2007

Safety impacts of right turns followed by U-turns

Fatih Pirinccioglu
University of South Florida

Scholar Commons Citation

Pirinccioglu, Fatih, "Safety impacts of right turns followed by U-turns" (2007). *Graduate Theses and Dissertations.* http://scholarcommons.usf.edu/etd/2322

Safety Impacts of Right Turns Followed by U-Turns

by

Fatih Pirinccioglu

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

Major Professor: Jian John Lu, Ph.D.
Edward Mierzejewski, Ph.D.
Ram Pendyala, Ph.D.
Huaguo Zhou, Ph.D.
Jayajit Chakraborty, Ph.D.

Date of Approval:
March 30, 2007

Keywords: traffic safety, traffic conflicts, direct left turn, access management, separation distance

DEDICATION

To my loving parents: Tacettin Pirinccioglu and Sukriye Pirinccioglu.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Jian John Lu, my academic supervisor, for his continuous guidance and advice during the past four and a half years. I would also like to thank Dr. Edward Mierzejewski, Dr. Ram Pendyala, Dr. Huaguo Zhou, and Dr. Jayajit Chakraborty, Ph.D. for serving my graduate advisory committee and their invaluable advices and suggestions.

The data used in this dissertation was from the projects sponsored by the Florida Department of Transportation (FDOT). Specifically, the author would like to express thanks to Gary H. Sokolow for his technical support and guidance. The assistance provided by FDOT is greatly appreciated. The author also would like to thank the Graduate Research Assistants at the Department of Civil and Environmental Engineering of University of South Florida for their assistance in field data collection and data reduction.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SAFETY IMPACTS OF RIGHT TURNS FOLLOWED BY U-TURNS

Fatih Pirinccioglu

ABSTRACT

The objective of this study was to determine the safety impacts of right turn followed by U-turn movements (RTUT) at signalized intersections as well as median openings. RTUT movements are the most common alternatives to direct DLT movements (DLT). In order to achieve such data in a shorter amount of time, conflict analysis was chosen to be useful in this study as opposed to crash analysis. Additionally, data collection sites were divided dependent on certain geometric criterion and conflict data was recorded by the use of video recording equipment. Seven out the eleven conflict types used during the study were related to RTUT movements while the remaining observed conflicts were related to DLT movements.

The safety comparison of right turns followed by U-turns to direct left turns at traffic signal sites indicated that DLT movements generated two times more conflicts per hour than RTUT movements. When the effects of traffic volumes have been taken into consideration, RTUT movements had a 5 percent higher conflict rate than DLT movements. At median opening sites, DLT movements generated 10 percent more conflicts per hour than RTUT movements. Furthermore, the other conflict rate, which

takes the effect of traffic volumes into consideration, was 62 percent higher for DLT movements as compared to RTUT movements.

Impacts of separation distance on safety of RTUT movements were investigated by a regression model. The model investigated impacts of U-turn bay locations and the number of lanes on major arterial on separation distance requirements. The model results indicated that U-turn bays located at signalized intersections and greater number of lanes on major arterials increases the minimum separation distance requirements.

Finally, on four lane arterials U-turn distributions at median openings were analyzed to investigate how U-turns are accommodated at such locations. A u-turn regression model was developed to investigate impacts of median modifications on signalized intersection safety. The model results indicated that median modifications across the high volume driveways may cause safety problems at downstream signalized intersection.

CHAPTER 1

INTRODUCTION

1.1 Background

As vehicle demands continue to increase on the highways, it has been necessary to look into different directions to solve safety and operational problems with the roadway systems. Conventional solutions often are not capable of alleviating congestion and safety problems without incurring significant improvement costs. These solutions such as widening of the roadways may help to achieve necessary goals; however, they are not always possible to apply to current conditions of the roadway systems. In many metro areas of the nation, either the space is very limited and expensive or there is no space available for these improvements.

Access management is one of the tools that engineers and planners have used to plan and design the roads to enhance the capacity and safety of road networks. The benefits of access management include; improved safety, traffic flow and fuel economy, increased capacity, reduced delay and vehicle emissions (TRB, 2003). The safety benefits of access management have been clearly documented by more than four decades of research. Many states in the nation established their own access management programs. Colorado was the first state to have a system wide access management program in 1979. Since then, other states adopted their access management programs. The State of Florida

Legislature adopted the State Highway System Access Management Act in 1988. The Transportation Research Board published the first Access Management Manual in 2003, which was a necessary resource for transportation engineers and planners.

Access management deals with driveway and median design by managing the movement ingress and egress of the driveways, spacing and placement of driveways and median openings. Driveway spacing, placement, and movement's ingress and egress of the driveways are directly related to the safety of the arterials. NCHRP 420 report documented impacts of access management on safety (Gluck at el., 1999). According to this report, driveway movements cause 10% of total crashes and 70% of intersection crashes in United States. Several other studies have documented that an increase on the number of access points on arterials have a positive impact on the crash rates (TRB, 2003). Figure 1.1 illustrates the results from those studies, which is the crash rate versus access points per mile (Koepke and Levinson, 1992). Moreover, access management applications not only affect the safety but also have impacts on the capacity of arterials.

One of the common applications of access management is construction of non-traversable medians. This application results in median closures and construction of restrictive (directional) median openings. The state of Florida designs their new or redesigned roadways with a posted speed of 40 mph or higher with directional median openings, which prevent direct left turns (DLT) from driveways. In theory, replacing full median openings with directional (restricted) median openings will force the driveway users to make a right turn from the driveway and search for the next possible U-turn movement bay available down-stream of the driveway. This median treatment accomplishes one of the principles of access management, which is to reduce the number of conflict points. Conflict points are defined as points at which traffic movements intersect each other. The reduction of conflict points means a less complex driving environment and a decreased chance of being involved in conflicts with other vehicles from a driver's perspective. In theory, converting a full median opening to a directional median opening will reduce the number of conflict points at an unsignalized intersection. Figure 1.2 shows conflict points at a typical four leg unsignalized intersection and a directional median opening location. Without a treatment, an intersection has 32 conflict points. However, if this intersection is treated with a directional median opening, only 8 conflict points remain (TRB, 2003).

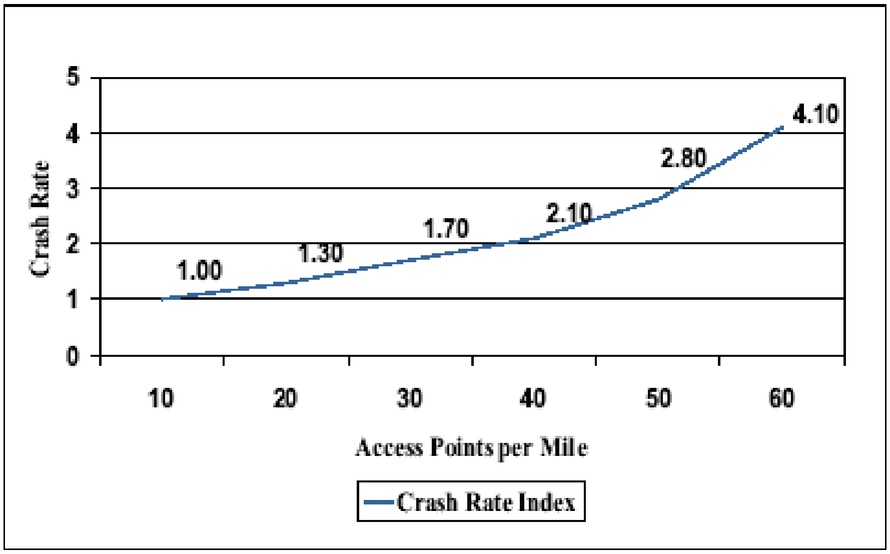


Figure 1.1 Crash Rates vs. Access Points Per Mile (Koepke and Levinson, 1992)

Although application of access management techniques improves the capacity and safety of the roadways, managing the driveway movements remains a challenge for engineers. Business owners that are concerned of loosing customers by access management modifications, such as closing driveways and converting full median openings to directional median openings, can oppose those improvements although it has been documented by many studies that safety and capacity will be dramatically enhanced and business impacts are small. In the state of Florida, many surveys have been done to evaluate the impacts of access management on drivers and businesses (FDOT District 4), (FDOT District 5, 1995). The majority of the drivers found changes safer and indicated that they would not be affected in the selection of businesses they usually used. The studies conducted on economic impacts of access management of businesses found that in general access management improvements do not affect businesses in a negative way.

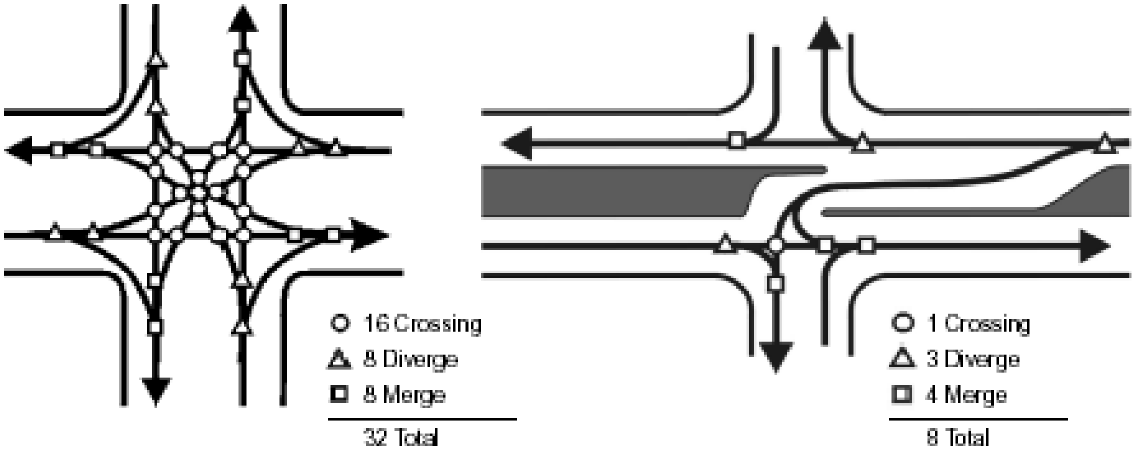


Figure 1.2 Conflict Points at Four-Leg Intersections (TRB, 2003)

Several research studies conducted to quantify safety and operational impacts of right turn followed a by U-turn movement. In 2001, a research project sponsored by Florida Department of Transportation (FDOT) was performed by Dr. John Lu and his colleagues in the University of South to evaluate an access management technique: Right turn followed by U-turn at median openings as an alternative to direct left turn from driveways and side streets (Lu et al., 2001). The research evaluated the safety and operational impacts of such an alternative on six-eight lane arterials. Additionally, U-turn locations for right turn followed by a turn were median openings. The safety impacts were evaluated by crash and conflict analysis. Then again, operational analysis compared operational characteristics such as delay and travel time. Results from that research indicated that this alternative as compared to direct left turns result in safety benefits and under certain traffic conditions result in operational benefits. The same research group completed another study in 2004, which compared right turn followed by U-turns at signalized intersections as an alternative to direct left turns (Lu et al., 2004). This study evaluated maneuvers on six-eight lane arterials. Results of this study also indicated that right turn followed by a turn is a safer alternative to direct left turn on six- eight lane arterials where U-turns were at signalized intersections.

1.2 Problem Statement

Right turn followed by a U-turn movement is considered the most common alternative to direct left turn movement, in case of a median opening closure or conversion to a directional median opening, the RTUT movement will be the only alternative for drivers to make a left turn to an arterial from driveways or side streets. Although previous studies stated some safety benefits for the restriction of DLT movements from driveways, there is a need to compare these movements and quantify the safety benefits under different geometric conditions. The main concerns about the RTUT movements are as follows:

Firstly, the change in width and characteristics of the main road needed to be considered and the results needed to be quantified and compared with earlier projects. One consideration behind this thinking is the shorter crossing distance needed by direct left turn vehicles in the case of 4-lane roadways since crossing 2 lanes at a time may not be as difficult as crossing three lanes. It may; therefore, be advisable to separately evaluate direct left turns and right turns followed by U-turns on 4-lane facilities.

Secondly, at four lane arterials, the turning radius for the U-turn movements can be small and this situation can make the U-turn maneuvers a challenge and unsafe. It is necessary to develop recommendations for U-turn locations on 4-lane roadways since such locations might have limited physical space (ex. narrow medians) to complete the maneuver, which is not an issue in the case of 6 lane roadways. Such tight locations on 4-lane roadways may also require extra pavement as well to complete the U-turn.

Finally, weaving maneuvers to reach the exclusive left turn lane after right turns from driveways could be a problem for drivers under heavy traffic conditions. Separation distance is defined as the distance between the driveway and the location of U-turn bay that can be a median opening or signalized intersection. Short separation distances could be dangerous for the drivers to complete maneuvers. On the other hand, very long weaving distances will cause an increase of travel time for drivers. It is necessary to estimate optimum weaving distances for different geometric conditions from the safety perspective.

The safety impacts of various geometric alternatives are evaluated in this study to enlighten the concerns about DLT and RTUT movements. Four different geometric conditions, which were selected for investigation and comparison purposes, are as follows and illustrated in Figure 1.3 and 1.4.

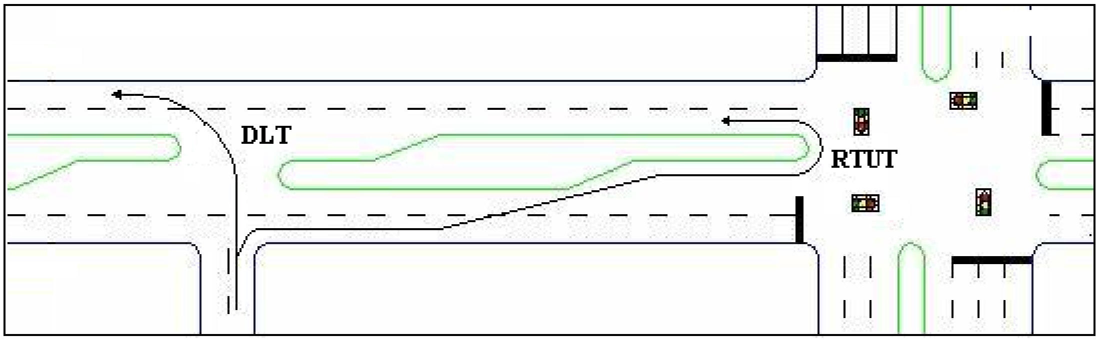


Figure 1.3 DLT vs. RTUT at a Signalized Intersection

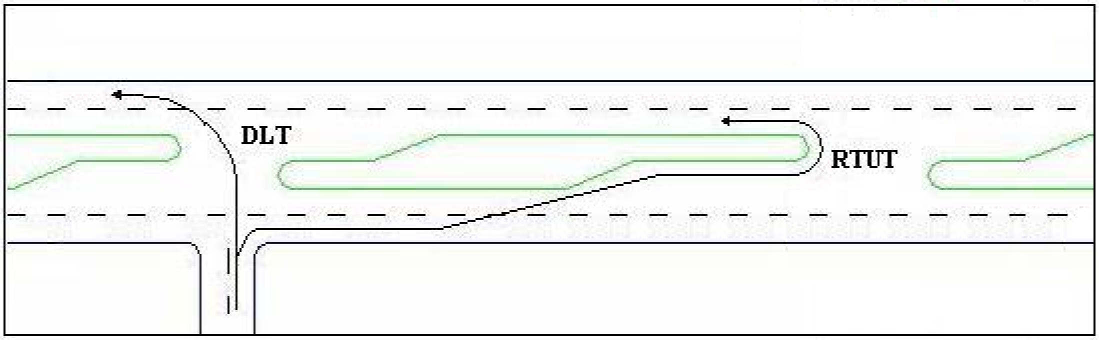


Figure 1.4 DLT vs. RTUT at a Median Opening

1.3 Research Objectives

The primary purpose of this study was to conduct a detailed evaluation and investigation on a widely used access management technique: right-turns followed by U-turns at signalized intersections and right-turns followed by U-turns at a median opening as alternatives to direct left turns from a driveway. Conflict analysis was chosen over crash analysis because of the increased advantages of conflict analysis. Some advantages are shorter data collection time than crash data and the effectiveness of a countermeasure can be evaluated in a shorter time. Safety affects of right turn followed by U-turns at signalized intersections and median openings will be quantified through field studies and data collection. More specifically, the objective consists of the following:

- To estimate the average number of traffic conflicts for both DLT and RTUT maneuvers on four lane arterials,
- To estimate the average conflict rates for each of the two left turning alternatives from driveways,
- To compare conflict rates for two left turning alternatives.
- To compare the severities of conflicts related to two left turning alternatives,
- To estimate the optimum weaving distance for RTUT movements under different geometric and traffic conditions and to develop a model to investigate the influence of traffic and geometric conditions on conflicts related to weaving movements,
- To investigate how U-turns are facilitated median openings on four lane arterials
- To develop a model to investigate safety impacts U-turn movements on signalized intersections.

1.4 Outline of Dissertation

This report consists of eight chapters. Chapter 1 provides an introduction to the research project and motivation for selecting the research topic. Chapter 2 summarizes the review of literature in this area. Chapter 3 describes the methodologies utilized to reach the objectives of the study. Chapter 4 describes the procedures followed to complete data collection in an efficient and appropriate manner. Chapter 5 includes analysis results and findings of the safety comparison of left turning alternatives. Chapter 6 summarizes the results of data analysis for locations of U-turns. Analysis used the conflict rates for determination of recommended separation distance. Chapter 7 provides safety analysis movements at U-turn locations. This chapter serves two purposes which were: analysis of impacts of U-turns on signalized intersections and analysis of geometric characteristics of median openings to facilitate U-turns. Finally, chapter 8 provides summary, conclusions and recommendations of this research.

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter summarizes findings from literature review relevant to the research subject. Current standards, regulations, and applications of the state of Florida and nation were reviewed. Also, projects and studies conducted by Transportation Research Board (TRB), The National Cooperative Highway Research Program (NCHRP), American Association of State Highway and Transportation Officials AASHTO, and other agencies in the nation, were reviewed.

2.2 Right Turn Followed by U-Turn Safety

Many states of the nation have several different applications and regulations to prevent direct left turn movements. Those states commonly used the solution of either closing the full median opening or converting it to a directional median opening. Those solutions diverted the left turn traffic to the next U-turn bays. Several studies have been conducted to evaluate impacts of those treatments.

The state of Michigan installed directional median openings to prevent direct left turns from driveways for more than two decades. There are several studies to evaluate the safety impacts of direct left turn treatments in the state of Michigan. One study, by Maki used traffic crashes to measure the safety improvements when replacing four full median openings in the city of Detroit (Maki, 1996). In that study before and after comparisons of several types of crashes were analyzed. A brief summary concludes that there is a 17.1% reduction in rear end crashes, 95.5% reduction in side angle crashes and 60.6 % reduction in side swipe crashes, which are mainly caused by direct left turns and cause injuries and fatalities because of the speed difference of the used traffic crashes to measure the safety improvements when replacing four full median openings in the city of Detroit. In that study before and after comparisons of several types of crashes were analyzed. Another additional important measure of safety is injuries, which were reduced by 74.6% after the improvements. Figure 2.1 shows crash comparisons of the Michigan study. Another study in Michigan, which was conducted by Kach, compared the crash rates of full median openings with directional median openings and related injuries caused by those crashes (Kach, 1992). Results of the study indicated that the average rate of crashes for directional median openings were 15 percent less as compared to full median openings. Also, injuries related to crashes were 30 percent less for directional median openings.

The study conducted at University of South Florida in 2001 evaluated right turns followed by U-turns at median openings as an alternative to direct left turns from the driveways on six or more lane arterials (Lu at al., 2001). This study found that, right turn followed by U-turn movements generated fewer conflicts as compared to direct left turn movements. Also severities of the conflicts were less for right turn followed by U-turn movements. Another study by University of South Florida completed in 2004 evaluated right turns followed by U-turns at signalized intersections as an alternative direct left turns (Lu et al., 2004). This study also found that RTUT at signalized intersection movements were safer than DLT movements and severities of RTUT movements were less than DLT movements.

Vargas and Gautam performed a case study regarding right turns followed by U-turns as an alternative to direct left turns in Florida (Vargus and Guatam, 1989). Several closely spaced median openings were closed and directional median openings were installed in advance of traffic signals. This study measured crash frequency distribution. Results of the study found that the overall number of crashes was reduced by 22%.

