the change in Period A was not related to DLT. Period B (from January 2014 to May 2014) is the construction period, and the increase in the crash frequency likely was related to the construction of the roadway, not DLT. Therefore, based on the analysis of the monthly crash frequency data, the implementation of the DLT design has had significant safety impacts.

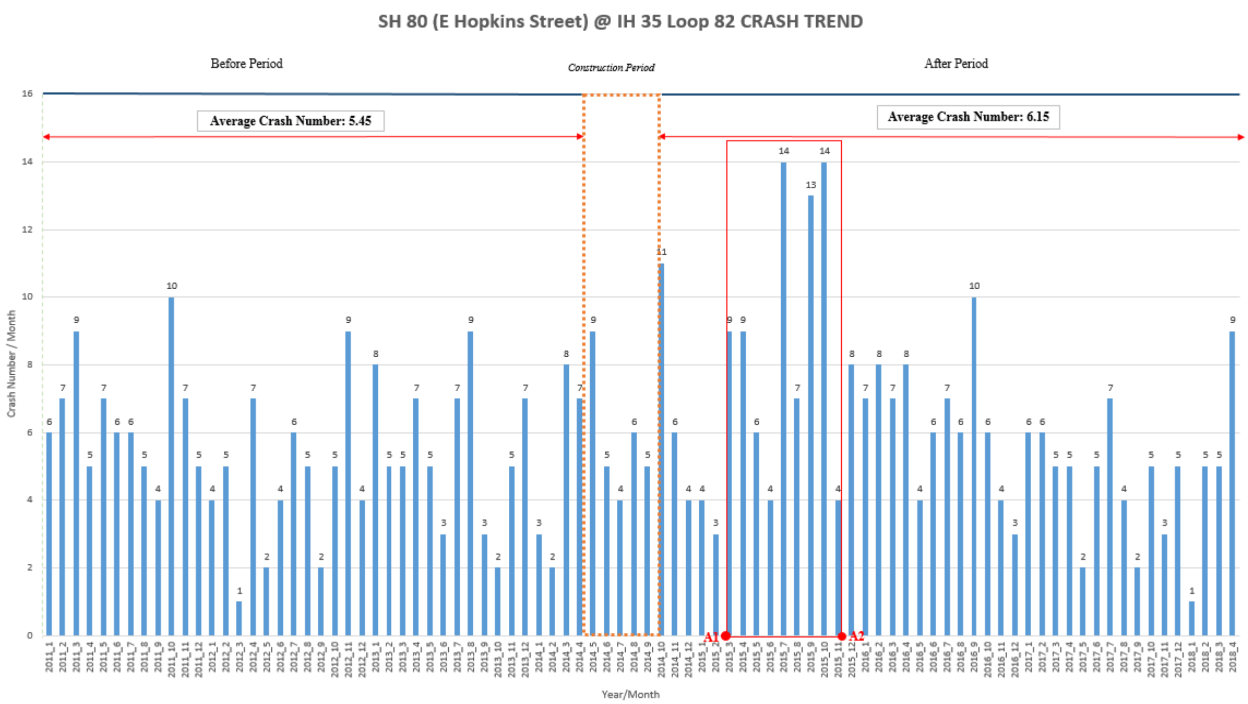


Change Point	Month, Year	Confidence Level
A1	3, 2011	95%
A2	9, 2011	98%
B1	1, 2014	99%
B2	5, 2014	91%

Figure 6-4: Monthly Crash Frequency during the Study Period (May 2014 to April 2017) at Intersection 1 (Loop 82, Aquarena Springs Drive @ IH 35)