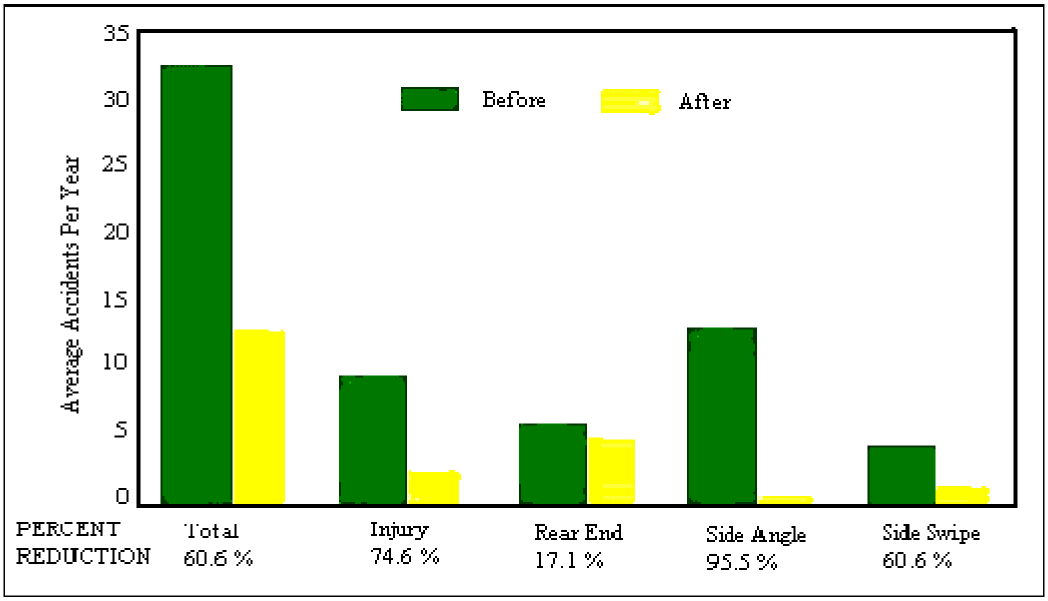


Figure 2.1 Crash Comparisons of the Michigan Study (Maki, 1996)

2.3 Safety of U-Turns

The safety of U-turn maneuvers was focused in several projects. Generally, these projects either focused on U-turns at signalized intersections or U-turns at unsignalized intersections. NCHRP Project 17-21 was conducted on the subject "Safety of U-turns at

Unsignalized Intersections" (Potts at al.,2004). Findings of this study indicated that urban arterials had 0.41 U-turn plus left turn accidents per median opening per year and rural arterials had 0.20 U-turn plus left turn accidents per median opening per year. This project concluded that there were no major concerns about the safety of U-turns at median openings. NCHRP 524 report also focused on the safety of U-turns at unsignalized intersections (Townes et al., 2004). This report included an intensive safety evaluation of U-turns by traffic conflicts and crash rates for different types of median openings and the places of the median openings on major roads. The data were related to three major conflicts and crash types were analyzed in that report. These are explained as follows: 1. Conflicts and crashes between the major road vehicles and the vehicles turning from the major road to the median opening. 2. Conflicts and crashes at within the median opening. 3. Conflicts and crashes between the major road vehicles and the vehicles turning from the median opening onto the major road. The data analysis of the report found that for most types of median openings, most observed traffic conflicts were between major road vehicles and the vehicles turning onto the major road from a median opening.

Carter et al. focused on operational and safety effects of increased U-turns on divided facilities (Carter et al., 2004). The safety part of the study found that 65 out of 78 sites had no collisions related to U-turns. The remaining 13 sites ranged from 0.3 to 3. 2.3

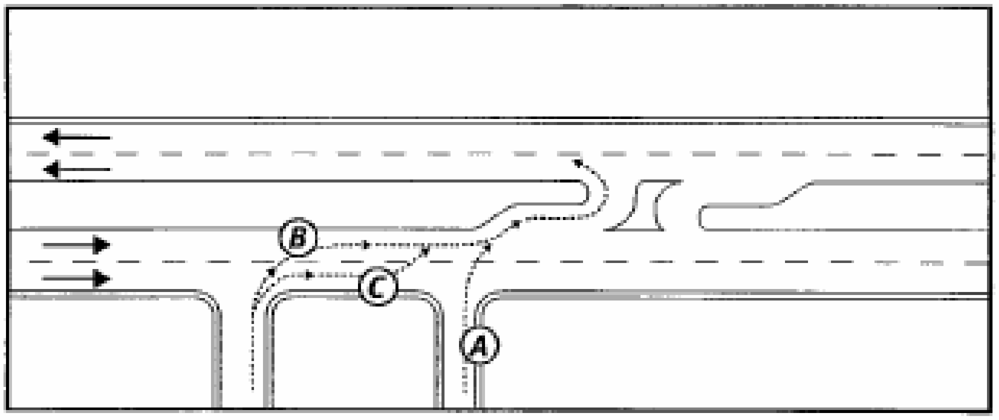
Florida is heavily encouraging restrictive medians on its higher designed at-grade arterial roadways. The 1993 Multi-lane Facilities Median Policy required that all new or reconstructed multilane highways with a design speed over 40 mph must be designed with a restrictive median (FDOT Rule Chapter 14-97). It also directs designers to find ways to use restrictive medians in all multi-lane projects, even those below the 40 mph design speed. One of the major purposes of installing restrictive medians is to eliminate left turn movements. By closing existing median openings in some major arterial roads or replacing them with directional median openings, left-turn exits onto major arterials are prohibited and the left turn egress movements would be made by turning right onto the arterial road and then making a U-turn at a downstream median opening or signalized intersection.

2.4 Weaving Issues Related to RTUT

Safety and operational performance of vehicles making RTUT highly depends on the length of offset distance between driveway and downstream U-turn location. However, previous studies concerning the safety and operational effects of U-turns have not specifically focused on the impacts of different offset distances.

The NCHRP 420 contains some guidelines about the weaving patterns for vehicles making RTUT under various separation distances between driveway exits and the downstream U-turn channels. There are three different types of weaving patterns for RTUT as shown in Figure 2.1.

Zhou and Hsu developed a working model to decide the optimal location of mid-block U-turn median openings on multilane divided roadways where the signalized intersections are coordinated (Zhou et al., 2003). A case study of that study showed that the average delay of U-turns will significantly decrease and the capacity of U-turns will increase if the U-turn median opening is located at an optimal location downstream of the driveway. Zhou’s study focused on determining an optimal distance between the driveway and the downstream mid-block median opening such that the waiting delay of vehicles making RTUT could be minimized. The findings of that study provided very useful insights on traffic operations and the safety of right turn plus U-turns design. However, that study did not look specifically at the crash data and the traffic conflicts that occurred at weaving sections. Further work needed to be conducted to evaluate the impacts of various weaving lengths on traffic safety performance.



Weaving Patterns

A ***Short separation:***
Drivers select a suitable simultaneous gap in all traffic lanes and then make a direct entry into the left-turn/u-turn lane

B ***Long separation, low volume approaching from the left:***
Drivers select a simultaneous gap in all traffic lanes, turn right, and make a direct entry maneuver into the left through lane

C ***Long separation, high volume or low volume and high-speed traffic from the left:***
Drivers wait for suitable gap, turn right, accelerate and make a lane change maneuver, then decelerate as they enter the left-turn lane

Figure 2.2 Weaving Patterns for RTUT (NCHRP 4-20)

Though several methods have been established to analyze weaving on freeways; most of these methods are not directly applicable to evaluate weaving that occurs in the non-freeway environment. The Highway Capacity Manual (2000) presents a methodology for the prediction of weaving speed and non-weaving speed in freeway weaving sections. This procedure is sometimes applied to at-grade arterials, although it has been recognized that weaving speed and non-weaving speed are not the best measures of traffic operations of at-grade weaving sections.

2.5 Traffic Conflicts

Traffic conflicts have been surrogate measures for traffic crashes and have been used since the 1970's for safety assessment purposes. General Motors Company invented the traffic conflict technique. The car manufacturer wanted to use the technique for evaluating the details of a vehicle design's influence on collision risks. Parker and Zeeger defined the conflicts as a traffic event involving the interaction of two or more road users usually motor vehicles, where one or both drivers take evasive action, such as braking or swerving, to avoid a collision (Parker and Zegeer, 1989). The traffic conflict technique is a methodology for field observers to identify conflict events at intersections by watching for strong braking and/or evasive maneuvers. The traffic conflict technique has a long history of development, including research on (Gettman and Head, 2003):

- Data collection methods
- Data collection standards
- Definitions of various types of conflicts
- Severity measures

- Relationship between conflicts and crashes
- Conflicts' are related to specific crash types.

Traffic conflicts were used for other purposes other than being safety measures for a location. An ITE study found that 33 percent of the reporting agencies used a left-turn conflict rate of four conflicts per 100 left-turn vehicles as a warrant for implementing the left turn phase in signal phasing (ITE, 1994). Torbic et al. investigated operational quality of service has an affect on the number of conflicts (Torbic et al., 1998) . The result of the study that intended to comprehend the relationship between traffic operations and the safety at signalized intersections found that an average stopped delay significantly affects the vehicle and lane change conflicts. Also, those types of conflicts decrease as the average total delay increases.

Sayed et al. described the application of the traffic conflict technique for the estimation of safety at an unsignalized intersection (Sayed et al., 1994). In this study, a computer simulation was used to simulate critical traffic events. Data was collected from 30 different surveys to establish the traffic conflict frequency and the severity standards. The standards established by this study allow the relative comparison of conflict risks from different intersections. Another research by Sayed established frequency and severity standards for signalized intersections acquiring data from 94 conflict surveys (Sayed and Zein, 1999). The study developed an intersection conflict index to compare the conflict risk at signalized intersections.

Weerasuriya and Pietrzyk used traffic conflicts to analyze intersections and develop expected conflict value tables for future studies where intersections do not have a history of crashes (Weerasuriya and Pietrzyk, 1998). Various types of intersections with varying lane numbers and volumes were analyzed in that research. The tables resulted from this study provided mean, variance and 90th and 95th percentile conflict rates. It was proposed that those tables could be used to estimate the safety problems at different intersections. The relationship between traffic volumes and conflicts has been another subject for researchers to investigate. Salman and Almaita had a research on three leg intersections (Salman and Almaita, 1995). The summation of all volumes entering the intersection and the square root of the product of the volumes that generated the conflicts were used to correlate conflicts and volumes. It was found that the correlation between the conflicts and the square root of the product of volumes was higher than that of the summation of volumes. Migletz. et al. defined the traffic volumes depending on the conflict types, which were through cross traffic conflicts, opposing left turn conflicts and same direction conflicts (Migletz et al.,1985). For opposing left-turn conflicts the volume was defined as the square root of the product of the left turn volume and opposing through volume summed over two approaches at unsignalized intersections. Through cross-traffic conflicts were related to the through cross traffic volume, which was defined as the square root of the product of through cross traffic from right (or left) volume with the through volume summed over the four approaches at both signalized and unsignalized intersections. Same direction conflicts were related to the same direction volume, which was defined as sum of the volumes of all the approaches. Katamine worked on 15 four leg unsignalized intersections to define the relationship between traffic volumes and conflicts (Katamine, 2000). Eleven types of conflicts were related to thirteen different volume definitions. The study found that the total volume entering the intersection was significantly correlated to most conflict types but using the total volume cannot explain the different conflicts’ occurrence at the intersections.

2.6 Conflicts vs. Crashes

The main purpose of the traffic studies is to enhance the safety of traffic locations or the movements at those locations. As it was mentioned in the previous chapter, reducing the number of crashes will reduce the injuries and fatalities related to them. Since the main purpose is to reduce the number of crashes, researchers have been using crashes to assess safety problems. However, problems have been documented with crashes. Firstly, the number of crashes at a specific site is usually too small to do any kind of analysis. Many years are required to obtain crash data from a specific site. Secondly, some property damage crashes have never been reported to the police. Also, the crash data may include human errors or may be missing. Thirdly, a reduction in the number of crashes may be the result of a successful counter measure, or to the fact that the period before the measure had a randomly high number of crashes (Parker and Zegeer, 1989, Torbic, 1998, Hauer, 1978, Chin and Quek, 1997).

Alternatively, traffic conflicts have some advantages as compared to traffic crashes: First, a researcher can collect the conflict data required for a site in a short period of time so it is not necessary to wait several years to make any improvements to a location (Parker and Zegeer, 1989). Second, the data collected can be used as supplementary data to crash data for analysis purposes (Parker and Zegeer, 1989). Third, the effectiveness of a countermeasure can be evaluated in a short time and can be changed in a short time with traffic conflicts (Parker and Zegeer, 1989). Fourth, traffic conflict provides information about volume; frequency of different kinds of conflicts and severity of conflicts while the crash data can only give information on property damage and injury severity (Zegeer and Deen, 1978). Fifth, conflict data includes human factors because the conflict data collection requires observation of the drivers at the field (Brown, 1994). Though researchers have intensely studied the correlation between crashes and conflicts, they have shown minute success in distinguishing their relationship to each other. Migletz et al found a 10% correlation between crashes and conflicts(Miglets at al., 1985). Engel found that the relationship between the total crashes and the total conflicts was not significant, but if different types of crashes and conflicts were studied the relationship would have been significant (Engel, 1985). Glauz at al. stated that the conflicts can be used to estimate the number of crashes in a particular year but it will not predict an actual number (Glauz et al., 1985). Therefore, traffic conflicts can be used as a replacement of the crashes.

2.7 Conflict Severity

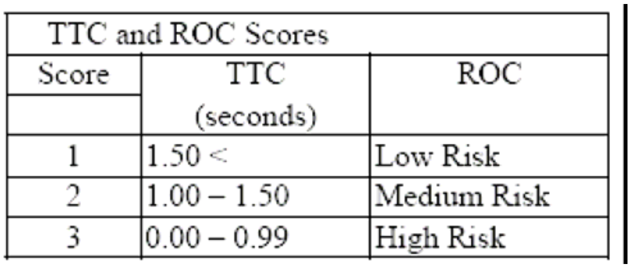
Obtaining the conflict data and comparing the conflict rates are one part of traffic conflict safety evaluation studies. The other measure is severity of conflicts that assess how close the conflicts are to be crashes. The researchers developed several methods to measure the severity of conflicts. The most widely used measure is the time to collision (TTC), which has been proposed by Hayward (Hayward, 1972). It has been defined as the time to collision of two vehicles if they continue on the same path without any evasive maneuver such as braking or swerving. The other measures were defined as the following (Gettman and Head, 2003):

- *Gap Time (GT):* Time lapse between completion of encroachment by turning vehicle and the arrival time of crossing vehicle if they continue with same speed and path.
- *Encroachment Time (ET):* Time duration during which the turning vehicle infringes upon the right-of-way of through vehicle.
- D*eceleration Rate (DR):* Rate at which crossing vehicle must decelerate to avoid collision.
- *Proportion of Stopping Distance (PSD):* Ratio of distance available to maneuver to the distance remaining to the projected location of collision.
- *Post-Encroachment Time (PET)*: Time lapse between end of encroachment of turning vehicle and the time that the through vehicle actually arrives at the potential point of collision.
- *Initially Attempted Post-Encroachment Time (IAPT):* Time lapse between commencement of encroachment by turning vehicle plus the expected time for the through vehicle to reach the point of collision and the completion time of encroachment by turning vehicle.

Some researchers have indicated that TTC is *the* surrogate measure of safety, while others refute that lower TTC indicates higher severity of crashes, primarily because speed is not included in the measure (Kruysse, 1995 Tiwari, 1995). That is to say that lower TTC certainly indicates a higher probability of collision, but cannot be directly linked to the severity of the collision. Some research indicates deceleration rate (DR) as the primary indicator of severity instead of TTC (Cooper and Ferguson, 1976, Darzentas et al., 1980).

Sayed et al stated that if only objective methods were used, the risk factor could be over estimated (Sayet et al., 1994). Hence, it was recommended to use both objective and subjective methods and combine them to obtain a more reasonable risk value. A subjective value denominated, Risk of Collision (ROC) was divided into three categories of risk consists of low, medium and high risk. In regard to TTC, this measure was categorized in three time intervals: 0 to 1 second, 1 to 1.5 seconds, and more than1.5 seconds.

Table 2.1 ROC and TTC Scores



TTC and ROC Scores		
Score	TTC (seconds)	ROC
1	1.50 <	Low Risk
2	1.00 – 1.50	Medium Risk
3	0.00 – 0.99	High Risk

2.8 Summary

Safety impacts of right turn followed by a turn evaluated by several studies in the past. However, impacts of geometric conditions to the safety those movements were not the topic of many research studies. Previous studies in this area usually focused on general safety evaluation of right turn followed by a U-turn movement. With increased use of non traversable medians on highways, it is essential to investigate those movements from different aspects and its elements such as separation distance and U-turn locations separately.

CHAPTER 3

METHODOLOGY

3.1 General

This chapter documents the methodologies that are used to achieve the research objectives of this study. This chapter consists of five sections. The first section explains the criteria employed during site selection process. The second section describes conflict types recorded at the field and used for analysis. Third section of this chapter explains the methodology used to determine sample sizes. Fourth section introduces the conflicts rates and explains extensive data reduction procedure. The last section of this chapter gives brief information about the conflict models used for data analysis.

3.2 Site Selection

Efficiency of the data collection and data reduction procedures are directly related to the selection of best possible sites. High volumes of RTUT and DLT will reduce the time required for data collection and reduction. Also, the geometric conditions of the sites must be suitable for the placement of data collection equipment to prevent disturbing drivers. The criteria are determined considering these challenges. Site selection criteria for four and six lane signalized intersection sites are as follows:

1. Traffic volume on the driveway should be relatively high so that the adequate turning vehicles could be studied
2. The minimum distance between the driveway and upstream signal should be at least 200 ft, which is the median value of the distance traveled during driver perception-reaction time and the impact distance due to a right turning vehicle
3. The downstream signal should be located at an appropriate distance away from the driveway in order to avoid the effects of possible spillbacks
4. Posted speed on the major road is equal to or greater than 40 MPH
5. Downstream signal has protected left turn phase to prevent the conflicts between the upstream traffic and the U-turn traffic at a signalized intersection
6. No protective island and exclusive lane for right turn movements from the cross road at the signalized intersection to observe the conflicts between U-turning vehicles and right turning vehicles from the crossroad
7. Right turn on red is allowed at the signalized intersection to observe the conflicts between U-turning vehicles and right turning vehicles
8. No protective island and exclusive lane for right turn movements from the cross road at the signalized intersection to observe the conflicts between U-turning vehicles and right turning vehicles from the crossroad
9. Right turn on red is allowed at the signalized intersection to observe the conflicts between U-turning vehicles and right turning vehicles

Figure 3.1 illustrates the location of traffic signals and direction of traffic streams at a typical signalized intersection site.

Site selection criteria for four and six lane median opening sites are as follows:

1. Traffic volume on the driveway should be relatively high so that adequate turning vehicles could be studied.
2. The minimum distance between the driveway and upstream signal should be at least 200 ft, which is the median value of the distance traveled during driver perception-reaction time and the impact distance due to a right turning vehicle
3. The downstream signal should be located at an appropriate distance away from the driveway in order to avoid the effects of possible spillbacks.
4. Posted speed on the major road is equal to or greater than 40 MPH.

Figure 3.2 illustrates the location of traffic signals and direction of traffic streams at a typical median opening site.

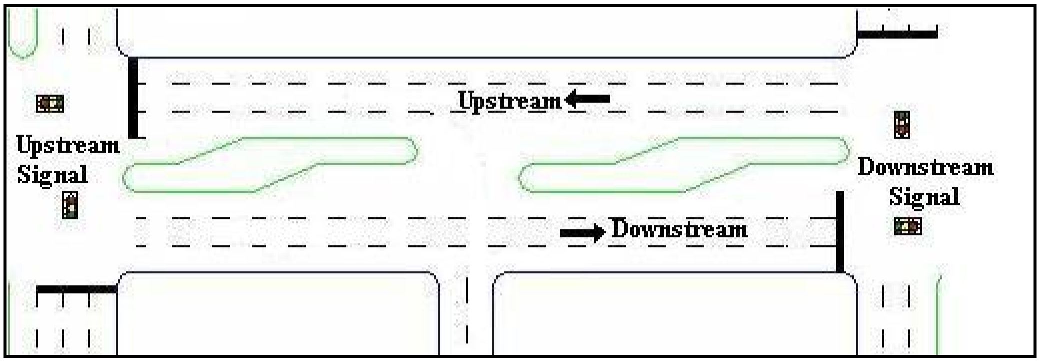


Figure 3.1 Signalized Intersection Site Components

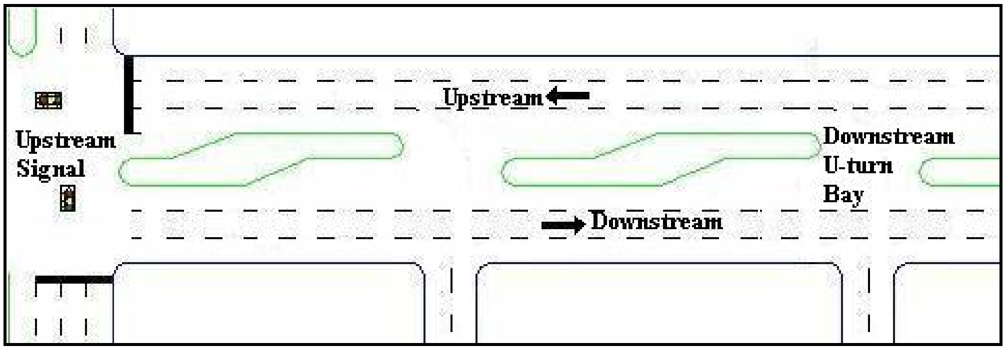


Figure 3.2 Median Opening Site Components

3.3 Types of Conflicts

As mentioned earlier, this research focused on four different geometric conditions. Eleven types of conflicts were used to quantify the safety effects of RTUT movements as an alternative to DLT movements. Conflicts related to direct left turn maneuvers were the same for both signalized intersection and median opening sites. On the other hand, right turn followed by U-turn related conflicts differed by two types of conflicts which were related to U-turn maneuvers at signalized intersection and median opening sites. For each geometric condition four types of conflicts were employed for DLT movements and five types of conflicts were employed for RTUT movements. These conflicts are explained below and illustrated in Figures 3.3 through 3.13

Right-Turn Out of the Driveway (RTUT1), occurs when a vehicle waiting at a driveway, turns to the right and gets onto the major road, placing another vehicle (conflicting vehicle) on the major-road with increased potential of a rear-end or sideswipe collision.