Location 2. SH 80 (Hopkins Street) @ IH 35

The second innovative intersection project on Hopkins Street opened on October 12, 2014, a few months later than the completion of the Aquarena Springs DLT project. The second project was 0.45-mile-long, and it had two at-grade intersections where the IH 35 frontage roads meet at SH 80 (Hopkins Street). This location includes two displaced left-turn lanes, one of which allows eastbound traffic to turn north onto the IH35 frontage road (EB DLT), and the other allows the westbound traffic to move south of the IH 35 frontage road (WB DLT). Figure 4 presents the monthly crash data during the study period. Before DLT, the average crash frequency was 5.45 crashes per month; after DLT, the average crash frequency is 6.15 crashes per month. This is about a 12% increase in the crash frequency, and it also is not a statistically significant value. (The p-value of the T-test statistic is 18% > 5%). The change point analysis showed that there were only two significant change points, i.e., A1: March 2015 and A2: November 2015. These two change points form an eight-month change period (from March 2015 to November 2015), and the average crash frequency during this eight-month period was 8.89 crashes per month, which is significantly higher than the overall average of the other months that were studied. (The p-value of the T-test statistic is 3% < 5%). Since the DLT intersection at this location was placed in service on October 12, 2014, it is apparent that the crash frequency increased substantially during the first year, after which it decreased to the normal level. This result indicates that there is a learning curve for travelers to become familiar with this new design. Therefore, both additional law enforcement and additional driver education are needed, especially during the first year after the implementation of DLT.



Change Point	Month, Year	Confidence Level
A1	3, 2015	98%
A2	11, 2015	100%

Figure 6-5: Monthly Crash Frequency during the Study Period (January 2011 to October 12, 2014) at Intersection 2 on SH 80 (Hopkins Street) @ IH 35

6.4.2.2 Collision diagram-based analysis

Location 1. Loop 82 (Aquarena Springs Drive) @ IH 35

Location 1 is the first phase of the displaced left turn intersection project in San Marcos, Texas. It stretches 0.32 miles long and contains 2 at grade intersections where IH 35 frontage roads meet with the Loop 82 (*Aquarena Springs Drive*). This location was converted to one displaced left turn lane for the northbound traffic, which opened on May 1st, 2014.