Slow-Vehicle, Same-Direction (RTUT2), occurs when a right turning vehicle is already on the major road and begins to accelerate while on the path of a major road vehicle, thus, the major road vehicle is encountered with increased potential of a rear-end collision.

Lane Change Conflict (RTUT3), occurs when a vehicle from a driveway that turned to the right changes from one lane to another (weaving) until it reaches the U-turn bay. This maneuver may place through-traffic vehicles with increased potential of rear-end and sideswipe collisions.

U-turn Conflict (RTUT4), occurs when a vehicle is making a u-turn at a signalized intersection, the vehicle behind the u-turn vehicle begins to accelerate while the U-turn vehicle is trying to make a U-turn. The vehicle behind the u-turn vehicle encounters potential of a rear end collision.

U-turn and Right Turn Across the Street (RTUT5), occurs when a vehicle is making a u turn at a signalized intersection, while another vehicle from the cross street is making a right turn into same direction with a increased potential of sideswipe or angle collision.

U-turn Conflict (RTUT6) occurs when a vehicle making a U-turn places vehicles coming from the opposite direction with increased potential of a sideswipe or angle crash. This type of conflict is illustrated in Figure 3.12.

Slow U-Turn Vehicle, Same-Direction Conflict (RTUT7), occurs when a vehicle completes the U-turn maneuver and accelerates: placing an oncoming major-road vehicle with an increased potential of a rear-end collision. This type of conflict is similar to conflict type C2, but it was exclusively designated for vehicles making a U-turn. In this type of conflict the speed differential involved could be even more dangerous than that of conflict type C2 because U-turn maneuvers are usually made at a very low speed making the stop distance greater. This type of conflict is graphically illustrated in Figure 3.13.

Left-Turn Out of Driveway: Conflict From Right (DLT1), occurs when a vehicle on the driveway turns to the left and places a major-road vehicle with the right-of-way with an increased potential of sideswipe and right-angle collision.

Direct-Left Turn and Left-Turn in From-Right Conflict (DLT2), occurs when a left turning vehicle from the driveway places a vehicle turning into the same driveway with an increased potential of a sideswipe or angle collision.

Direct-Left-Turn and Left-Turn in From-Left Conflict (DLT3), occurs when a left turning vehicle from the driveway places a vehicle turning into the opposite driveway with an increased potential of a sideswipe or angle collisions.

Left-Turn Out of Driveway: Conflict From Left (DLT4), occurs when a left turning vehicle located on the median storage area places an oncoming major-road vehicle with increased potential of a rear-end or sideswipe collision.

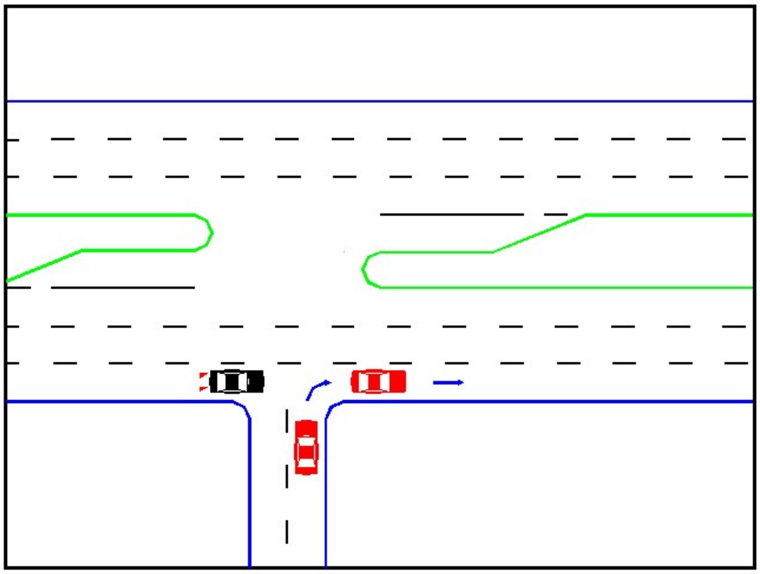


Figure 3.3 Right-Turn Out of Driveway (RTUT1)

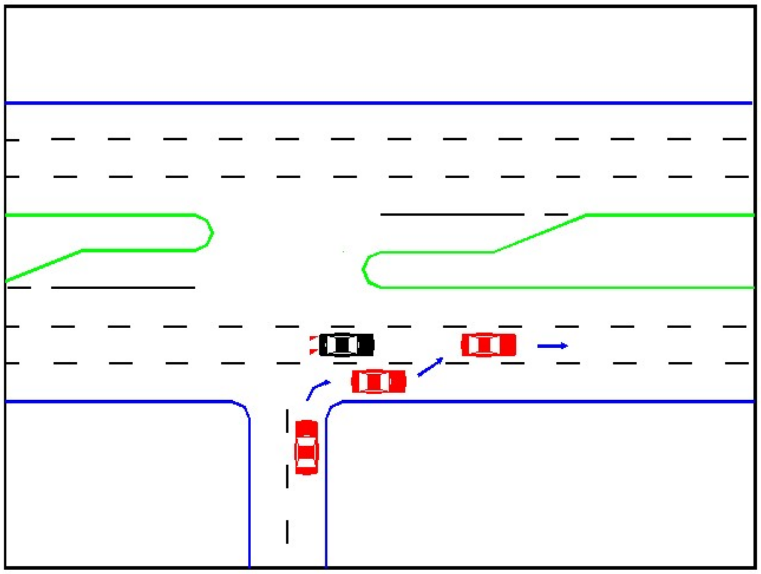


Figure 3.4 Slow-Vehicle, Same-Direction Conflict (RTUT2)

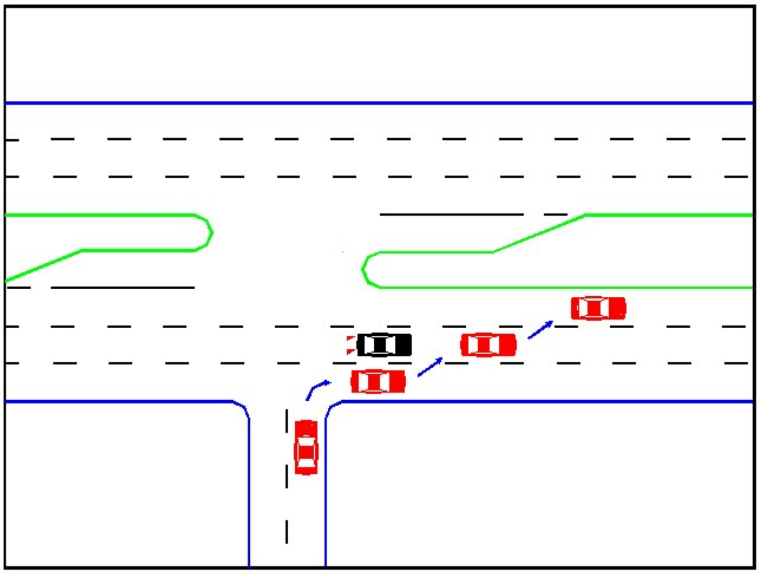


Figure 3.5 Lane Change Conflict (RTUT3)

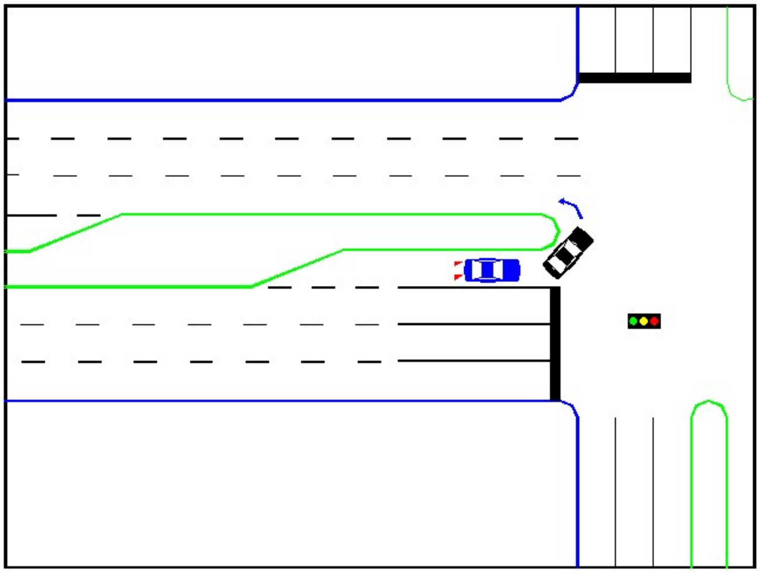


Figure 3.6 U-Turn Conflict (RTUT4)

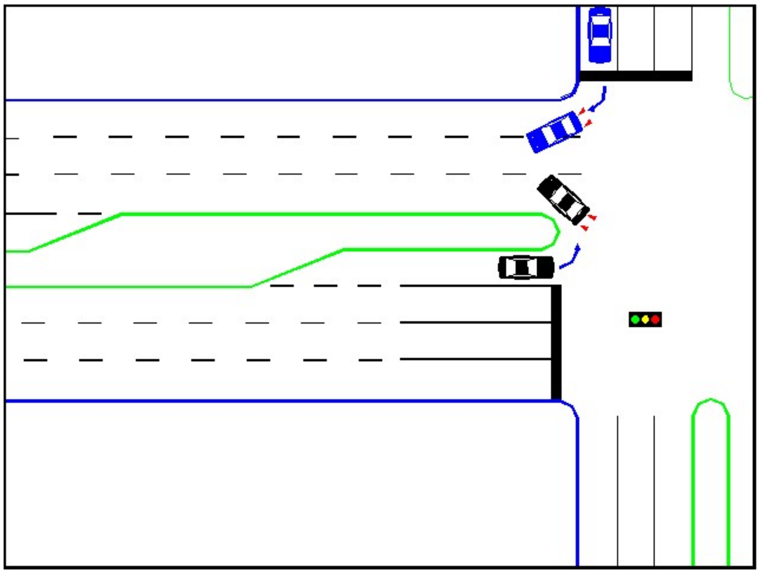


Figure 3.7 U-Turn and Right Turn Across the Street (RTUT5)

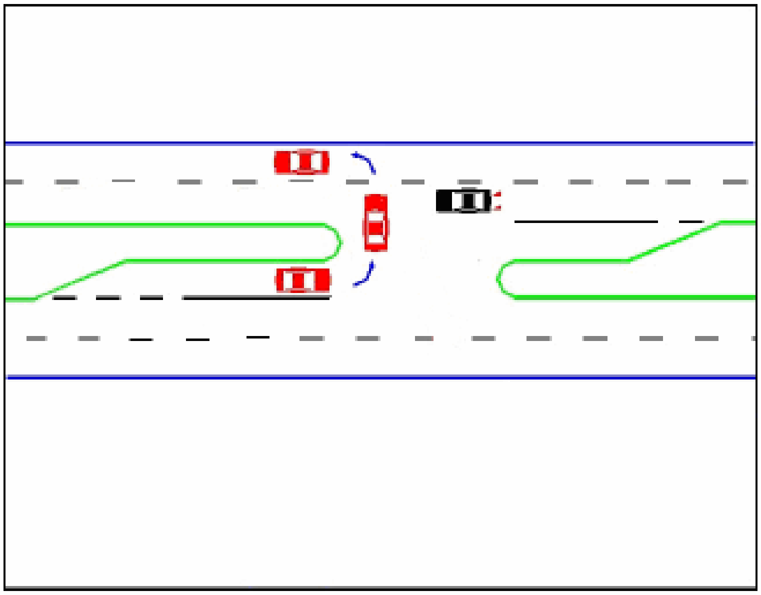


Figure 3.8 U-Turn Conflict (RTUT6)

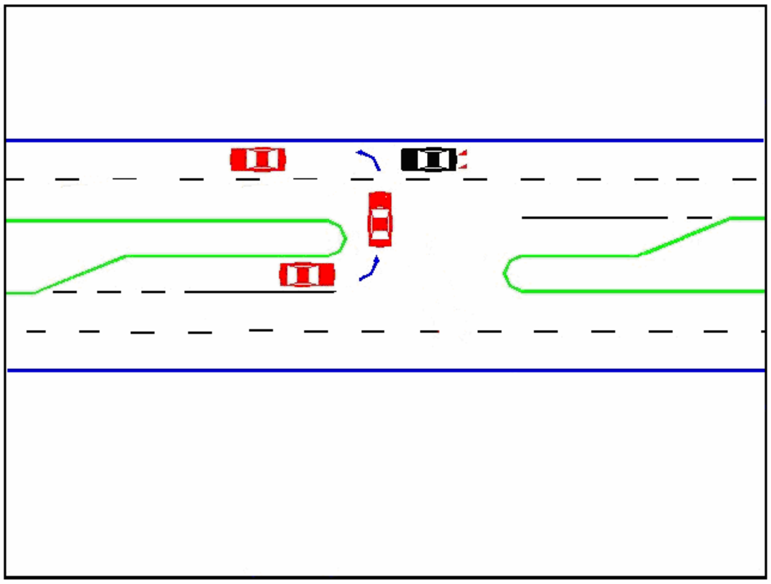


Figure 3.9 Slow U-Turn Vehicle, Same-Direction Conflict (RTUT7)

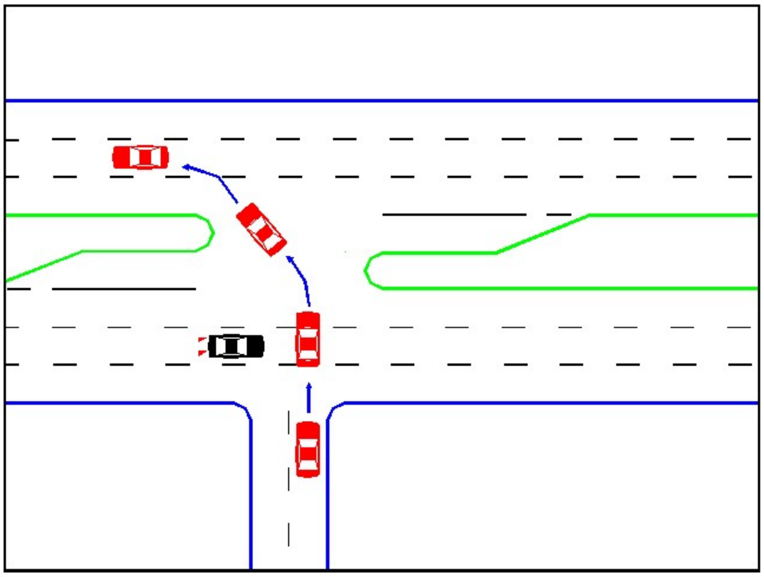


Figure 3.10 Left-Turn Out of Driveway: Conflict From Right (DLT1)

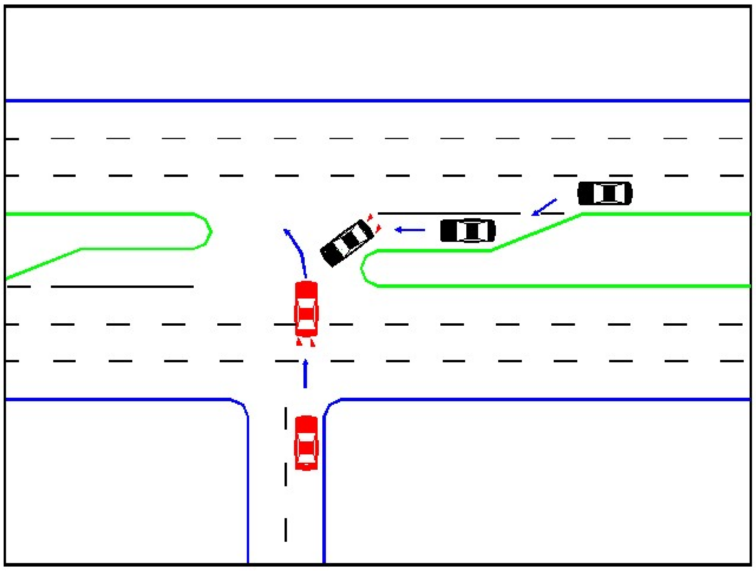


Figure 3.11 Direct-Left Turn and Left-Turn in From-Right Conflict (DLT2)

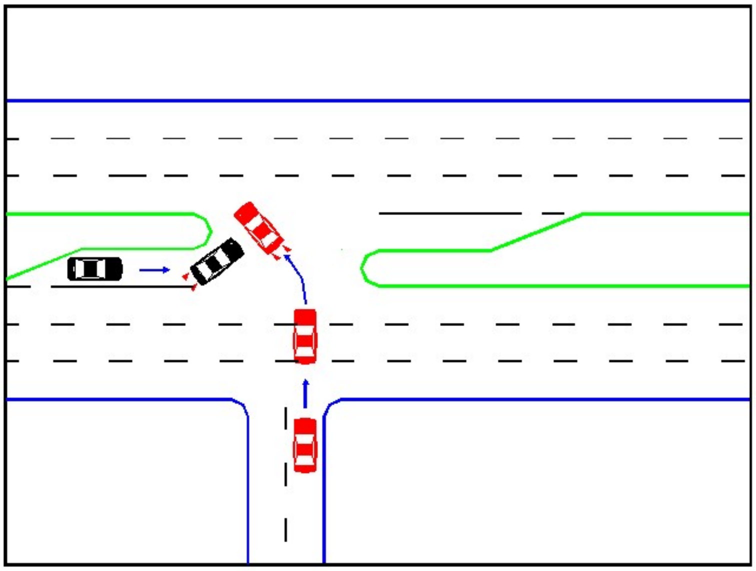


Figure 3.12 Direct-Left-Turn and Left-Turn in From-Left Conflict (DLT3)

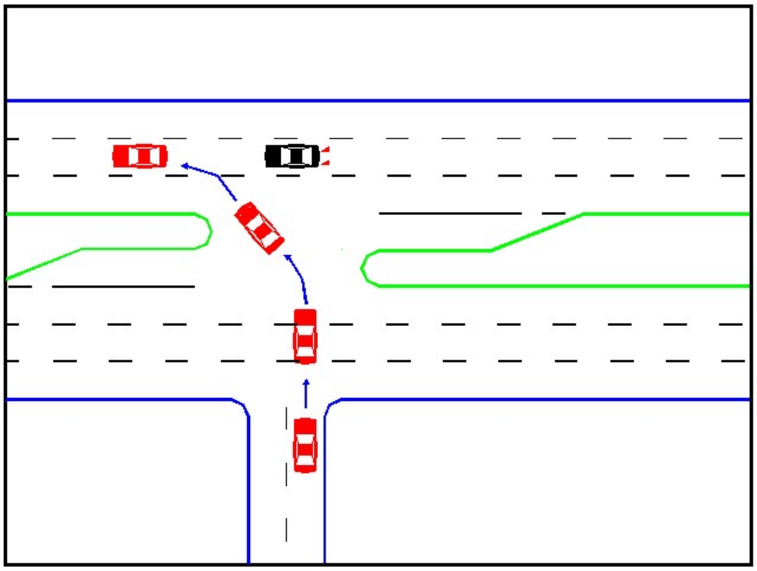


Figure 3.13 Left-Turn Out of Driveway: Conflict From Left (DLT4)

3.4 Sample Size

Sample size, as in all engineering studies related to statistics, was required to be calculated prior to data collection. The procedure to calculate the sample size depends on the conflict rates to be analyzed. Engineers use two types of conflict rates for conflict studies: conflicts per unit time and conflicts per vehicle observed. There are two procedures to calculate the sample size based on the conflict rates (Robertson et al., 1994).

The first procedure is based on the conflict per unit time as shown in Equation 3.1. The outcome for this procedure is the minimum number of hours that the data need be collected at the field. This procedure requires error of the mean and variance from previous studies, level of significance and level of error.

$$n = \left(100 \times \frac{t}{p}\right) \times \frac{\sigma_e^2}{Y^2} \qquad 3.1$$

where,

n = number of hours of observation needed,

t = statistic from the normal distribution related to the selected level of significance α,

p = error of the hourly mean,

σ_e^2 = hourly variance of conflicts estimated from previous studies, and

Y = hourly mean number of conflicts of a specific type

The second procedure based on the conflict per vehicles observed is shown in equation 3.2. Sample size, calculated by this procedure is the minimum number of vehicles to be observed. This procedure requires conflicting rate, level of significance and level of error.

$$n = p \times (1 - p) \times \left(\frac{z}{D}\right)^2 \qquad 3.2$$

where,

n = number of vehicles to be counted,

p = expected proportion of vehicles observed that are involved in a conflict,

z = statistic that is based on the level of significance desired,

D = permitted level of absolute error of sample size.