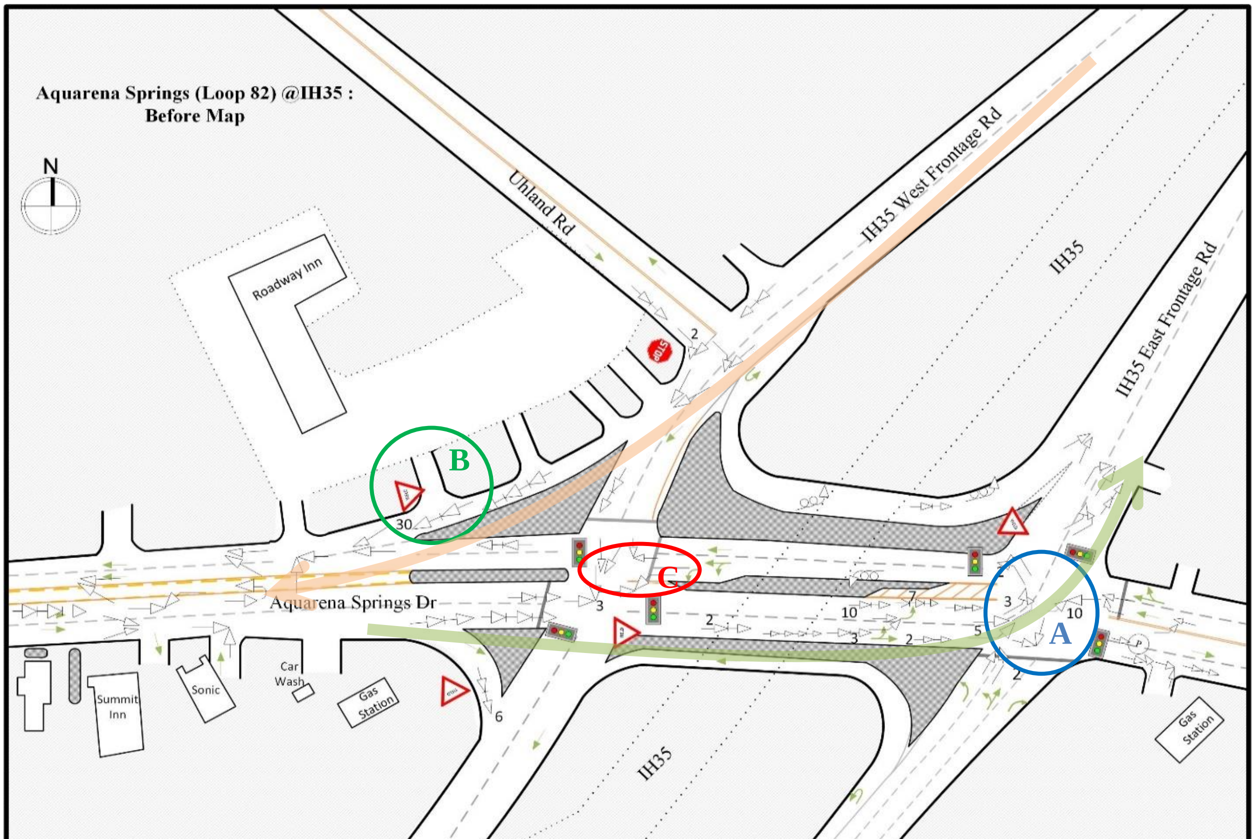


Figure 6-6(a). Collision Diagrams Before the Implementation of DLT (January 2011 to April 2014)

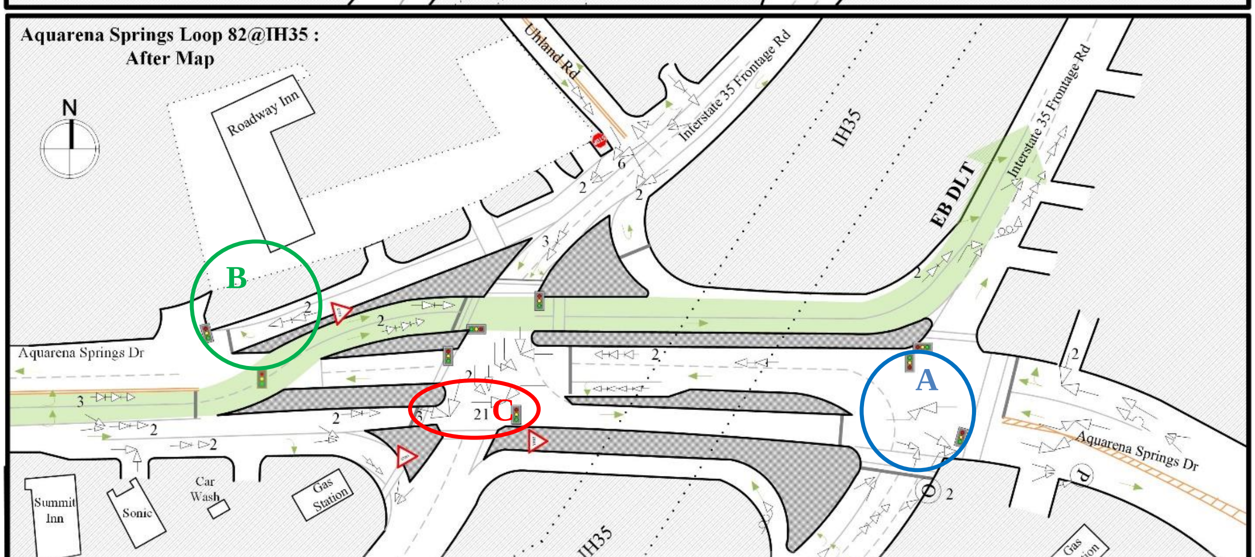


Figure 6-6(b). Collision Diagrams After the Implementation of DLT (May 2014 to April 2017)

Figure 6-6: Collision Diagrams at Intersection 1 (Loop 82, Aquarena Springs Drive @ IH 35

Figure 6-6(a) presents the collision diagram for this intersection before the implementation of DLT. This diagram allows the identification of the overall safety problems at this location, and they are discussed below.

Safety problems before the implementation of DLT

Before the implementation of DLT at this location, there were two places where crashes occurred frequently (presented below) due to the two heavy traffic flows:

1. Traffic flow entering IH 35: Many vehicles move eastbound on Aquarena Springs Drive, make left turns at Location A (blue circle), and then merge onto the IH 35 east frontage road. Due to the heavy left-turn traffic at location A, many crashes related to left turns occurred at this location, e.g., there were 10 left-turn crashes and five dual left-turn crashes from January 2011 to April 2014. By conducting further analysis based on police reports, three major factors were identified that contributed to the high left-turn crash rate before implementing DLT, i.e.,