In this study, both conflict rates are used. In this case, ITE Manual of Engineering Studies recommends using the advantageous procedure. For the first procedure, mean and variance values were unknown from previous studies. Although, Parker and Zeeger established tables that include the mean and variance values for signalized and non-signalized intersections, those values were not given for the movements studied in this project. For the second procedure, conflicting rate is not known but with a conservative assumption, result of 384 vehicles was calculated. After the data collection, sample size values can be verified.

$$n = 0.50 \times (1 - 0.50 \times \sqrt{\frac{1.96}{0.50}} = 384 \text{ Approach vehicles}$$

3.5 Data Reduction Procedure

Data reduction was a long process, so it needed to be done in a systematic way to increase the time efficiency. The data collected for safety analysis were initially checked for accuracy and quality purposes at the end of every data collection day. Data reduction process started with identifying the vehicles, which were making RTUT and DLT movements. The tapes that covered the entire study locations were watched and all the vehicles egress of the driveways were observed. If a vehicle made a DLT, the times for the specific vehicles were recorded. The same procedure was applied to RTUT making vehicles as well. Those times for DLT and RTUT vehicles are shown in Table 3.1 and 3.2. All of the times are required to be in second's accuracy for the reason that those times were used for different purposes with different tapes. By identifying RTUT and DLT vehicles, the traffic volumes of these movements were obtained at the same time without extra work.

After the initial reduction of data, these movements were carefully observed for indicators of conflicts. In case a conflict related to the studied movements was observed, its time of the occurrence, type and severity were recorded. This procedure was conducted until all the DLT and RTUT movements were observed for safety analysis. When all of the vehicles were studied for conflicts and recorded, conflict data was checked for accuracy and errors. A conflict can be recorded more than once because two different cameras especially for the DLT movement's median conflicts can cover the same conflicts.

Table 3.1 Data Reduction Recording Times for Signalized Intersection Sites

	DLT	RTUT
Time 1	Vehicle leaves the driveway	Vehicle leaves the driveway
Time 2	Vehicle enters the median opening	Vehicle enters the queue at the Signalized intersection
Time 3	Vehicle leaves the median opening	Vehicle makes the U-turn

Table 3.2 Data Reduction Recording Times for Median Opening Sites

	DLT	RTUT
Time 1	Vehicle leaves the driveway	Vehicle leaves the driveway
Time 2	Vehicle enters the median opening	Vehicle enters the queue at U-turn bay
Time 3	Vehicle leaves the median opening	Vehicle makes the U-turn

Usually, conflict studies are considered to be eleven hours for one day, starting at 7:00 AM and ending at 6:00 PM. Traffic Conflict Technique for safety and Operation's - Engineer's Guide recommends adjusting the data for the periods which data were not collected. Equation 3.3 is used to calculate the number of conflicts for the non-observed periods.

$$\mathrm{ANOC} = \frac{C_1 + C_2}{2} \times \frac{(\mathrm{TTNOP})}{\mathrm{RP}} \qquad 3.3$$

where,

ANOC = adjusted non-observed period conflicts,

C1 = number of conflicts occurred before the non-observed period,

C2 = number of conflicts occurred after the non-observed period,

TTNOP = total time of non-observed period,

RP = duration of recording period

After calculating adjusted non-observed period conflicts, the daily numbers of conflicts were obtained by adding all observed and non-observed conflicts. Application of this procedure made the data needed ready for calculation of several types of conflicts rates. For descriptive analysis and comparison purposes two types of conflict rates will be used in this study and these rates are presented in Table 3.3

Table 3.3 Definition of Conflict Rates

Rate	Definition
Conflicts per Hour	$\mathrm{CR}_1 = \frac{\text{Number of conflicts}}{\text{Number of hours}}$
Conflicts per Thousand Involved Vehicles	$\mathrm{CR}_2 = \frac{\text{Number of conflicts}}{\sqrt{(V_1)\times(V_2)}} \times 1000$

where,

CR_1 = conflict rate 1.

CR_2 = conflict rate 2.

V_1 = traffic volume on arterial, according to conflict type.

V_2 = volume of RTUT/DLT maneuver, according to conflict type

3.6 Conflicts Models

Modeling of available data facilitates the best use of information and may be quite useful at the stage of hypothesizing potential countermeasures. Conflict modeling can be used as a tool for estimation (prediction) of signalized and unsignalized intersection safety for purposes of countermeasure evaluation. The other use of conflict modeling is used as a tool for the evaluation of the impact of design and environmental variables on safety so as to inform planning and engineering decisions. One of the most important objectives of this study was to develop explanatory models of this type. In addition, predictive models will be developed to forecast optimum weaving distance weaving movement and optimum turning radius for U-turn movements at median openings and signalized intersections. The regression models will be developed to determine the impact of variables associated with traffic conflicts. The type of regression model will be determined according to the goodness of fit data to the models. The following models and variables associated with conflicts are as follows:

Separation Distance Model will be employed to investigate the impact of weaving distance and traffic volumes on conflict rates and also predict the optimum weaving distance from a safety perspective. The following variables will be used in the regression model:

V_{RTUT} = RTUT Volume at the driveway (vph)

V_{AD} = Main road volume, downstream (vph)

D_W = Weaving distance (ft.)

U-turn Model will be employed to investigate the impact of U-turn radius and traffic volumes on U-turn conflicts and to estimate a safe U-turning radius for different geometric and traffic conditions. The following variables will be used in the regression model:

V_{UT} = U-turn volume at median opening and intersection (vph)

V_{AD} = Main road volume, downstream (vph)

R_U = U-turn radius (ft)

CHAPTER 4

DATA COLLECTION

4.1 Introduction

Field data collection provides information required for further analysis and evaluation. The amount and type of data acquired depends on the type and purpose of analysis. The methodologies applied during field data collection are summarized in this chapter. In addition to the data collection efforts, data reductions procedures, characteristics of study locations, data collection equipment and data collection challenges are described in the following sections of this chapter.

4.2 Identification of Conflicts

Before proceeding to conflict data collection, it is essential to determine how to identify traffic conflicts. Conflicts, unlike accidents, do not have consequences after they occur. The observer has to identify the conflict during the indication of the conflict being observed. The traffic does not stop and the vehicles continue to flow after the conflict. Conflicts are defined as evasive maneuvers to avoid collision. Indicators of conflicts are applying brakes, swerving and noticeable deceleration of vehicles.

Brake applications are frequently used to identify conflicts. Observers should not only be aware of the vehicles' brake lights, but also the speed of the vehicles and conditions to identify a conflict. Hence, there are some situations where drivers may apply brakes for several different reasons other than a conflict situation. Especially, at some sites of this study, following the downstream of driveways, signalized traffic intersections are present. The vehicles, those traveling on major roadways, apply brakes to slow down as they approach a signalized intersection. This precautionary brake application may be interpreted as a traffic conflict even though a conflict did not occur between the vehicles. Another condition is that drivers may apply brakes cautiously even when a conflict is not present in a situation (40). Figure 4.1 illustrates how a conflict is identified by brake lights.

Figure 4.1 Identification of Traffic Conflicts by Brake Lights

Swerving is another indicator of a traffic conflict. Drivers may change the direction of the vehicle or the lane they choose to travel instead of applying brakes to avoid collision. Swerving does not occur as frequently as brake applications because the drivers might put their selves into another conflict situation by swerving. The driver has to decide an evasive maneuver in an instant of time. Brake application is usually safer than swerving because of the fact that the driver does not have the time to check the side lanes to change the lane in case of a conflict. The observer, in identifying a conflict by swerving, has to be careful not only to check if the vehicle swerves but also if the driver avoids collision by swerving (20). Figure 4.2 shows a swerving maneuver to avoid collision (white vehicle on main road swerves).

Figure 4.2 Identification of Traffic Conflicts by Swerving

Noticeable deceleration is more of a subjective indicator and it is rarely used in the cases of a vehicle's brake lights having a mechanical failure, when the brake lights are obstructed or not able to be seen from the angle of a video camera. Both swerving and noticeable deceleration is more subjective and harder to identify compared to applying brakes. Traditionally, conflict studies were conducted at the field. Trained observers were required to conduct the studies. Conflicts had to be identified and recorded in very short periods of time. In this study, by recording the data to video tapes, the time pressure was reduced for the observers, therefore a conflict could be watched more than once and the problems mentioned above about the indicators of conflicts can be reduced in exchange of the time spent on data reduction. Identifying the conflicts is a time consuming process. A systematic and efficient procedure was developed in previous studies. For this procedure an algorithm shown in Figure 4.3 is used to identify the conflicts. Once the conflict was identified it had to be recorded, Traffic Conflict Technique: Observer's Guide included a standard form for conflict studies but the conflicts in this study were slightly different from the conflicts explained in that guide. Some modifications were made to the conflict forms so that they could be used in this study. The conflict forms were used for signalized intersections sites and median opening sites.

4.3 Data Collection Equipment

Traditionally, experienced observers collect the conflict data at the field. However, this methodology is not very efficient and feasible. Especially, conflict data related to complex maneuvers such as RTUT is very difficult to obtain manually. Because of these limitations data recording equipment were used for field data collection. With advancements in technology, high quality video cameras were suitable for the purpose of data collection. Prior to the selection of data collection equipment challenges and problems with similar projects were determined. During equipment selection those challenges and difficulties were considered.

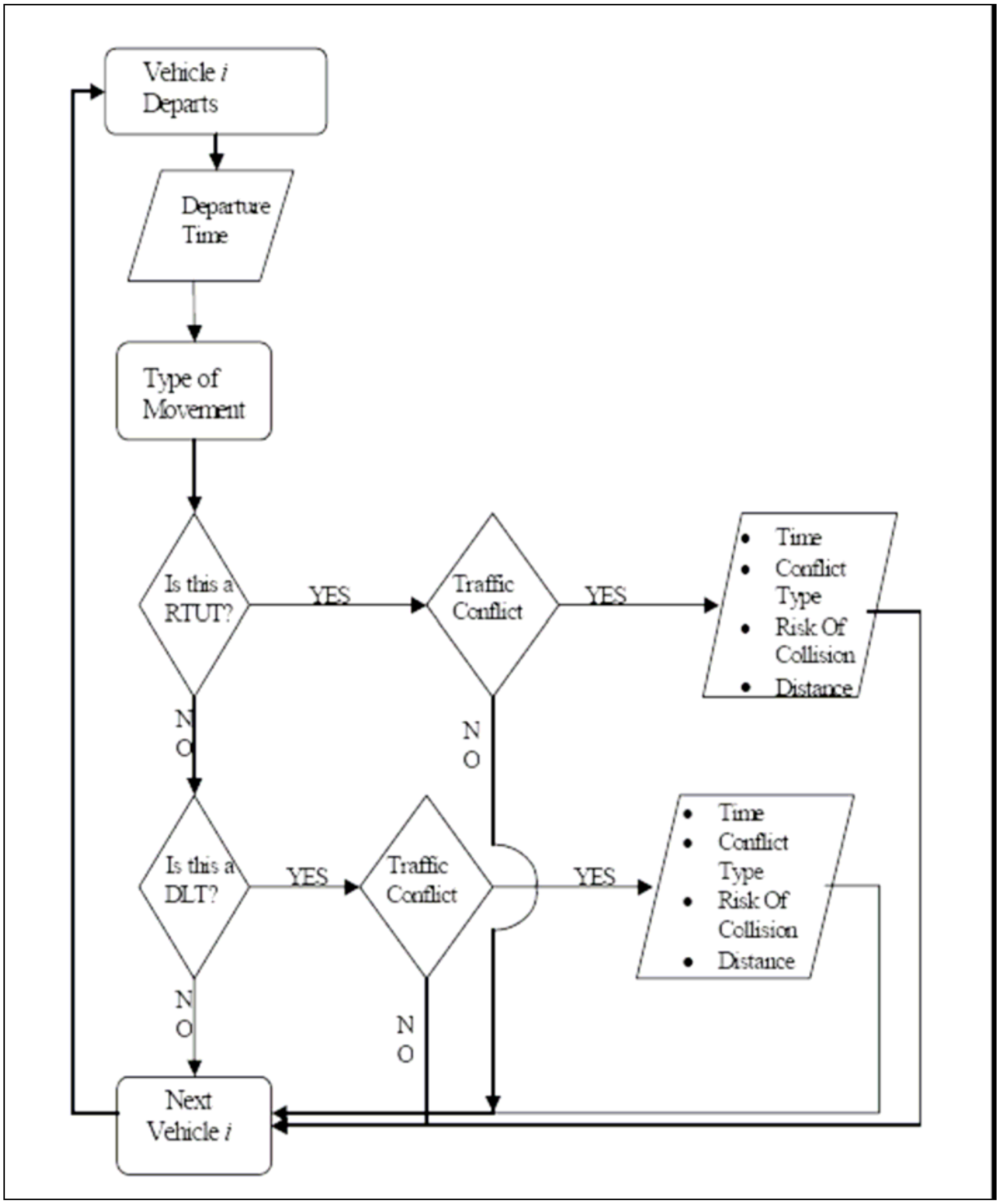


Figure 4.3 Flow Chart Describing Conflict Identification and Data Required by Observers

In the earlier projects, the time for transferring the data from 8mm tapes to VHS tapes was a concern. To avoid this time loss and increase the efficiency of data collection, a system was developed as illustrated in Figure 4.3. In this system, data was recorded to the VHS tapes directly from video cameras. Eight mm tapes could only last two hours and were changed every two hours, which brought the issue of loosing the image, zoom and angle of cameras for needed data. On the other hand, VHS tapes allow six hours of continuous data collection without having to change tapes. Also, using this system, the problem of changing the video camera batteries during the time of data collection was eliminated. The power needed for the system was another concern. This issue was solved by using marine batteries and inverters that could last up to twenty hours, 2 days of data collection, with a single charge. Those batteries supplied power to the VCRs, TVs and Video cameras. TV's were used to control the collected data simultaneously during the recording to prevent any data loss. Scaffoldings were necessary to use for the reason of getting the needed image. Also, staff did not have to climb the scaffoldings, which the video cameras were placed on, to check the image of the video. If the cameras were not placed at a suitable height from ground level then the movements of smaller vehicles could be covered by the movements of larger vehicles. Another concern was synchronization of the cameras because the vehicles were observed from several cameras at the same time. The video cameras had to have the same time in second's accuracy. Traffic volumes were also needed for analysis purposes. During the data collection periods, Hi-Star device, an automatic volume and speed recorder, was installed on the pavement to collect the speed and volumes of the vehicles on major roadways. Other minor volume requirements were obtained from videos by manual counts.

Figure 4.4 Data Collection Equipment

4.4 Study Locations

In this study, the conflict data were used for different purposes. Data collection locations were classified based on the purpose of data analysis. All possible data collection locations around Tampa Bay area identified from area maps were based on the determined criteria. Identified sites were examined to determine if the sites were suitable for data collection. Pilot surveys were conducted at those locations to determine if the driveway volumes were sufficient enough for data collection. After selection of all data collection locations, over 1000 hours of data were collected. Data collection locations were grouped based on analysis purposes and described in following sections.

4.4.1 Safety Comparison Sites

Sixteen sites were selected for data collection in the Tampa Bay Area and Plant City. Data collection sites were divided into two sets by geometric criteria. The difference between the two sets was the location of the U-turn maneuvers. At the first set of sites, the drivers had to complete U-turns of RTUT at a signalized intersection. These types of sites are named as “Signalized Intersection Sites”. These sites were numbered from one to eight. Three of the signalized intersection sites had directional median openings across the driveways that restrict direct left turns from the driveways. Five of the signalized intersection sites had full median openings across the driveways. On the other hand, at the second set of sites the U-turns were at median openings and these sites are named as “Median Opening Sites”. These sites were numbered from nine to sixteen. Four of the median opening sites had a directional median opening across the driveway and the other four sites had full median openings across the driveways. Table 4.1 presents geometric characteristics of sites used for conflict data collection for separation analysis.

Eleven types of conflicts related to RTUT and DLT maneuver were recorded. Comparison analysis requires recording all conflicts at the same time. In order to record all types of conflicts at the same time, usually five cameras were used. Figure 4.4 illustrates the location of cameras at a typical data collection site for safety comparison data.

Table 4.1Signalized Intersection and Median Opening Site Geometric Characteristics

Signalized Intersection Sites							
Site			N_1	N_2	Sp	Median Type	l(ft)
Arterial		Location					
1	Bruce B. Downs Blvd.	New Tampa Blvd.	4	Single	45	D	930
2	Bruce B. Downs Blvd.	Cross Creek	4	Single	45	F	885
3	Bearss Ave.	22nd st.	4	Single	45	F	510
4	Fletcher Ave.	Dale Mabry Hwy.	4	Dual	45	F	570
5	Alexander	Redman	4	Single	40	F	285
6	Bruce B. Downs Blvd.	Tampa Palms	4	Dual	45	D	655
7	Gunn Hwy.	Sheldon	4	Single	45	F	785
8	56th St.	Fowler Ave.	4	Dual	50	D	290
Median Opening Sites							
Site			N_1	N_2	Sp	Median Type	l(ft)
Arterial		Location					
9	Bruce B. Downs Blvd.	Pepple Creek.	4	N/A	45	D	800
10	Thonotosassa Rd.	Goldfinch Dr.	4	N/A	45	D	665
11	US 301	SR 60	4	N/A	45	D	695
12	US 301	Brittany	4	N/A	45	F	575
13	Bearss Ave	Dale Mabry Hwy	4	N/A	45	F	1150
14	Gunn Hwy.	Normandie	4	N/A	45	F	540
15	Gunn Hwy.	Anderson	4	N/A	45	F	850
16	Thonotosassa Rd.		4	N/A	45	FD	590

N1: # of through lanes; N2: # of exclusive left turn lanes at signalized intersection (single or dual) Sp: the speed limit of the selected arterial; D: directional median opening; F: Full median opening; l: the offset distance from subject driveway to dow

4.4.2 Separation Distance Sites

Based on determined criteria, conflict data were collected at 61 locations. The locations were grouped into four sets depending on U-turn bay locations and the number of lanes on major arterials. Three types of conflicts were selected for conflict data analysis. These conflicts include right-turn out of the driveway conflict (RTUT1), slow-vehicle same-direction conflict (RTUT2), and lane change conflict (RTUT3). Usually one video camera was enough to capture conflicts related to weaving maneuvers. The video camera usually located at a sufficient distance in advance of studied driveways. Table 4.2 presents the characteristics of sites used for conflict data collection for separation analysis.

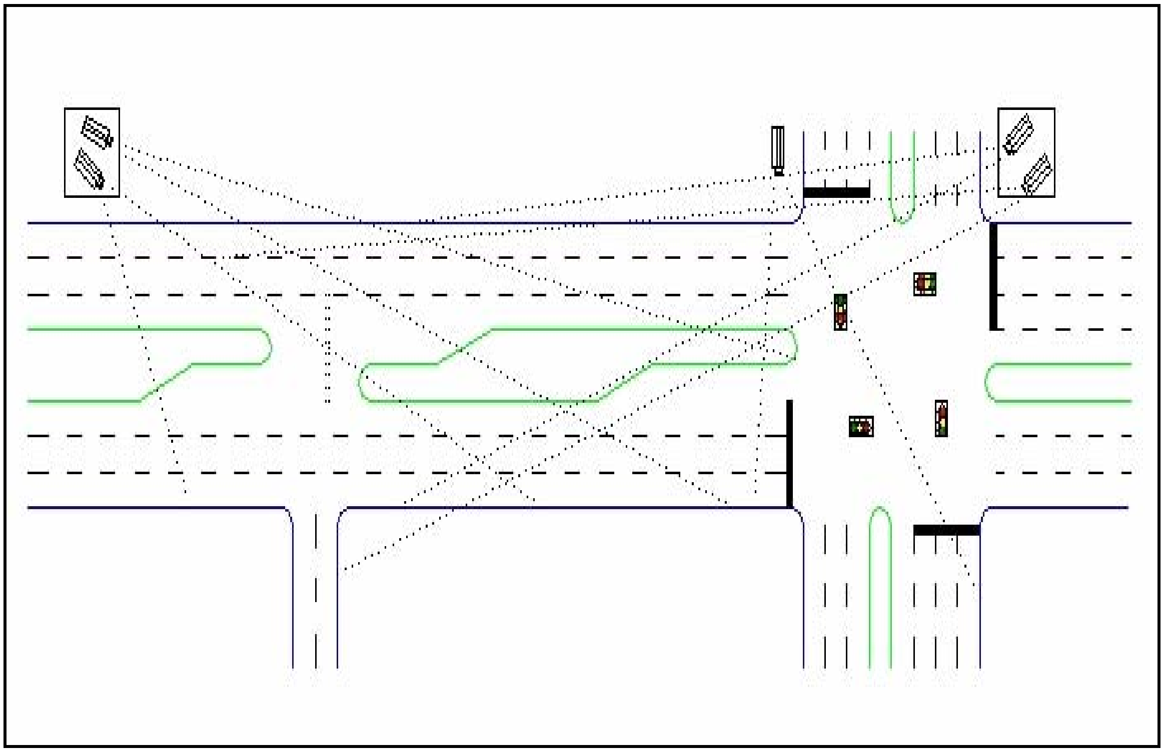


Figure 4.5 Location of Video Camera at a Typical Site

Table 4.2 Selected Sites for Separation Distance Analysis

Number of Lanes	Location of U-turn Bay	
	Median Opening	Signalized Intersection
4-Lane	16	13
6 or 8 Lane	16	16

4.4.3 U-Turn Analysis Sites

Data related to U-turn movements were collected for conflict analysis and geometric analysis. Conflict data were collected at signalized intersections independent from RTUT movements. Eight signalized intersections with high U-turn volumes were selected. Geometric analysis of U-turns was conducted at median opening locations. Six sites were selected for data collection.