   - Disregarding the left turn signage

   - Drivers making left turns failed to yield the right of way

   - Drivers making dual left turns failed to keep their vehicles in a single lane

2. Traffic flow exiting IH 35: Many vehicles exit from the southbound lanes of IH 35, merge onto the west frontage road of IH 35, and then make right turns at location B (red circle) to merge into the traffic on Aquarena Springs Drive. Before the implementation of DLT, this right-turn merge point was controlled by a “Yield” sign. Due to the high volume of vehicles making right turns and the high volume of traffic on Aquarena Springs Drive, it is difficult for the drivers who want to make a right turn to find a sufficient gap to make a safe merge, so a long queue of vehicles forms in the right turn lane, which is the reason for the high rate of rear-end crashes at this location (30 crashes in 40 months).

Figure 6-6(b) presents the collision diagram for this intersection after the implementation of DLT. By comparing the collision diagrams before and after the implementation of DLT, several findings related to the safety impacts of displaced left turn were identified, and they are discussed below.

Finding A: Northbound left-turn related crashes decreased after the implementation of DLT at Location A (blue circle)

Since DLT eliminated left-turn movements at this intersection, only one left-turn crash has occurred here since DLT was implemented. This crash occurred in November 2014, a few months after the completion of the DLT project. The driver was unfamiliar with the new design and disregarded the “no left turn” sign late at night. Subsequently, no other left-turn crash had occurred at this location during our study period from May 2015 to April 2017.

Finding B: Rear-end crashes were reduced after the implementation of DLT at Location B (green circle)

At this location, another safety benefit gained by implementing the DLT design was the reduction of rear-end crashes at the point where traffic from IH 35 westbound frontage road merges onto Aquarena Springs Drive (*Location B*: *green circle*). After installing DLT, a traffic light was added at this point, and it is coordinated with the signal light that was installed to control the displaced left-turn traffic at the left-turn crossover location. Because of this change, the merging traffic can merge safely during the time the displaced left-turn traffic has the green light to move across to the left side. As a result, the rate of rear-end crashes at this location decreased significantly to two crashes in 35 months.

Finding C: Left-turn crashes increased after the implementation of DLT at location C (red circle)

Despite these improvements, some crash rates increased unexpectedly for the southbound left turn traffic after the implementation of DLT. At location C (red circle) in Figure 2, only one left-turn crash occurred before implementation of DLT, while 21 left-turn crashes have occurred at this location after the implementation of DLT.

Based on the descriptions in the police reports, the major cause for this type of crashes is that the left turn drivers failed to yield the right of way at the permissive left-turn phase. This very likely was caused by the geometric change after the implementation of DLT. To move the displaced left-turn traffic, an additional lane was added at the left-most side and the EB traffic through the lane was reduced from two lanes to one lane. As a result, EB through traffic volume per lane increased, and it is difficult for the WB left-turn vehicles to find a safe space between oncoming vehicles to make turns during the permissive phase.

Location 2. SH 80 (Hopkins Street) @ IH 35

Figure 6-7(a) shows the collision diagram that was developed for this intersection before the implementation of DLT. This diagram indicate that the highest crash rate is at location A (green circle), where the right turn traffic from the frontage road for IH35 south merges with the traffic on SH 80. Similar to Intersection 1, before the implementation of DLT, this right-turn merge point was controlled by a yield sign. Due to the high right-turn volume and the high traffic volume on SH 80, it is difficult for right-turn vehicles to find sufficient gaps to merge safely, so a long queue forms in the right-turn lane, and this caused the high rate of rear end crashes at this location (27 crashes in 43 months).