4.5 Field Procedure

Data was collected under normal traffic conditions, good weather, daylight and dry pavement. During the time of congested traffic conditions, either data collection was stopped, or the collected data were not used for the analysis. Conflict studies consider a day of data collection, as eleven hours from 7:00 AM to 6:00 PM. Sites studied in this project were the driveways from shopping plazas and activity centers, which had few traffic movements' egress of the driveways during early hours. Traffic volumes from the driveways had reached the desired values around the noon peak hours. Data collection started usually prior to noontime and continued until the end of the data collection day. Another reason to start the data collection at those times is that the set up of the data collection equipment takes two to three hours of time.

A typical data collection day started with the set up of equipment. At a typical site, two scaffoldings were used. Before setting up any necessary electronic equipment, scaffoldings were assembled and placed at suitable locations. The reason for starting with the scaffoldings is that the procedure requires all the manpower available before assigning any of the staff to any camera locations. After the setup of scaffoldings, all the equipment was set up and made ready for the start of the data collection day. Placement of the video cameras requires experienced personnel because if the data needed were not collected (correct image), it would be a waste of resources and reliability so the data collected would dramatically be reduced. Another issue is synchronization of the video camera times, which is implemented before the placement of the cameras. After the synchronization and placement of the video cameras, data collection started with all the cameras at the same time. Assigned staff stayed with the video cameras and all the equipment was to be checked frequently so that recording was continued to avoid any loss of data.

CHAPTER 5

SAFETY COMPARISON

5.1 General

This chapter presents safety comparison of different left turn alternatives on four lane arterials. Safety of right-turn followed by U-turn movements on four lane arterials was a concern because of geometric limitation. In safety analysis three alternatives include: (1) direct left-turns at a driveway; (2) right-turns followed by U-turns at a downstream signalized intersection; and (3) right-turns followed by U-turns at a downstream median opening. Sixteen locations were selected for conflict data collection. The data from those locations were used to determine conflicts rates which serves purpose of safety comparison for driveway left-turn alternatives under different levels of conflicting traffic volumes.

5.2 Data Analysis of RTUT vs. DLT at Signalized Intersection Sites

5.2.1 Descriptive Analysis

Prior to data analysis and investigation of data, verification of sample sizes was necessary. In this study, it was not possible to estimate the necessary sample size prior to data collection because there were no past studies that used the same methodology and geometric conditions. As it was mentioned previously in the Chapter 3, verification of sample size can only be performed after data collection and data reduction processes. The sample size calculation process primarily requires the total number of DLT and RTUT movements observed. These numbers are obtained for DLT and RTUT movements for each signalized intersection site. The total number of 2240 DLT movements and 1260 RTUT movements were observed at signalized intersection sites. Another required component for the sample size calculation was the number of conflicts observed for each conflict type at signalized intersection sites. After obtaining all of the required data, the total number of movements was divided by the number of conflicts for each type of conflict to acquire the necessary proportions. These proportions were used in the formula previously explained in methodology chapter. 95 percent level of confidence and 5 percent permitted level of error were used for sample size estimation. The results for sample size verification of RTUT movements are presented in Table 5.1. The sample size was satisfactory for all types of RTUT related conflicts. In addition, the results for DLT movements are presented in Table 5.2. Also, the sample size was satisfactory for all DLT related conflicts.

The errors were checked after the data reduction process. A typical error for this type of field study may be the recording of the same conflict(s) more than once. That type of error can be possible because every camera at the site records each movement at the same time and data reduction was performed by viewing those videos recorded by the cameras more than once. In case of recording a conflict more than once, the videos were reexamined and the errors were corrected.

Table 5.1 Sample Size Verification for RTUT Movements, Signalized Intersection

Conflict (1)	Average Number of Conflicts (2)	RTUT Vehicles (3)	P_{RTUT} (4)=(2)/(3)	n (5)	Sample Size Satisfied
RTUT1	73	1260	0.06	84	Yes
RTUT2	32	1260	0.03	38	Yes
RTUT3	24	1260	0.02	29	Yes
RTUT4	53	1260	0.04	62	Yes
RTUT5	54	1260	0.04	63	Yes
P_{RTUT} : Percentage of RTUT vehicles involved in a conflict. n : Number of vehicles estimated for sample size					

Table 5.2 Sample Size Verification for DLT Movements, Signalized Intersection

Conflict (1)	Average Number of Conflicts (2)	DLT Vehicles (3)	P_{DLT} (4)=(2)/(3)	n (5)	Sample Size Satisfied
DLT1	171	2240	0.08	108	Yes
DLT2	50	2240	0.02	34	Yes
DLT3	13	2240	0.01	9	Yes
DLT4	101	2240	0.05	66	Yes
P_{DLT} : Percentage of DLT vehicles involved in a conflict. n : Number of vehicels estimated for sample size					

In addition, technical problems, such as broken down equipment during the data collection process, are considered as an error. If technical problems existed during the data collection process, the collected data at the time frame of the technical problem were discarded because all of the conflicts are required to be video taped at the same time.

After the initial process of checking errors and data reduction, the total numbers of conflicts observed at each site for each type of conflict were obtained and are presented in Table 5.3.

Table 5.3 Summary of the Total Number of Conflicts Observed, Signalized Intersection

Site	Conflicts	Conflict Type									Total
		RTUT1	RTUT2	RTUT3	RTUT4	RTUT5	DLT1	DLT2	DLT3	DLT4	
1	No.	22.0	15.0	7.0	25.0	16.0	N/A	N/A	N/A	N/A	85.0
	%	25.9	17.6	8.2	29.4	18.8	-	-	-	-	100.0
2	No.	3.0	1.0	2.0	1.0	1.0	38.0	14.0	5.0	28.0	93.0
	%	3.2	1.1	2.2	1.1	1.1	40.9	15.1	5.4	30.1	100.0
3	No.	2.0	1.0	1.0	1.0	1.0	17.0	5.0	1.0	10.0	39.0
	%	5.1	2.6	2.6	2.6	2.6	43.6	12.8	2.6	25.6	100.0
4	No.	4.0	1.0	1.0	3.0	4.0	44.0	12.0	4.0	25.0	98.0
	%	4.1	1.0	1.0	3.1	4.1	44.9	12.2	4.1	25.5	100.0
5	No.	1.0	1.0	0.0	0.0	2.0	30.0	11.0	1.0	6.0	52.0
	%	1.9	1.9	0.0	0.0	3.8	57.7	21.2	1.9	11.5	100.0
6	No.	18.0	10.0	9.0	12.0	13.0	N/A	N/A	N/A	N/A	62.0
	%	29.0	16.1	14.5	19.4	21.0	-	-	-	-	100.0
7	No.	2.0	1.0	2.0	2.0	2.0	42.0	8.0	2.0	32.0	93.0
	%	2.2	1.1	2.2	2.2	2.2	45.2	8.6	2.2	34.4	100.0
8	No.	21.0	2.0	2.0	9.0	15.0	N/A	N/A	N/A	N/A	49.0
	%	42.9	4.1	4.1	18.4	30.6	-	-	-	-	100.0
Total	No.	73.0	32.0	24.0	53.0	54.0	171.0	50.0	13.0	101.0	571.0
	%	12.8	5.6	4.2	9.3	9.5	29.9	8.8	2.3	17.7	100.0

During a regular data collection day eleven-hour data collection was recommended. (7:00 AM-6:00 PM). However, it was not possible to start data collection as early as it was recommended in the Traffic Conflict Technique for safety and Operation's - Engineer's Guide. In case of data collection time being shorter than eleven hours, it was recommended that the data should be adjusted as it was explained in Chapter 3. The data were adjusted by using the formula explained in Chapter 3 to be used in data analysis. Table 5.4 presents the summary of the total number of conflicts adjusted for each site for each conflict type.

Table 5.4 Summary of the Total Number of Conflicts Used for Analysis, Signal

Site	Conflicts	Conflict Type									Total
		RTUT1	RTUT2	RTUT3	RTUT4	RTUT5	DLT1	DLT2	DLT3	DLT4	
1	No.	33.5	22.7	10.7	38.1	34.3	N/A	N/A	N/A	N/A	139.3
	%	24.0	16.3	7.7	27.4	24.6	-	-	-	-	100.0
2	No.	12.8	3.7	9.2	5.5	3.7	74.8	22.4	5.7	50.8	188.6
	%	6.8	2.0	4.9	2.9	2.0	39.7	11.9	3.0	26.9	100.0
3	No.	3.7	2.8	3.7	2.8	2.8	34.6	11.6	2.2	21.0	85.2
	%	4.3	3.3	4.3	3.3	3.3	40.6	13.6	2.6	24.6	100.0
4	No.	1.0	0.3	1.0	1.0	4.9	109.5	29.5	9.4	62.2	218.7
	%	0.5	0.1	0.5	0.5	2.2	50.1	13.5	4.3	28.4	100.0
5	No.	2.8	1.8	0.0	0.0	4.6	94.8	41.7	2.0	23.0	170.7
	%	1.6	1.1	0.0	0.0	2.7	55.5	24.4	1.2	13.5	100.0
6	No.	7.6	22.0	20.2	27.5	27.5	N/A	N/A	N/A	N/A	104.8
	%	7.3	21.0	19.3	26.2	26.2	-	-	-	-	100.0
7	No.	3.7	2.8	7.3	6.4	6.4	115.0	22.0	5.5	88.0	257.1
	%	1.4	1.1	2.8	2.5	2.5	44.7	8.6	2.1	34.2	100.0
8	No.	35.6	3.5	3.5	15.3	25.7	N/A	N/A	N/A	N/A	83.6
	%	42.6	4.2	4.2	18.3	30.7	-	-	-	-	100.0
Total	No.	100.7	59.6	55.6	96.6	109.9	428.7	127.2	24.8	245.0	1248.0
	%	8.1	4.8	4.5	7.7	8.8	34.4	10.2	2.0	19.6	100.0

Table 5.5 Average Daily Number of Conflicts, Signalized Intersection

Site	Conflict Type									Total
	RTUT1	RTUT2	RTUT3	RTUT4	RTUT5	DLT1	DLT2	DLT3	DLT4	
1	16.8	11.4	5.4	19.1	12.2	N/A	N/A	N/A	N/A	64.9
2	6.4	1.9	4.6	2.8	1.9	24.9	7.5	1.9	16.9	68.8
3	1.9	1.4	1.9	1.4	1.4	8.7	2.9	0.6	5.3	25.5
4	5.0	1.4	1.1	3.9	5.3	54.8	14.9	4.7	31.1	122.2
5	1.4	0.9	0.0	0.0	2.3	19.0	8.3	0.4	4.6	36.9
6	19.3	11.0	10.1	13.8	13.8	N/A	N/A	N/A	N/A	68.0
7	1.9	1.4	3.7	3.2	5.1	57.8	11.0	2.8	44.0	130.9
8	17.8	1.8	1.8	7.7	12.9	N/A	N/A	N/A	N/A	42.0

To illustrate a more general perspective of DLT and RTUT movements' number of daily conflicts, the data for all signalized intersection sites were combined and the average daily number of conflicts for both movements were calculated by the conflict type. Figures 5.1 and 5.2 graphically illustrate the average daily number of conflicts for each conflict type related to RTUT and DLT movements respectively.

The RTUT movements generated an average of 29.8 conflicts per day. Conflicts caused by U-turn maneuvers corresponded to 45 percent of RTUT related conflicts. Although U-turns maneuvers took place at signalized intersections and conflicting vehicle volumes were very low as compared to other conflict types, the number of conflict movements can be considered fairly high because the drivers do not expect the U-turn until the last moment; therefore, they approach the U-turn vehicles without caution which causes conflicts. On the other hand, weaving maneuvers generated 55 percent of RTUT related conflicts. When we consider each conflict type separately:

conflict RTUT1 was 30 percent of all RTUT related conflicts, and conflict types RTUT2 and RTUT3 corresponded to 13 and 12 percent, respectively. The reason for conflict RTUT1 to occur more than conflict RTUT2 is that the drivers usually preferred to make a right turn onto the inner lane of the major road in this study. U-turn maneuver conflicts RTUT4 and RTUT5 were 22 and 23 percent of RTUT conflicts respectively.

The DLT movements generated approximately 56.4 conflicts per day. The conflicts with the major road vehicles were 81 percent of DLT related conflicts. The conflicts, which took place within the median opening, were 19 percent of all DLT related conflicts. These results seem to be logical because the conflicts with the major road vehicles had higher conflicting volumes than the conflicts that occurred within the median opening. When each DLT conflict type was considered, conflict DLT1 occurred most often and was 50 percent of all DLT related conflicts. For the other conflict types; DLT4, DLT2, and DLT3 were 31, 15, and 4 percent, respectively.

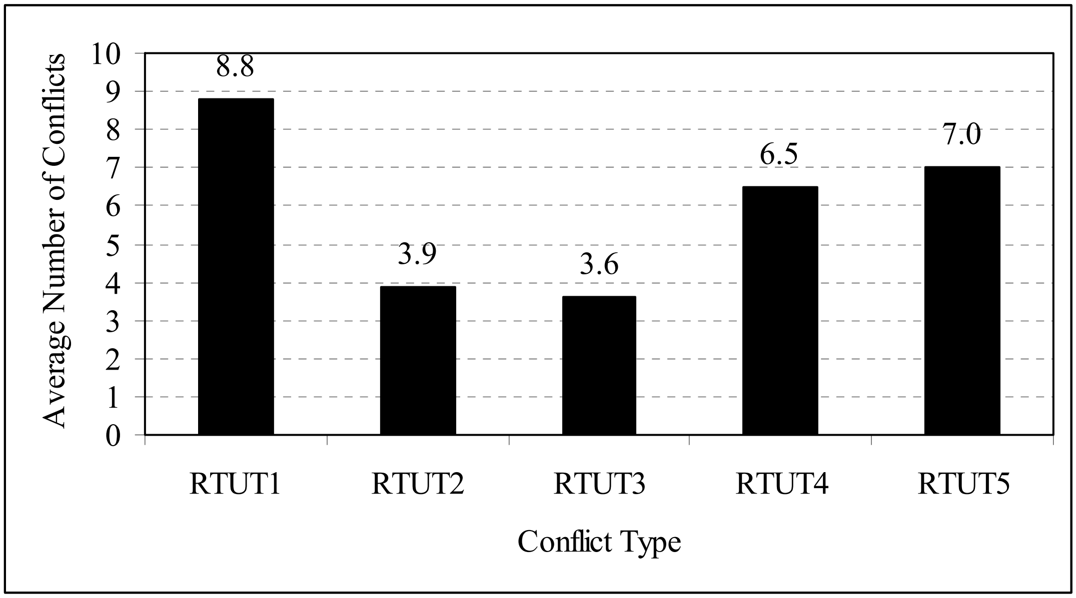


Figure 5.1 Average Number of Daily Conflicts by Type, RTUT Movement

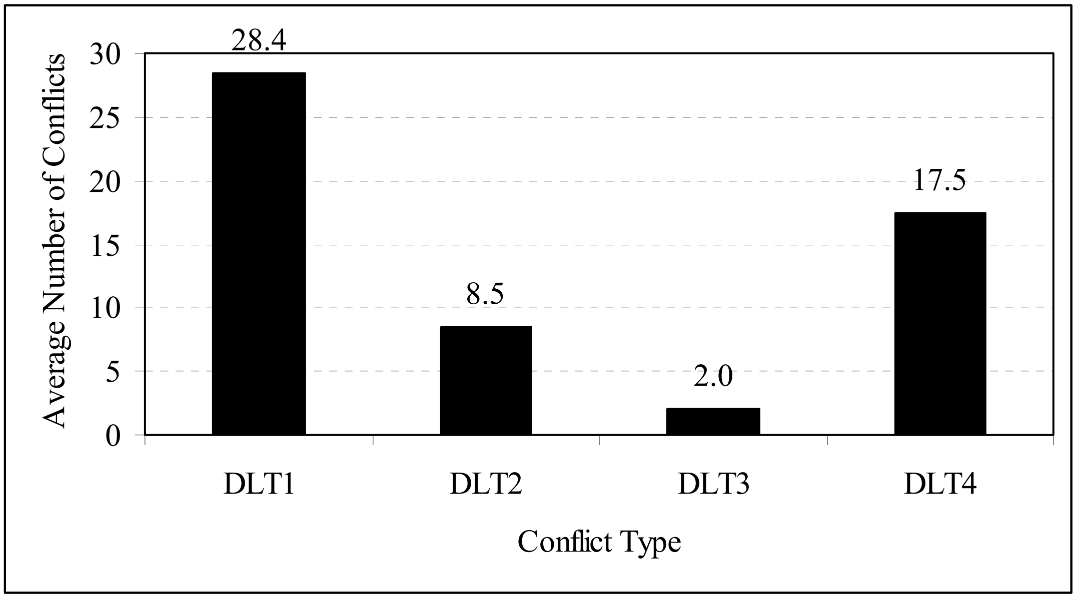


Figure 5.2 Average Number of Daily Conflicts by Type, DLT Movement, Signalized Intersection

When DLT and RTUT conflicts were compared, DLT movements had approximately two times more conflicts than the RTUT movements on an average daily basis. These results are calculated without the effects of volume and other factors. Especially, for full median opening sites drivers' choice of DLT movements over RTUT movements resulted in lower volumes of RTUT movements compared to DLT movements volumes. The purpose of the descriptive analysis was to describe and explore the data for better understanding of the data collected at the field. The conflict rates would provide a better description of safety for both of the movements. Also, the use of conflict rates will provide a more accurate comparison of both alternatives.

5.2.2 Conflict Rates

In this study, for the safety comparison of DLT and RTUT movements, two types of conflict rates were utilized. The conflicts per hour for each type of conflict were calculated and the results were presented for each site for each type of conflict. Another conflict rate, the number of conflicts per thousand vehicles involved, was calculated for each site. The average of the conflict rate for both alternatives was also calculated. Results are presented and discussed in the following subsections.

5.2.2.1 Conflicts Per Hour

The conflict rate, conflicts per hour, is acquired by utilizing the formula explained in Chapter 3. Figure 5.3 illustrates the average conflicts per hour for RTUT related conflicts. The average of RTUT related conflicts was not affected by peak hour and non-peak hour change, but the conflict types were affected in negative and positive ways by peak and non-peak hours. Conflict RTUT1 decreased 26 percent during the peak hours and, because of heavy traffic conditions, drivers had to make right turns with a narrow radius to the outer lane of the roadway and continue with weaving maneuvers. Because of this reason, conflict types RTUT2 and RTUT3 increased by 24 and 62 percent, respectively. In addition, the U-turn maneuver related conflict RTUT4 reduced by 14 percent while conflict RTUT5 increased by 23 percent. Figure 5.4 illustrates the average conflicts per hour for DLT related conflicts. All of the direct left turn related conflicts were increased during peak-hour periods except for conflict DLT3. The conflicts DLT1 and DLT4 were with major road vehicles and increased by 34 and 24 percent, respectively. This fairly high increase can be explained by the increase in the traffic volume of DLT maneuvers and the major roads. Also conflict DLT2, which occurred within the median opening, increased by 52 percent during peak-hour periods because of higher traffic volumes of left turn ingress and egress off the driveways.

Figure 5.5 presents the average number of conflicts per hour for RTUT and DLT movements. When both peak and non-peak periods were compared, both movements had higher conflict rates during the peak hours. When conflicts per hour for both alternatives were compared, DLT movements generated approximately two times more average conflicts per hour than RTUT movements.