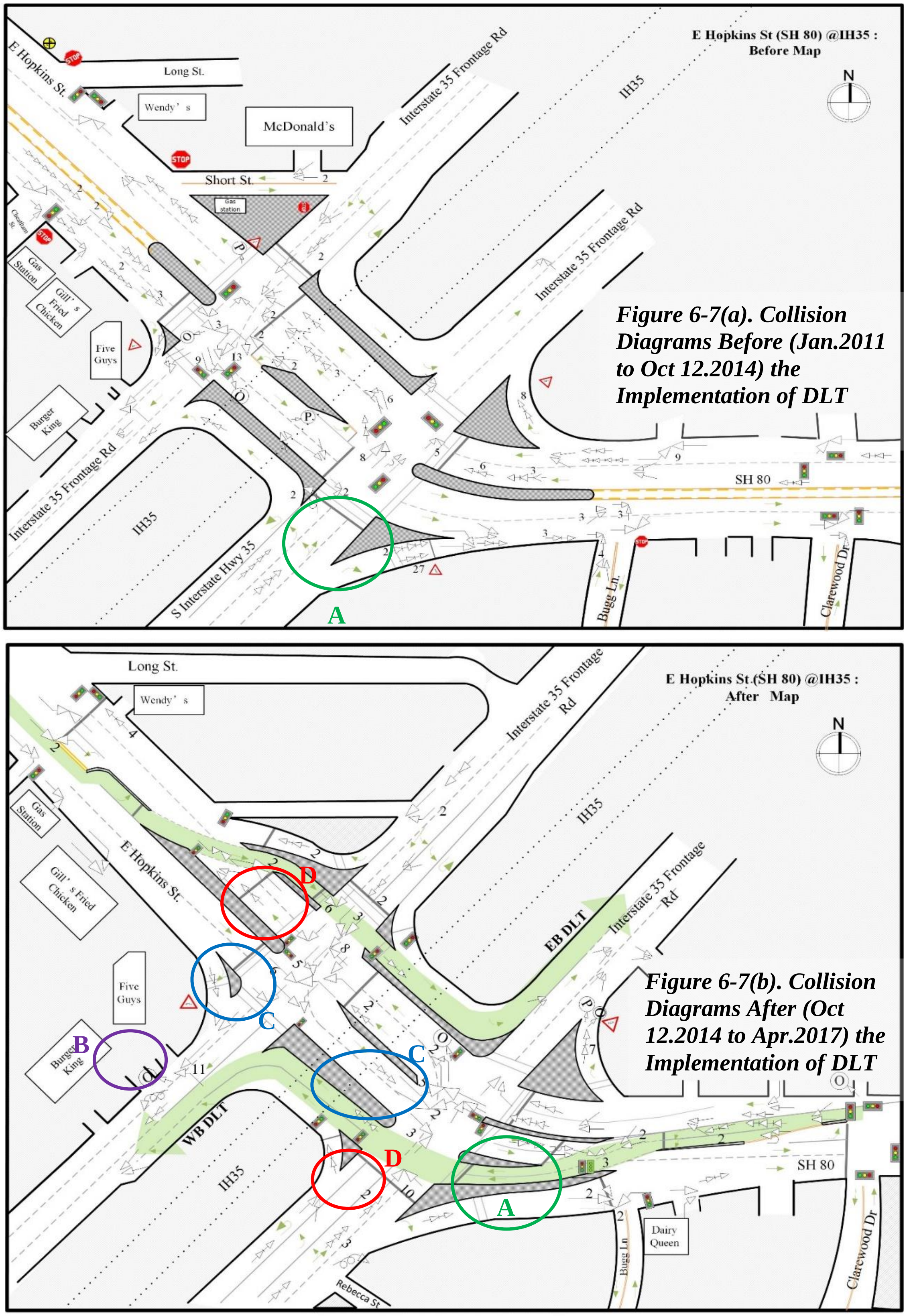


Figure 6-7(a). Collision Diagrams Before (Jan.2011 to Oct 12.2014) the Implementation of DLT

Figure 6-7(b). Collision Diagrams After (Oct 12.2014 to Apr.2017) the Implementation of DLT

Figure 6-7: Collision Diagrams at Intersection 2 SH 80 (Hopkins Street) @ IH 35

Figure 6-7(b) presents the collision diagram for this intersection after the implementation of DLT. By comparing the collision diagrams before and after DLT, several findings related to the safety impacts of displaced left turns were identified and discussed.

Finding A: Rear-end crashes decreased after the implementation of DLT at Location A (green circle).

After installing DLT, the rear-end crash rate at location A was reduced significantly. Similar to Intersection 1, at this right turn merge point, a traffic light was added, and the right-turn traffic can merge safely during the time the displaced left-turn traffic has the green light for moving across to the left side. As a result, the rear-end crash rate at this location was reduced significantly, i.e., to only 1 crash in 43 months.