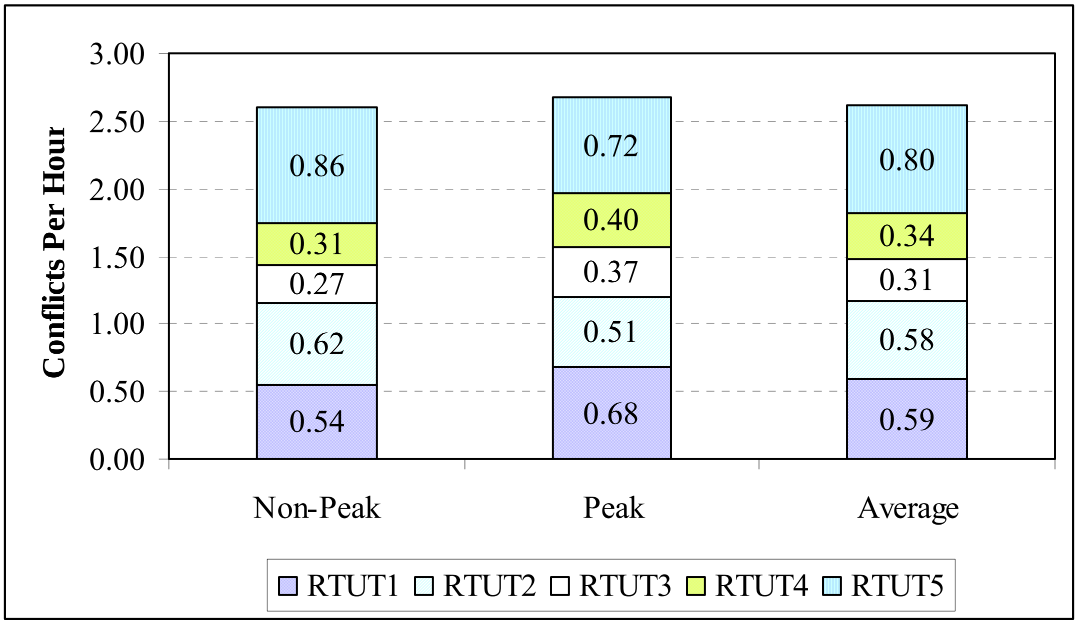


Figure 5.3 Conflicts by Time Period, RTUT Movement, Signalized Intersection

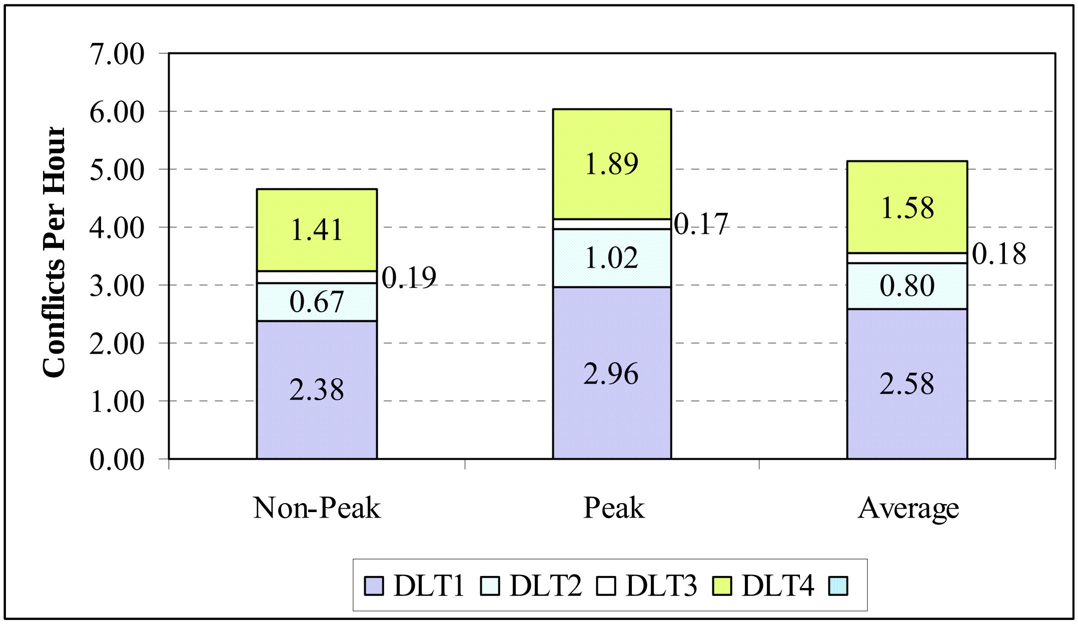


Figure 5.4 Conflicts by Time Period, DLT Movement, Signalized Intersection

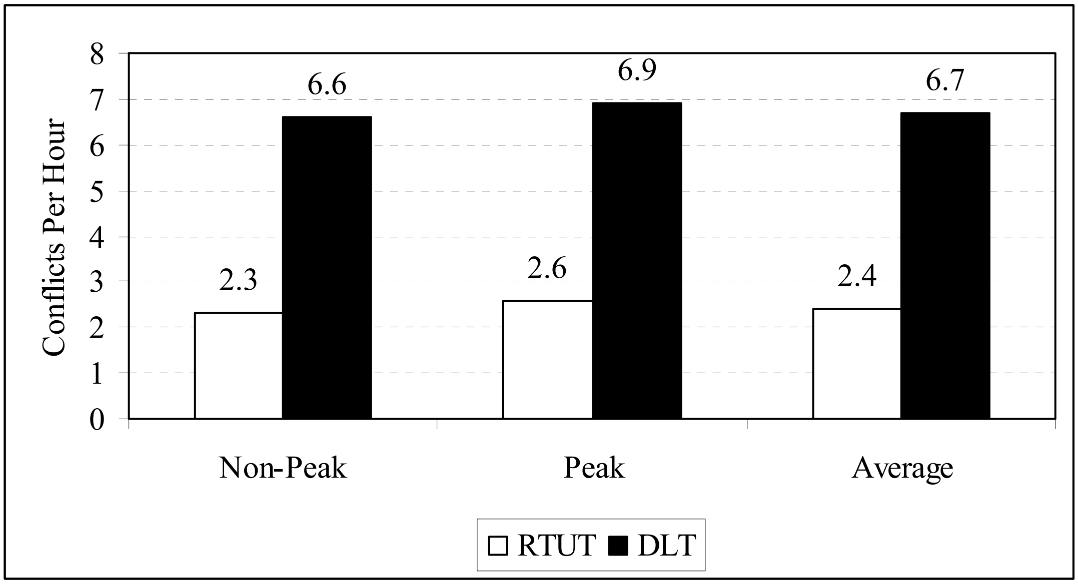
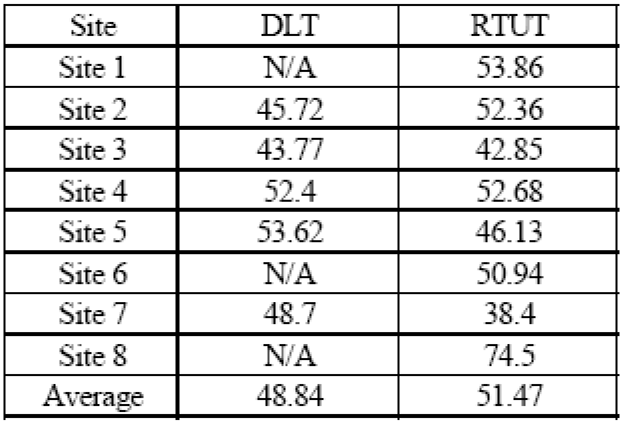


Figure 5.5 Conflicts by Time Period, DLT and RTUT Movements Comparison

5.2.2.2 Conflicts Per Thousand Involved Vehicles

The second conflict rate that takes traffic volumes effect into consideration was the conflicts per thousand vehicles involved. Based on the results of previous studies, the square root of the product of the volumes involved in conflicts was considered as the best option when calculating the conflict rate. The total number of conflicts, through traffic vehicles, maneuvering vehicles, and conflict rates were obtained for each site. Table 5.6 presents the number of conflicts per thousand involved vehicles at each site. RTUT movements had higher conflict rates at all sites with the exception of Site 3 and Site 7. In addition, when the average conflict rate of all sites was considered, RTUT movements' average conflict rate was 5.4 percent more than DLT movements. The reason for the higher RTUT conflict rate is due to the very low conflicting volume of U-turn maneuvers while the high number of conflicts related to these maneuvers occurred at signalized intersections. Table 5.6 and Figure 5.6 show the results of conflicts per thousand vehicles involved.

Table 5.6 Number of Conflicts per Thousand Vehicles Involved, Signalized Intersection



Site	DLT	RTUT
Site 1	N/A	53.86
Site 2	45.72	52.36
Site 3	43.77	42.85
Site 4	52.4	52.68
Site 5	53.62	46.13
Site 6	N/A	50.94
Site 7	48.7	38.4
Site 8	N/A	74.5
Average	48.84	51.47

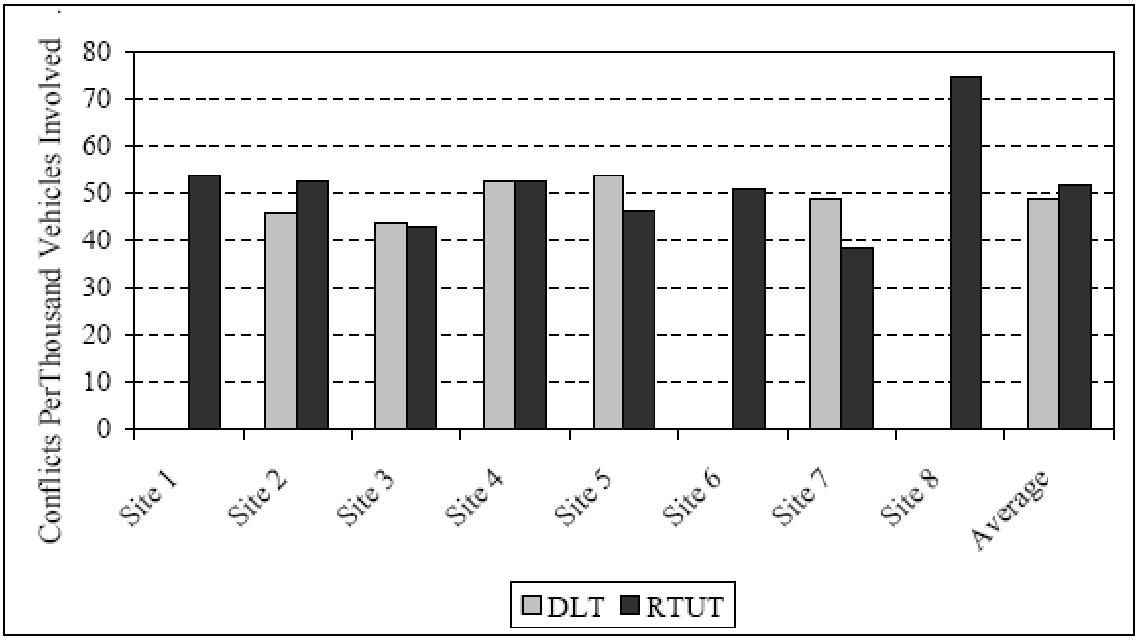


Figure 5.6 Conflicts Per Thousand Involved Vehicles, Signalized Intersection

5.3 Data Analysis of RTUT vs. DLT at Median Opening Sites

5.3.1 Descriptive Analysis

Sample size verification details were discussed previously in the subchapter of data analysis of signalized intersection sites. The total number of 2350 DLT movements and 1770 RTUT movements were observed at median opening sites. The results for sample size verification of RTUT and DLT movements are presented in Table 5.8 and 5.9, respectively. Sample size for RTUT and DLT movements were satisfactory for all types of conflicts.

Table 5.7 Sample Size Verification for RTUT Movements, Median Opening

Conflict (1)	Average Number of Conflicts (2)	RTUT Vehicles (3)	P_{RTUT} (4)=(2)/(3)	n (5)	Sample Size Satisfied
RTUT1	63	1770	0.04	53	Yes
RTUT2	62	1770	0.04	52	Yes
RTUT3	31	1770	0.02	26	Yes
RTUT6	61	1770	0.03	51	Yes
RTUT7	75	1770	0.04	62	Yes

P_{RTUT} : Percentage of RTUT vehicles involved in a conflict.
n : Number of vehicles estimated for sample size

The data for median opening sites are presented in two tables. The number of conflicts observed, for each type of conflict at each site are presented in Table 5.10. Furthermore, the numbers of conflicts used for analysis are presented in Table 5.11. In this table the data were adjusted for non-observed times.

Table 5.8 Sample Size Verification for DLT Movements, Median Opening

Conflict (1)	Average Number of Conflicts (2)	DLT Vehicles (3)	P_{DLT} (4)=(2)/(3)	n (5)	Sample Size Satisfied
DLT1	188	2620	0.07	102	Yes
DLT2	80	2620	0.03	45	Yes
DLT3	16	2620	0.01	9	Yes
DLT4	135	2620	0.05	75	Yes

P_{DLT} : Percentage of DLT vehicles involved in a conflict.
n : Number of vehicles estimated for sample size

The average daily number of conflicts for each median opening site and conflict type were obtained and these values are presented in Table 5.12.

Table 5.9 Summary of the Total Number of Conflicts Observed, Median Opening

Site	Conflicts	Conflict Type									Total
		RTUT1	RTUT2	RTUT3	RTUT6	RTUT7	DLT1	DLT2	DLT3	DLT4	
9	No.	26.0	20.0	11.0	31.0	26.0	N/A	N/A	N/A	N/A	114.0
	%	22.8	17.5	9.6	27.2	22.8	-	-	-	-	100.0
10	No.	16.0	17.0	6.0	12.0	17.0	N/A	N/A	N/A	N/A	68.0
	%	23.5	25.0	8.8	17.6	25.0	-	-	-	-	100.0
11	No.	16.0	18.0	12.0	13.0	24.0	N/A	N/A	N/A	N/A	83.0
	%	19.3	21.7	14.5	15.7	28.9	-	-	-	-	100.0
12	No.	1.0	1.0	0.0	1.0	2.0	39.0	19.0	4.0	30.0	97.0
	%	1.0	1.0	0.0	1.0	2.1	40.2	19.6	4.1	30.9	100.0
13	No.	2.0	3.0	1.0	1.0	2.0	26.0	12.0	2.0	15.0	64.0
	%	3.1	4.7	1.6	1.6	3.1	40.6	18.8	3.1	23.4	100.0
14	No.	1.0	2.0	1.0	2.0	2.0	35.0	22.0	3.0	28.0	96.0
	%	1.0	2.1	1.0	2.1	2.1	36.5	22.9	3.1	29.2	100.0
15	No.	1.0	1.0	0.0	1.0	2.0	42.0	14.0	5.0	27.0	93.0
	%	1.1	1.1	0.0	1.1	2.2	45.2	15.1	5.4	29.0	100.0
16	No.	0.0	0.0	0.0	0.0	0.0	57.8	37.4	5.0	86.4	186.6
	%	0.0	0.0	0.0	0.0	0.0	46.0	15.0	2.0	35.0	98.0
Total	No.	63.0	62.0	31.0	61.0	75.0	199.8	104.4	19.0	186.4	801.6
	%	7.9	7.7	3.9	7.6	9.4	24.9	13.0	2.4	23.3	100.0

Table 5.10 Summary of the Total Number of Conflicts Used for Analysis, Median Opening

Site	Conflicts	Conflict Type									Total
		RTUT1	RTUT2	RTUT3	RTUT6	RTUT7	DLT1	DLT2	DLT3	DLT4	
9	No.	52.7	35.1	23.2	48.2	55.3	N/A	N/A	N/A	N/A	214.5
	%	24.6	16.4	10.8	22.5	25.8	-	-	-	-	100.0
10	No.	43.3	41.5	13.6	35.5	49.4	N/A	N/A	N/A	N/A	183.3
	%	23.6	22.6	7.4	19.4	27.0	-	-	-	-	100.0
11	No.	28.1	30.0	18.5	21.5	38.5	N/A	N/A	N/A	N/A	136.6
	%	20.6	22.0	13.5	15.7	28.2	-	-	-	-	100.0
12	No.	3.1	3.1	0.0	2.2	4.4	57.2	25.1	5.7	43.8	144.6
	%	2.1	2.1	0.0	1.5	3.0	39.6	17.4	3.9	30.3	100.0
13	No.	5.6	8.7	2.4	3.1	5.6	38.1	14.7	2.9	22.0	103.1
	%	5.4	8.4	2.3	3.0	5.4	37.0	14.3	2.8	21.3	100.0
14	No.	3.7	5.9	2.4	4.9	5.9	51.9	32.2	4.5	40.9	152.3
	%	2.4	3.9	1.6	3.2	3.9	34.1	21.1	3.0	26.9	100.0
15	No.	2.2	1.7	0.0	1.1	2.4	71.5	23.8	8.4	46.1	157.2
	%	1.4	1.1	0.0	0.7	1.5	45.5	15.1	5.3	29.3	100.0
16	No.	0.0	0.0	0.0	0.0	0.0	57.8	37.4	5.0	86.4	186.6
	%	0.0	0.0	0.0	0.0	0.0	31.0	20.0	2.7	46.3	100.0
Total	No.	138.7	126.0	60.1	116.5	161.5	276.5	133.2	26.5	239.2	1278.2
	%	10.9	9.9	4.7	9.1	12.6	21.6	10.4	2.1	18.7	100.0

Figures 5.7 and 5.8 graphically illustrate the average daily number of conflicts for each conflict type related to RTUT and DLT movements respectively.

RTUT movements generated an average of 53.5 conflicts per day. 27 percent of the RTUT related conflicts were conflict type C5. This conflict type occurred between slow U-turn vehicles. The other conflict types: RTUT1, RTUT2, RTUT3, and C4 were 23, 21, 10, and 19 percent of all RTUT related conflicts, respectively. U-turn maneuvers at the median openings generated 46 percent of all RTUT related conflicts while weaving maneuvers generated 54 percent of all RTUT related conflicts.

Table 5.11 Average Daily Number of Conflicts, Median Opening

Site	Conflict Type									Total
	RTUT1	RTUT2	RTUT3	RTUT6	RTUT7	DLT1	DLT2	DLT3	DLT4	
9	17,6	11.7	7.7	16.1	18.4	N/A	N/A	N/A	N/A	53.9
10	14.4	13.8	4.5	11.8	16.5	N/A	N/A	N/A	N/A	61.0
11	9.4	19.0	6.2	7.2	12.8	N/A	N/A	N/A	N/A	54.6
12	1.6	1.6	0.0	1.1	2.2	28.6	12.6	2.9	21.9	72.5
13	2.8	4.4	1.2	1.6	2.8	19.1	8.9	1.5	11.0	53.3
14	1.9	3.0	1.2	2.5	3.0	26.0	16.1	2.3	20.5	76.5
15	1.1	0.9	0.0	0.9	2.1	17.9	6.0	2.1	11.5	42.5
16	0.0	0.0	0.0	0.0	0.0	56.4	18.7	2.5	43.2	120.8

An average of 66 conflicts was observed for DLT movements. The data show that conflict type DLT1 occurred most often and were 45 percent of the all DLT related conflicts. For the other conflict types: DLT4, DLT2, and DLT3 were 33, 19, and 3 percent respectively. Conflict types DLT1 and DLT4 are conflicts with main road vehicles; therefore, it was expected for these types of conflicts to occur more frequently than conflict types DLT2 and DLT3,which occur within the median opening.

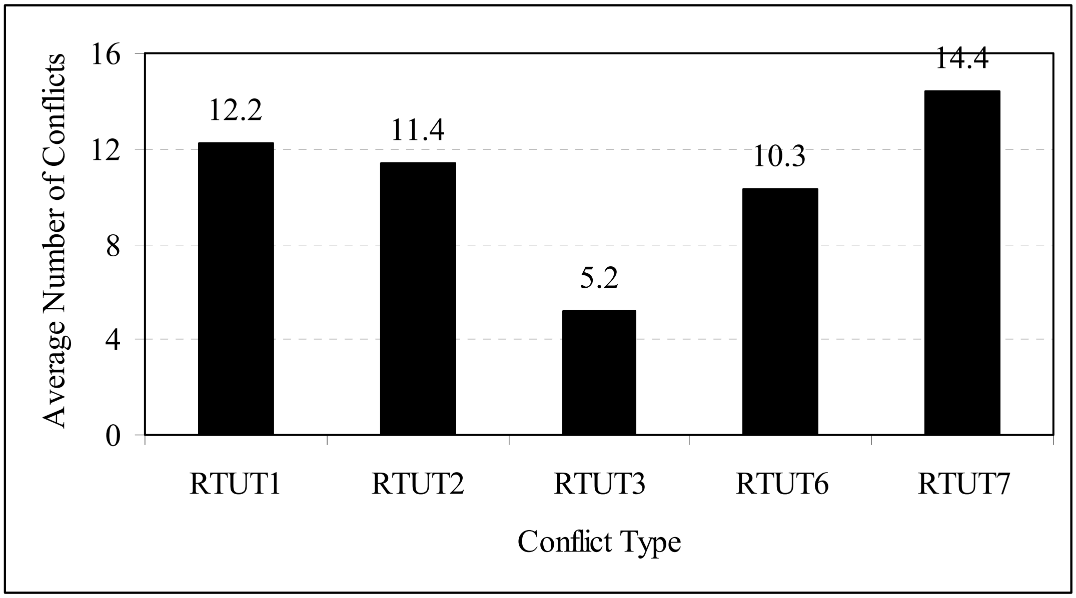


Figure 5.7 Average Number of Daily Conflicts by Type, RTUT Movement, Median Opening

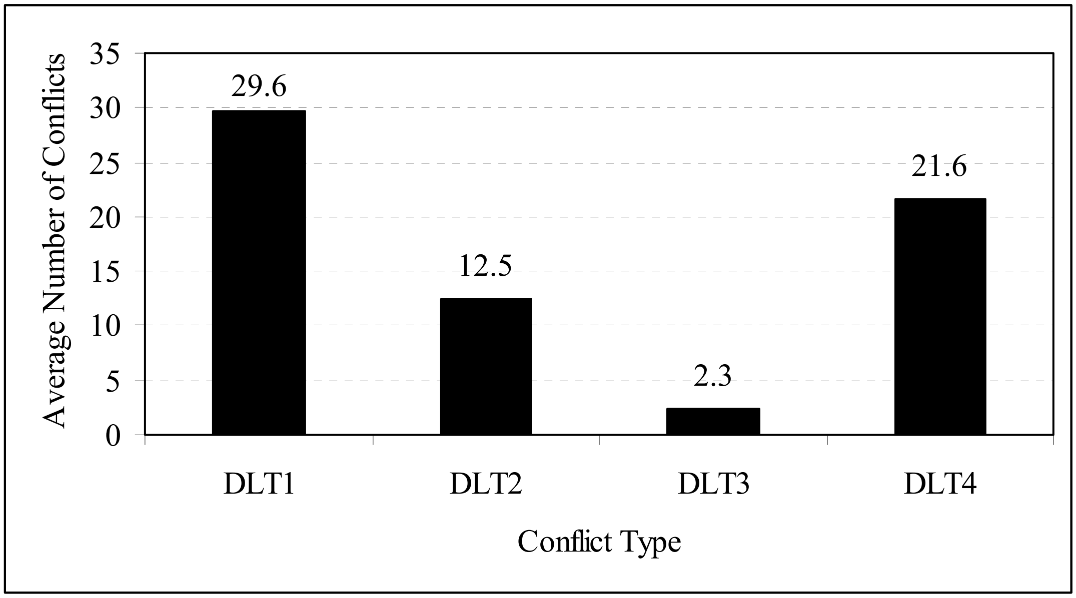


Figure 5.8 Average Number of Daily Conflicts by Type, DLT Movement, Median Opening

When DLT and RTUT conflicts were compared, DLT movements had approximately 23 percent more conflicts than RTUT movements on an average daily basis. These results are calculated without the affects of volume and other factors. Also, the use of conflict rates will provide a more accurate comparison of both alternatives.

5.3.2 Conflict Rates

5.3.2.1 Conflicts Per hour

When comparing the conflict rate, conflicts per hour, DLT movements generated more conflicts per hour than RTUT movements. Figure 5.9 illustrates the average conflicts per hour for peak and non-peak periods and the average of conflicts per hour for RTUT related conflicts. In general, RTUT movement conflicts were affected by peak hour traffic significantly, the conflicts per hour increased for all the RTUT conflicts. RTUT conflict types RTUT1, RTUT2, RTUT3, RTUT6, and RTUT7 were increased by 23, 56, 25, 20 and 15 percent during peak hour periods respectively. On the other hand, all DLT related conflicts increased during peak hours as it is illustrated in Figure 5.10. DLT conflict types DLT1, DLT2, and DLT3 were increased by 14, 21, 44 and 11 percent during peak hour periods.

Figure 5.11 presents the average number of conflicts per hour for RTUT and DLT movements. When both peak and non-peak periods are compared, both movements have high conflict rates during the peak hours. On average, DLT movements generated 10 percent more conflicts per hour than RTUT movements.

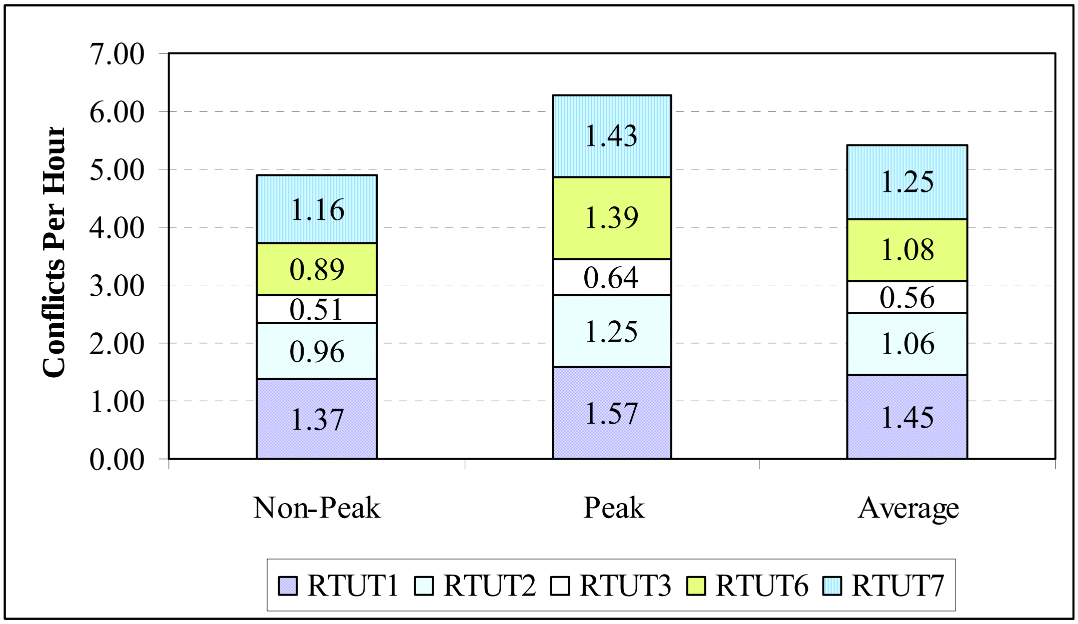


Figure 5.9 Conflicts by Time Period, RTUT Movement, Median Opening

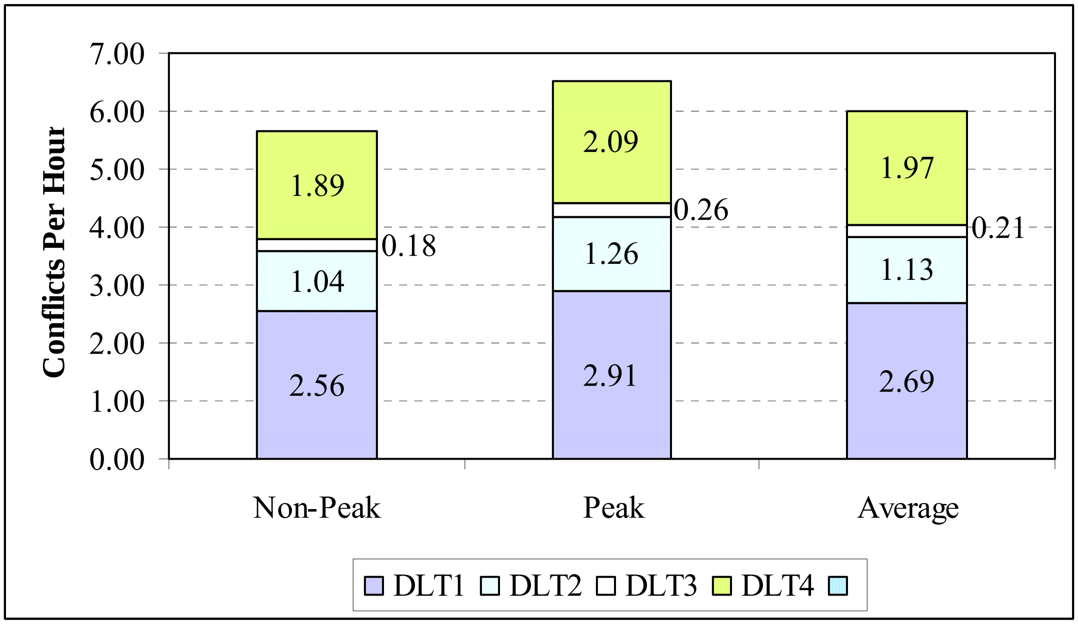


Figure 5.10 Conflicts by Time Period, DLT Movement, Median Opening

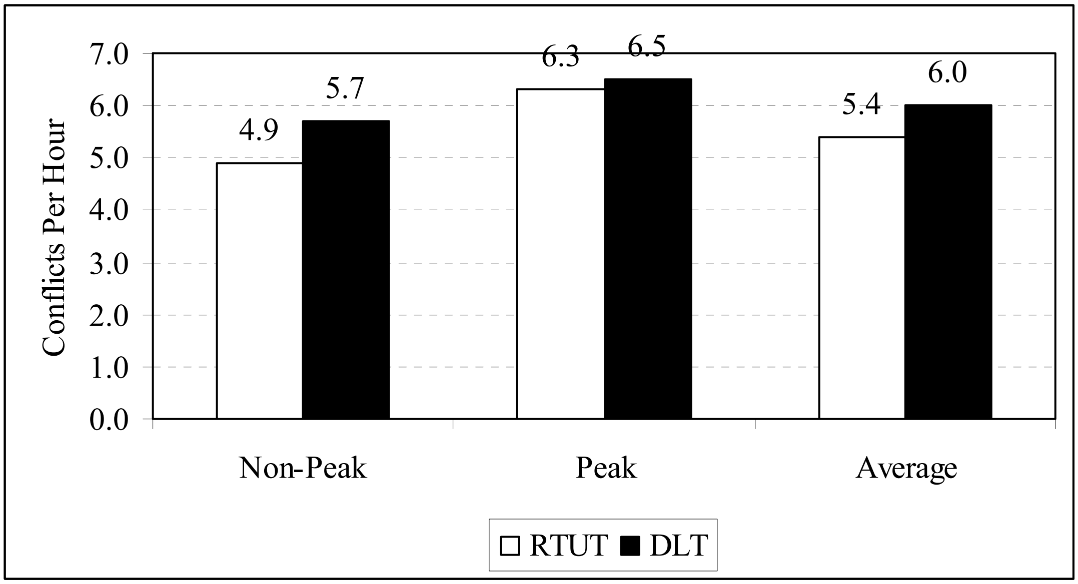


Figure 5.11 Conflicts by Time Period, DLT and RTUT Movements Comparison, Median Opening

5.3.2.2 Conflicts Per Thousand Involved Vehicles

This conflict rate was utilized for median opening sites as well. The total number of conflicts, through traffic vehicles, maneuvering vehicles, and conflict rates were obtained for each site at a median opening. Table 5.13 and Figure 5.28 present the number of conflicts per thousand vehicles involved at each median opening site. The values given in Table 5.13 indicate that all sites had low conflict rates for RTUT movements. Moreover, Table 5.13 indicates hat the average conflict rate for RTUT was 39 percent lower than that of DLT movements.

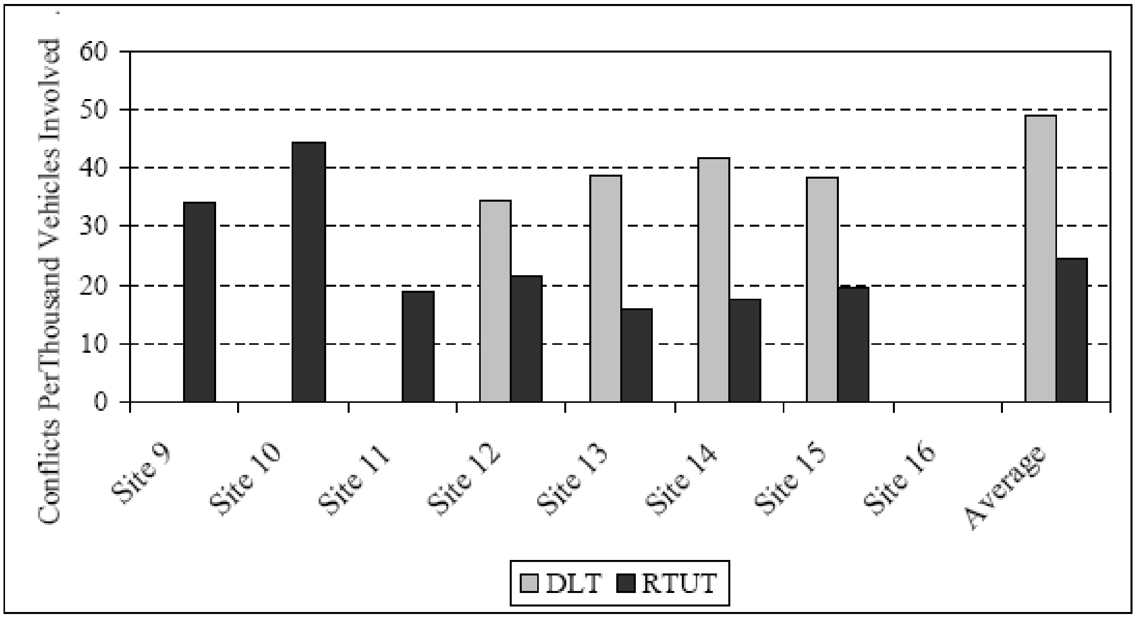


Figure 5.12 Conflicts Per Thousand Involved Vehicles, Median Opening

Table 5.12 Number of Conflicts Per Thousand Involved Vehicles, Median Opening

Site	DLT	RTUT
Site 9	N/A	33.93
Site 10	N/A	44.43
Site 11	N/A	18.92
Site 12	34.52	21.32
Site 13	38.61	15.83
Site 14	41.59	17.64
Site 15	38.47	19.53
Site 16	45.42	N/A
Average	39.72	24.51

5.4 Severity Analysis

The severity of conflicts was analyzed by considering a subjective score that was based on the Risk of Collision (ROC) of the maneuver. An objective score, that was based on the concept of Time to Collision (TTC) was considered as well but conflict types C4 and C5 which are RTUT related conflicts and conflict types C7 and C8 which are DLT related conflicts were not possible to define by an objective method (TTC) because the maneuvers do not occupy the same path and the speed data were not available for those maneuvers. Also, the lane change conflict (C3) cannot be defined by TTC when there was little or no speed difference between vehicles that were involved in a conflict. The ROC score is subjective because it depends on the observer but it can still be used for comparison purposes. The conflict score ranged from 1 through 3 as it is presented in Table 5.7.

5.4.1 Severity Analysis of Signalized Intersections

Figure 5.13 illustrates the average ROC scores for RTUT movements. Conflict types RTUT1, RTUT2, and RTUT3 have higher severity scores as compared to conflict types RTUT4 and RTUT5. Conflict types RTUT1, RTUT2 and RTUT3 have higher severity scores because of higher speed differences between main road vehicles and right turning vehicles from the driveway. On the other hand, conflict types RTUT4 and RTUT5 occurred at signalized intersections where speed differences between vehicles were relatively low. Figure 5.14 illustrates the average ROC scores for DLT movements. Conflict types DLT1 and DLT4 have higher severity as compared to conflict types DLT2 and DLT3. These results were expected because higher severity conflicts occur more frequently with the main road vehicles running at high speed than the other conflicting vehicles. Median opening related conflicts DLT2 and DLT3 have lower severities because of low speeds and low speed differences of vehicles involved in the conflicts. The average severity of RTUT and DLT movements are illustrated in Figure 5.15. The RTUT movements had an average severity score of 1.40 while the average severity score for DLT movements was 1.88.

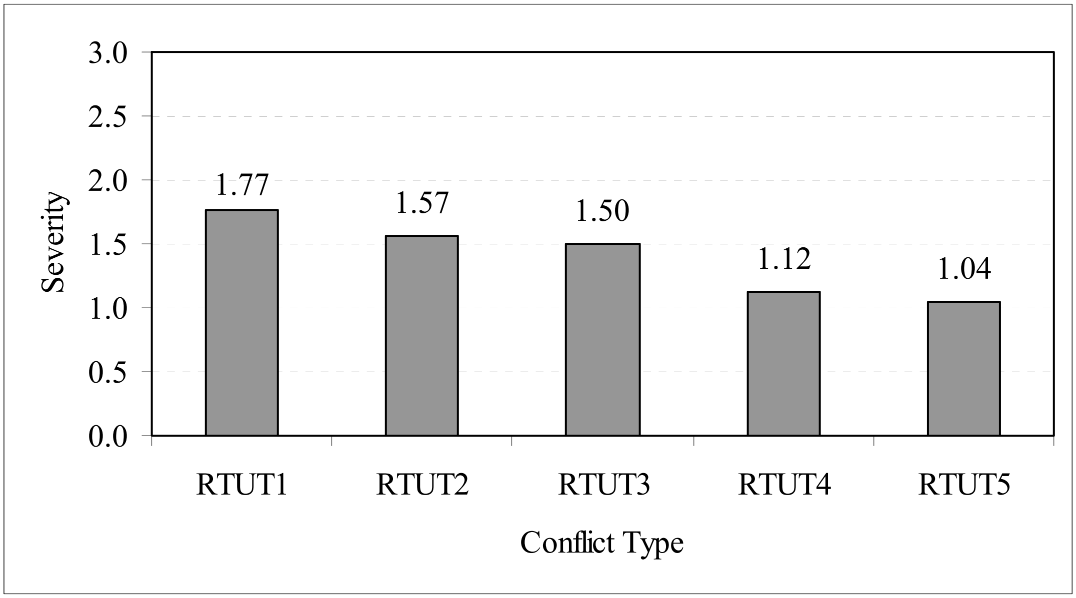


Figure 5.13 Average ROC Scores for RTUT Movements, Signalized Intersection

5.4.2 Severity Analysis of Median Openings

The frequency of the severity for each conflict type with ROC score were obtained for median opening sites and are illustrated in Figures 5.41 through 5.49. Based on these figures, the average ROC scores were calculated for all conflicts.

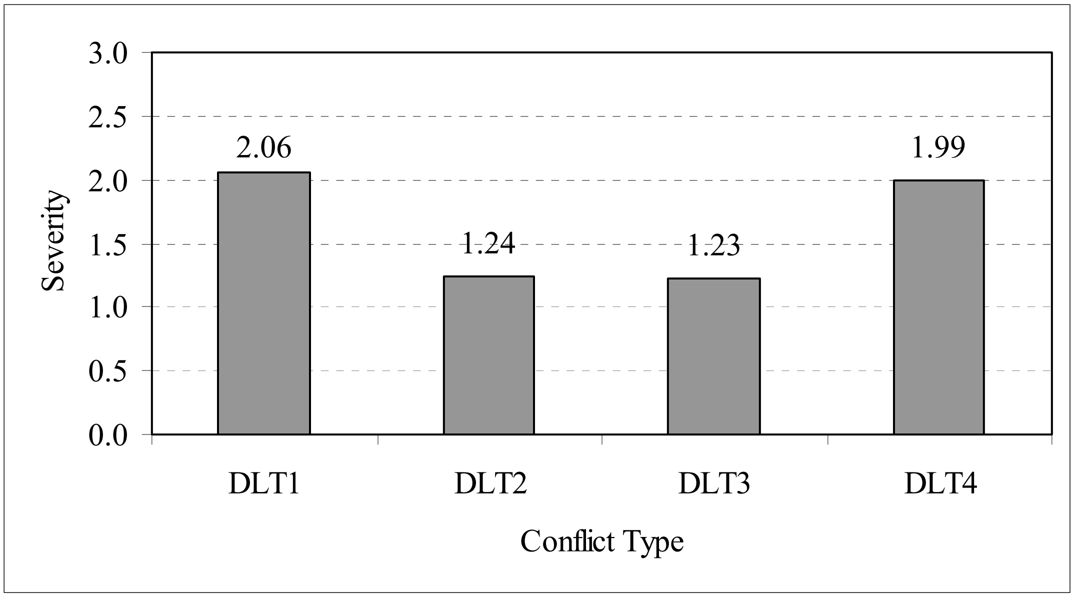


Figure 5.14 Average ROC Scores for DLT Movements, Signalized Intersection

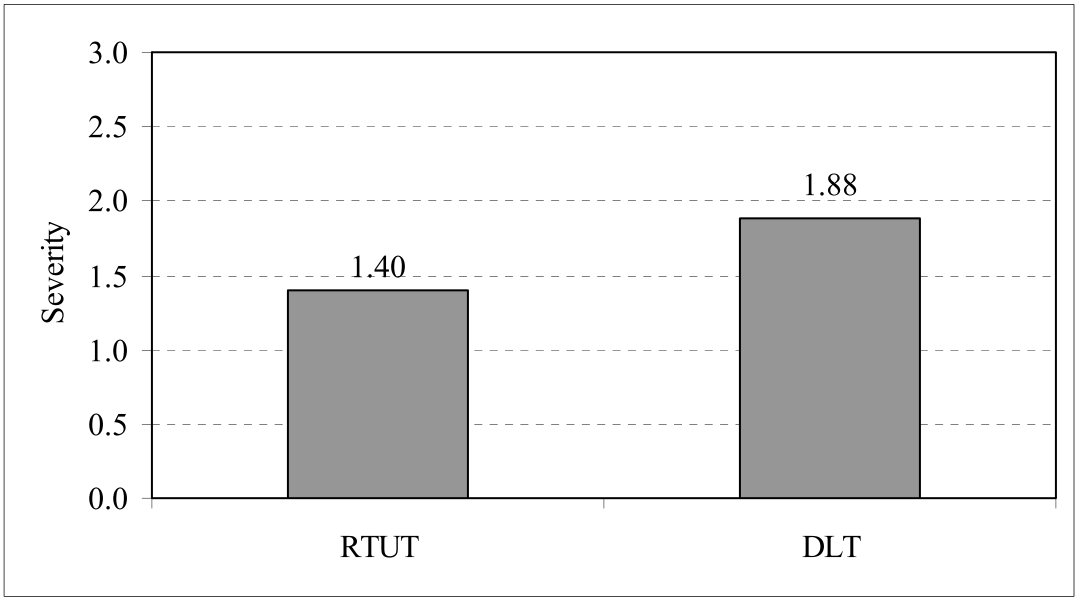


Figure 5.15 Severity Comparison for DLT and RTUT Movements by ROC, Signalized Intersection

The frequency of the severity for each conflict type with ROC score were obtained for median opening sites and are illustrated in Figures 5.41 through 5.49. Based on these figures, the average ROC scores were calculated for all conflicts.