Finding B: Angle crashes increased at a downstream location of the WB DLT at Location B (purple circle)

As circled in green, 11 angle crashes occurred at a downstream location of the WB DLT near a driveway on the west frontage road for IH 35. The crash reports for 11 crashes indicated that the high rates of crashes involving right turn angles occurred right after the drivers of displaced left-turn vehicles made left turns and tried to make right turns into the shopping plaza at the corner of this intersection. Figure 4-8 shows the vehicles' travel paths before and after their left turns. The blue represents the turning path before the implementation of DLT, and the red lines represent the turning path after the implementation of DLT. The green dashed line represents the upstream through traffic from the frontage road for IH 35 west. Figure 6-8 shows that, because of the DLT design, drivers of left-turn vehicles must make more lane changes to access the shopping plaza on the right side of the roadway. These lane changes must be done immediately after they make turns through the DLT lane, which increases the chance of colliding with the through-movement vehicles from the frontage road of IH 35 west.

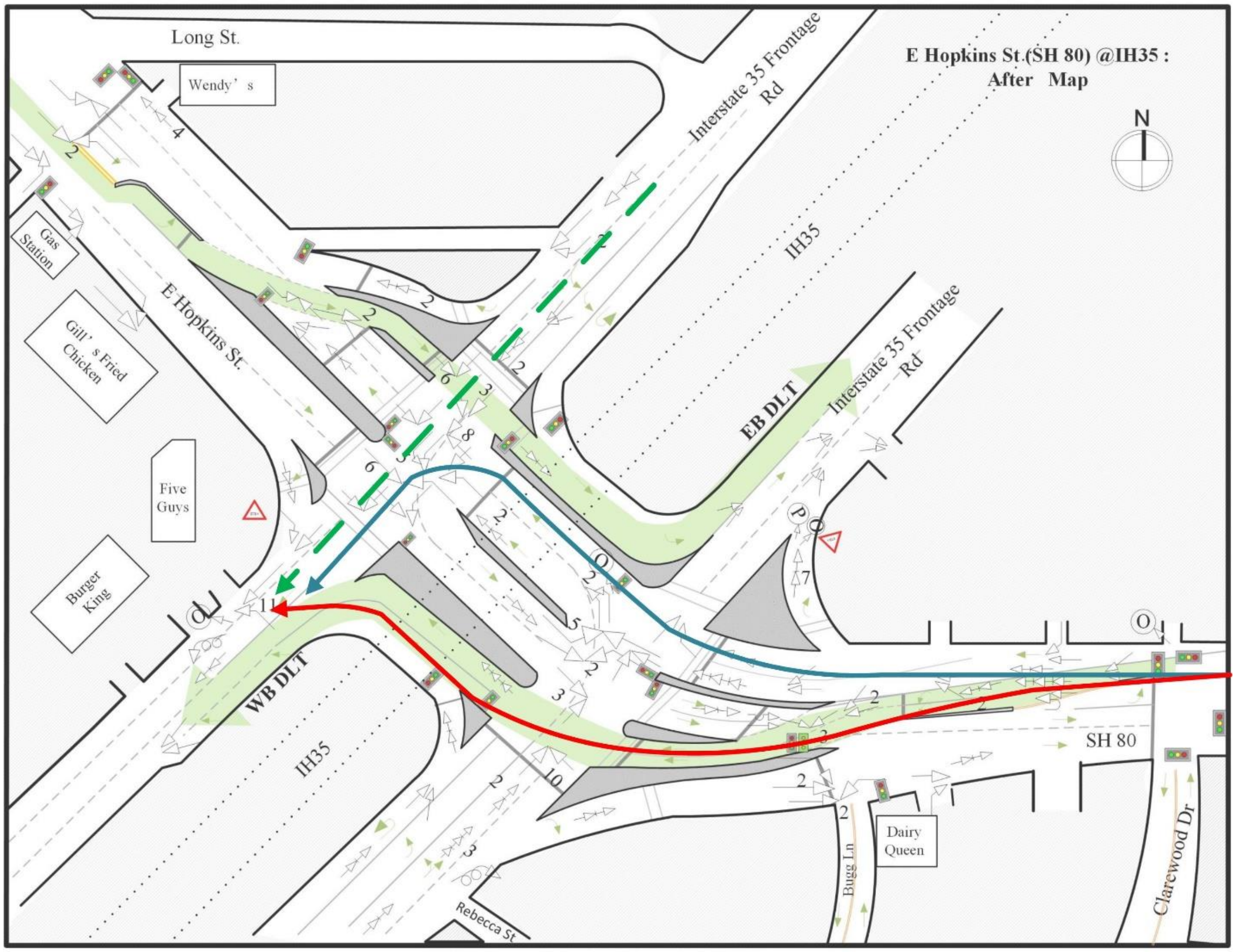


Figure 6-8: Diagram Comparing the Paths of Vehicles before and after Their Southbound Left-Turn Movements

<u>Finding C: Illegal left-turn crashes increased after the implementation of DLT at location Cs (blue circle)</u>

At this intersection, there have been 11 illegal left-turn crashes after the implementation of DLT because the drivers were unfamiliar with the design of this new intersection. Among the 11 crashes, six were southbound turn crashes and five were northbound turn crashes. All of these crashes occurred during the first year after the installation of DLT. According to police reports, most of these crashes occurred at night when there was inadequate lighting. Even though traffic signs prohibiting left turns were installed at these locations, drivers may still overlook or disregard them and make illegal left-turns, especially at night. Therefore, for the implementation of DLT intersections, improving the lighting conditions of intersections and installing more visible traffic signs (such as signs with flash beacons) are strongly recommended. In addition, more law enforcement and driver education are needed, especially during the first year after the implementation of DLT.

Finding D: T-bone angle crashes caused by running red lights increased after the implementation of DLT at Location Ds (red circle)

From the crash diagram, we identified another type of crash that occurred frequently after the implementation of the DLT design, i.e., T-bone angle crashes between the DLT vehicles and the cross-street vehicles. Figure 6-7 (b) shows that there were two hot spots of such crashes, i.e., location Ds, circled in red. The hot spot on the west side had six crashes, and the hot spot on the east side had 10 crashes. Both spots are close to the stop bars. The police reports indicated that all 16 of these crashes were caused by vehicles running red lights, mostly from the DLT approaches. This may be due to left-turn drivers not expecting that they must stop at the main intersection; rather, they seem to have expected that they could move continually through the intersection after they got the green light to enter the DLT "channel." This finding indicated that, in a DLT intersection, it is important to coordinate the signal timing between the intersections at the left-turn crossover and the main intersection to reduce the likelihood that drivers of vehicles at the DLT intersection would have to stop at the main intersection. In addition, it also was noticed that, at these locations, the stop bars of two conflicting approaches are very close together. If drivers at one approach make a mistake and fail to stop their cars at the stop bar when the light turns red, there will not be enough time and space for the drivers at the conflict approach to making any evasive actions to avoid crashes. To prevent such T-bone crashes caused by running red lights, an advanced signal warning system could be used for both directions to ensure that drivers obey the traffic signals. In addition, driver education must be enhanced.

6.5 Conclusions and Recommendations

In this study, the safety impacts of the DLT design were assessed by conducting both statistical analysis and the analysis of collision diagrams based on crash data collected over an eight-year period at two intersections in San Marcos, Texas. These analyses were conducted before and after the implementation of DLT. The analyses identified the following key findings:

1) DLT has good performance in reducing collisions during left turns at the main intersections.

2) DLT will help right-turn vehicles merge safely and efficiently onto the intersection legs with DLT lanes, thereby reducing the congestion and rear-end crashes at the right-turn merge points.

3) Many illegal left-turn crashes occurred late at night and during the first year after the implementation of DLT. Therefore, improving the lighting conditions of intersections and installing more visible traffic signs (such as signs with flash beacons) are strongly recommended. In addition, more law enforcement and driver education are needed, especially during the first year after the implementation of DLT.

4) Because of the design of DLT, left turn vehicles are moved to the far-left side lane, and, after making left turns from the DLT lanes, more lane changes are needed for them to access destinations on the right side of the roadway. The factors undoubtedly will increase the likelihood of collisions between the DLT vehicles and the through vehicles.

Therefore, for DLT intersections where attractions are located (such as shopping plazas, gas stations, and hospitals), more access management is needed at the corners. For example, it is recommended that the entrance to the attractions be moved away from the area where the DLT exits are located to provide longer distances for DLT vehicles to make lane changes to access the attractions.

5) At DLT intersections, it is important to coordinate the signal timing between the intersections at left-turn crossover and the main intersection to reduce the likelihood that DLT vehicles will have to stop at the main intersection. In addition, advanced signal warning systems could be used to assist drivers in obeying the traffic signals.

6) More law enforcement and driver education are needed, especially during the first year after the implementation of DLT.

The findings above will provide useful information for traffic engineers to safely implement displaced left-turn intersections in the future. However, given that these findings are based only on two selected DLT intersections in Texas, more studies at more DLT intersections are needed in the future to further validate and improve the findings of this study.

Chapter 7. Summary and Conclusions

7.1 Introduction

The intersection has been the most congested and dangerous roadway segment in the whole transportation system. With the increasing traffic demand, traditional intersection designs could not well accommodate large traffic volumes. Therefore, their associated problems, such as traffic congestion, travel delay, crashes, and road environment raised concerns. In this context, innovative intersections, also known as alternative or unconventional intersection design, were put forward by engineers to treat the increasingly serious traffic problems. Unlike conventional intersection designs, which usually accommodate traffic by improving signal systems or increasing rights of way by simply widening the road, the innovative intersection is a more comprehensive design measure that is intended to utilize the roadway resources fully and to consider how to benefit different roadway users.

This research focuses on three widely implemented innovative intersection designs: displaced left turn (continuous-flow intersection), medium U-turn (the Michigan left), and the restricted crossing U-turn (superstreet), to investigate their operational and safety impacts. In addition, although these selected three innovative intersections have already been implemented in several states, they are still new. Therefore, they still lack comprehensive design standards. This research reviewed federal and state DOT design standards and made suggestions about several critical design elements. The displaced left turn was selected to conduct further operational and safety analysis.

7.2 Summary and Conclusions

In this research, existing studies and design guidelines for the displaced left turn (DLT) intersection, the median U-turn (MUT) intersection and the restricted crossing U-turn (RCUT) were reviewed and synthesized respectively. It is clear that all three innovative intersection designs can improve intersection capacity and reduce delay and travel time when appropriately implemented. In addition, geometric design guidelines were reviewed and summarized. Although there are some references from federal or state DOT for designing and implementing such innovative intersections, comprehensive design guidelines are still lacking. However, with the growing popularity of those innovative intersections, more research will be performed to supplement existing documents.

In this research, a simulated base analysis was conducted to compare the operational performance of DLT intersections with conventional intersections under various traffic conditions. Average delay and travel time were collected for analysis. Simulated results showed that, compared with conventional intersections, the DLT intersection produced less delay for all scenarios, especially when traffic volume was moderate to high or left turn percentage was high. For the travel time, the results indicated that the conventional intersection produced less EBT travel time than the DLT intersection when traffic volume was less. When traffic volume reached 6,000 vph, the DLT intersection started to show its advantage and had less travel time. For EBL travel time, the DLT intersection always performed better than the conventional intersection, especially with higher traffic volume.

Also, one important design element, left turn crossover distance for the DLT intersection, was investigated by conducting a simulation study. The simulation results show that intersection average delay reduced with the increase of crossover distance. In addition, when left turn crossover distance increased to 400ft and above, there was slightly decrease with the increase of the crossover distance. For the travel time, both EBT and EBL travel times decreased with the increase of crossover distance. Based on the simulation results and construction costs, 400 ft is recommended as the appropriate left turn distance.

Compared with numerous operational analyses, fewer studies evaluated the safety impacts of those innovative intersections. Although some research found that those innovative intersection designs could produce safety benefits, they were based on very limited, historical crash data. To fill this gap, in this study, two DLT intersections in Texas were selected to conduct a comprehensive safety assessment. Both a statistical analysis and collision diagram based before and after studies were conducted to analyze the safety impacts of displaced left turn designs. According to the results, some key findings were obtained, and recommendations were provided.

However, given that our findings were based on two selected displaced left turn intersection designs, it was not possible for us to make a comprehensive safety analysis of the DLT design. Thus, more case studies are needed to investigate further the safety impacts of the DLT intersection.

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