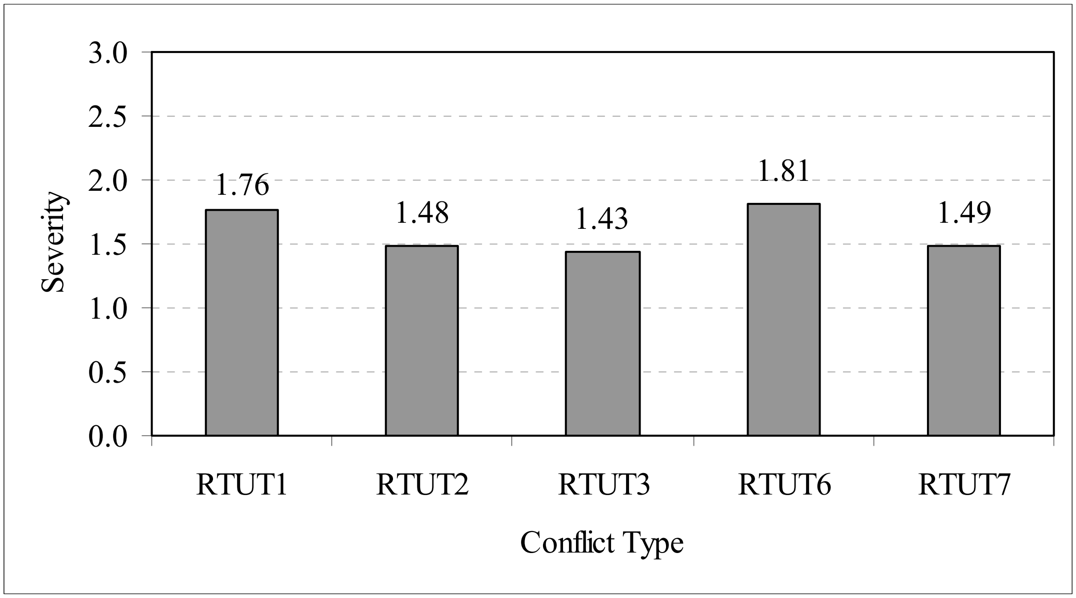


Figure 5.16 Average ROC Scores for RTUT Movements, Median Opening

Figure 5.16 illustrates the average ROC scores for RTUT movements for median opening sites. Conflict types RTUT1 and RTUT6 had higher severity when compared to conflict types RTUT2, RTUT3 and RTUT7 because of the speed difference with the major road vehicles are higher for the conflicts RTUT1 and RTUT6. On the other hand, the speed difference for conflicts RTUT2, RTUT3 and RTUT7 was relatively low. Figure 5.17 illustrates the average ROC scores for DLT movements. Conflict DLT1 and DLT4 have significantly higher average severity scores compared to conflicts DLT2 and DLT3. Overall comparison in the average severity scores of RTUT and DLT movements indicated that DLT movements had more severe conflicts than RTUT movements. DLT movements had an average severity score of 1.91 while RTUT movements had an average severity score of 1.60.

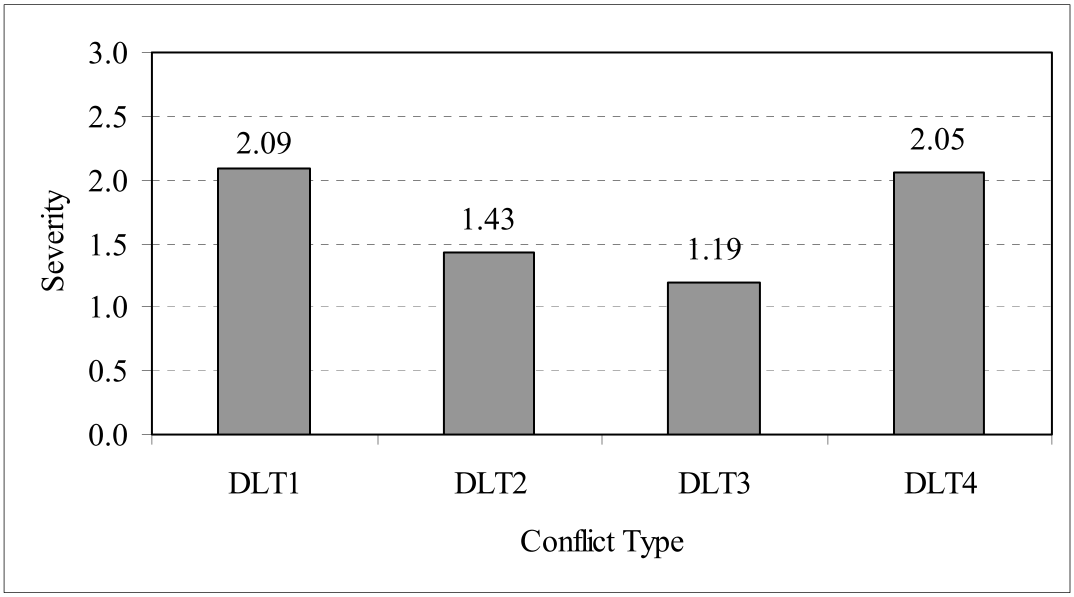


Figure 5.17 Average ROC Scores for DLT Movements, Median Opening

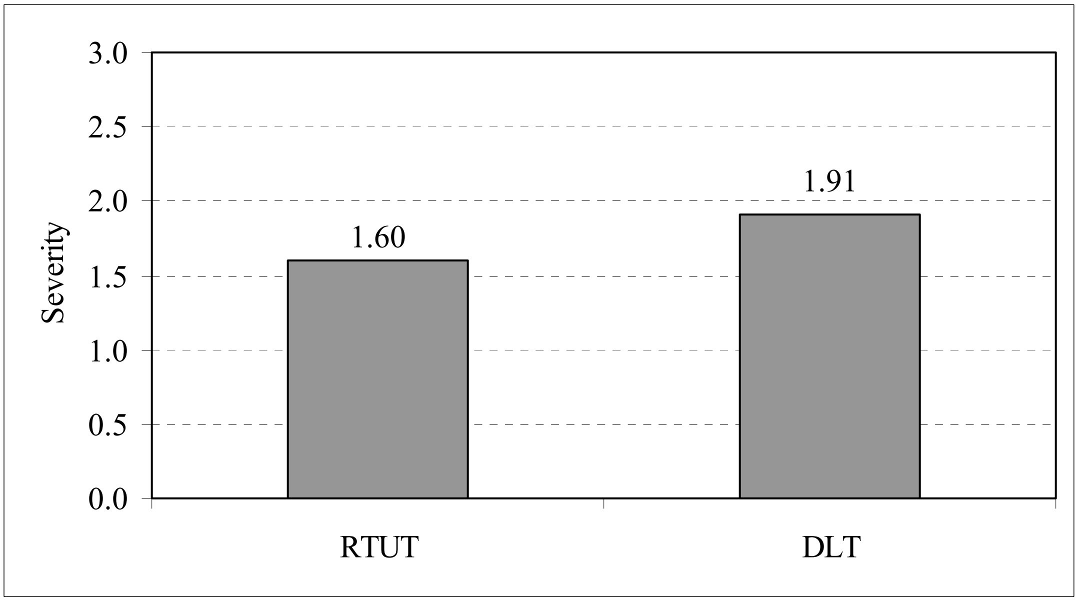


Figure 5.18 Severity Comparison for DLT and RTUT Movements by ROC, Median Opening

5.5 Summary

This chapter focused on the analysis of two left turn alternatives, DLT and RTUT movements at signalized intersections and at median opening sites at four lane arterials. The number of conflicts were presented and compared for DLT and RTUT movements. Two types of conflicts rates were utilized for the safety comparison of these movements. Also, these conflict rates were presented and compared. The severity of conflicts was analyzed by considering a subjective score that was based on the Risk of Collision (ROC) of the maneuver. The comparison of RTUT and DLT movements from safety perspective indicated that RTUT is a safer alternative to DLT. In addition, RTUT related conflicts had lower average severity scores than DLT related conflicts.

CHAPTER 6

LOCATION OF U-TURNS

6.1 Introduction

Location of U-turns is an important factor for driver choice of making right-turns followed by U-turns maneuvers and safety of left turn alternatives. It is essential to evaluate how the separation distances between driveways and U-turn locations impact the safety performance of vehicles making right-turns followed by U-turns. Based on determined criteria, conflict data were collected at 61 locations. Three types of conflicts are selected for conflict data analysis. These conflicts include right-turn out of the driveway conflict (RTUT1), slow-vehicle same-direction conflict (RTUT2), lane change conflict (RTUT3). In this chapter, conflict data analysis results are presented and minimum separation distance recommendations are provided based on analysis results.

6.2 Conflict Rate

Weaving maneuvers to reach the exclusive left turn lane after right turns from driveways could be a problem for drivers under heavy traffic conditions. Short weaving distances could be dangerous for the drivers to complete maneuvers. On the other hand, very long weaving distances will cause the increase of a travel time for drivers. It is necessary to estimate optimum weaving distances for different geometric conditions from safety perspective.

The conflict data by itself would not take the traffic conditions into consideration. Especially, the geometric conditions of the sites have also affects on traffic conflicts. To identify the influence of the geometric conditions on conflicts, these geometric conditions are studied separately. In addition, traffic volumes on subject driveways and main arterials have direct affects on conflict occurrence. Traffic conflict rates, that will take the influence of volumes on conflicts, were employed.

In earlier studies, conflict rates which take traffic volumes into consideration showed some differences for the use of traffic volumes as variable of traffic conflicts. For this study, the conflict rates presented in methodology chapter are employed and results were obtained. The results showed that these conflicts rates cannot sufficiently reflect the effects of driveway volumes. The driveways, selected in this study had volume variation of 25 vehicles per hour -100 vehicles per hour while the variation of volumes on main arterials did not vary to a large extent. Another issue was the large difference between the driveway volumes and main road volumes. Because of the two differences in two conflicting volumes, both conflict rates presented below could not explain the affect of driveway volume on conflict rate.

These issues could be solved by defining a conflict rate that can take both driveway volume and arterial volume into consideration directly. This problem is solved by the conflict rate presented in Equation 6.1. Results obtained by using this conflict rates was found to reflect the effect of driveways volumes accurately and also showed that the results were consistent with other studies.

$$CR = \frac{Number\ of\ conflicts}{V_1 + V_2} \times 1000 \qquad (6.1)$$

In this study, to investigate the weaving maneuvers, conflict data were collected at 61 locations. These locations varied by separation distance, U-turn location and number of lanes on main road. Three types of conflicts occurred between the RTUT vehicles and major road vehicles were considered as weaving conflicts. Every conflict occurred between major road user and weaving vehicles were recorded regardless of weaving vehicles making a U-turn or not. The conflict rate at the selected roadway segments varies from 16.1 to 50.4 with an average of 28.8. The observed conflict rate data were fitted to a normal distribution. The histogram of conflict rate data distribution is presented in Figure 6.1

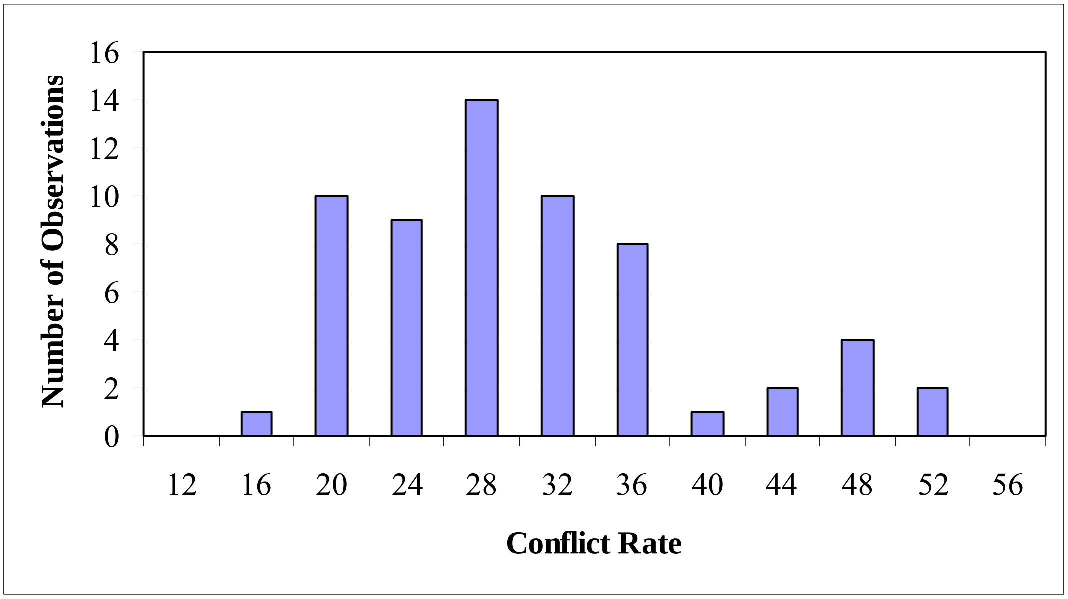


Figure 6.1 Distribution of Conflict Model

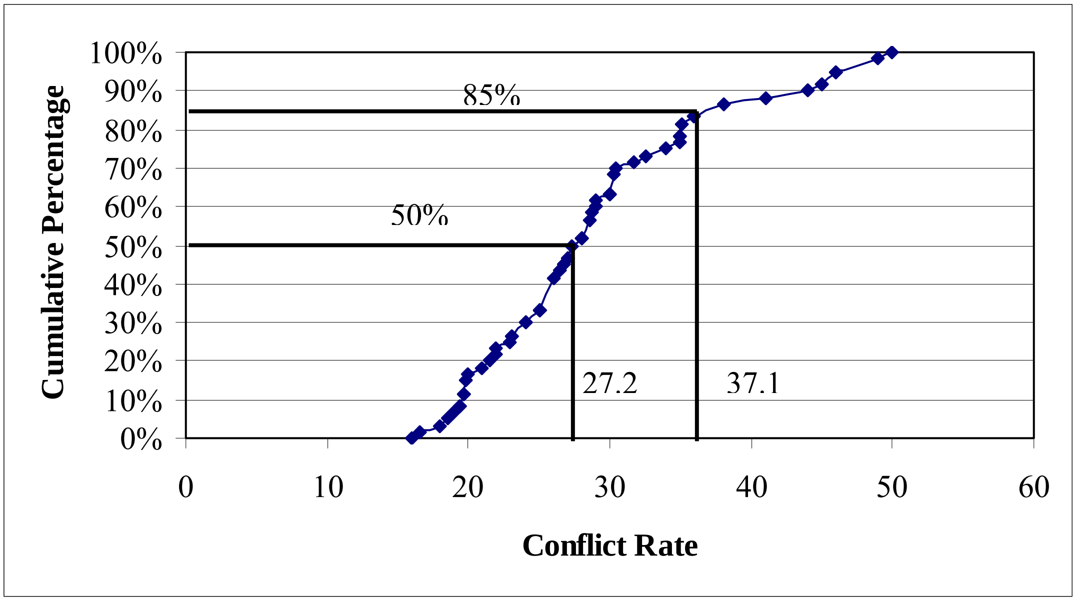


Figure 6.2 Cumulative Percentages of Conflict Rates

6.3 Conflict Model

Initially, several methods were employed to analyze the conflict data. The linear regression method was found to be the most suitable method to investigate the factors that impact conflict rates. The dependent variable of the model is defined as conflict rate. The stepwise regression method was used to determine significant independent variables. Traffic volumes were not considered as one of the independent variables in the model since the conflict rates were computed by input of number of conflicts and conflicting traffic volumes. The separation distance and the major-arterial speed limit are considered as independent variables. The major-arterial speed limit was not found to be significant at a 90% confidence level and was not included into the conflict rate model. Two dummy variables, "U-turn Location" and "Lane" were defined to distinguish between four geometric conditions, which include:

1. U-turn at a signalized intersection on four lane arterials
2. U-turn at a median opening on four lane arterials
3. U-turn at a signalized intersection on six-eight lane arterials
4. U-turn at a median opening on six-eight lane arterials

Descriptive statistics for variables included in the model are shown in Table 6-1. The range of the separation distance at selected roadway segments is from 190 ft to 1380 ft.

Table 6.1 Descriptive Statistics of Collected Data

Parameters	N	Min.	Max.	Mean	Std. Deviation
Conflict Rate	61	16.1	50.4	28.84	8.51
Seperation Distance	61	190	1380	607.56	275.23
U-Turn Location	61	0	1	0.47	0.50
Lane	61	0	1	0.52	0.50

The regression results are presented in Table 6-2. The R^2 value for conflict rate model is .33. The conflict rate model for separation distance analysis is given in Equation 6.2.

$$CR = 81.586 - 8.997\ln(SD) + 3.427UL + 4.436Lane \tag{6.2}$$

where,

CR = Conflict rate of vehicles of weaving vehicles (conflicts per thousand vehicles involved)

ln(SD) = logarithm of separation distance between the driveway and U-turn bay (ft.)

UT = Dummy variable; location of U-turn bays after weaving sections. (= 1 if U-turn bay is at a signalized intersection, = 0 if U-turn bay is at a median opening)

Lane = Dummy variable; number lanes on major arterial (= 1 if major arterial has six-eight lanes, = 0 if major arterial has four lanes)

Table 6.2 Conflict Model Regression Results

Independent Variables	Coefficient	t	Sig.
Intercept	81.586	6.631	0.000
ln(SD)	-8.997	-4.586	0.000
U-Turn Location	3.427	1.876	0.067
Lane	4.436	2.428	0.018
$R^2=0.33$ $R^2_{adj}=0.30$			

The independent variables used in the model were significant based on t-statistics at 90 percent level of confidence. The sign of separation distance variable was negative which indicates that the conflict rate decreases when the separation distance increases. Additionally, location of U-turns has a significant positive impact on conflict rate, which implies U-turn bays located at signalized intersections requires longer separation distances. More to the point, six- eight lane arterials requires longer separation distances than four lane arterials. The reason lies behind is that the vehicles has to weave through more lanes which is more complex driving environment leads to more conflicts from safety point of view. The residuals of two crash rates model were plotted against the fitted conflict rate data in Figure 6.3. It was found that the residuals were randomly distributed around the y=0 axis, indicating the fact that the model was correctly specified and the homogeneous assumption about the error term was not violated.

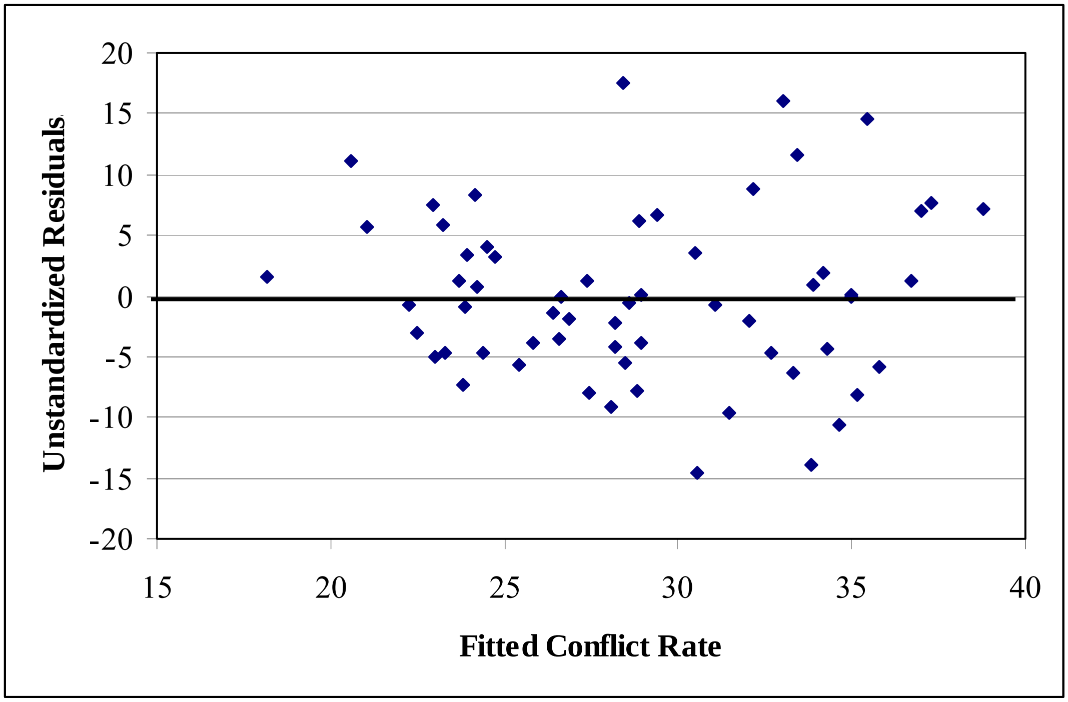


Figure 6.3 Unstandardized Residuals vs. Fitted Conflict Rate

6.4 Minimum Separation Distance

In order to determine the critical value of separation distance, the 50th percentile value of conflict rate turned out to be of great significance. By applying the 50th percentile value of conflict rate into the regression model in the previously mentioned section allows the evaluation of the critical separation distance for vehicles making RTUT movements under dissimilar roadways conditions. The methodology determines a straightforward theoretical conclusion. The critical 50th percentile value of conflict rates was found to be 27.25. If a roadway segment has a separation distance less than the critical value it will have a conflict rate greater than the median level. Figures 6.4 and 6.5 present the procedures to attain critical values of separation distance under different roadway conditions.

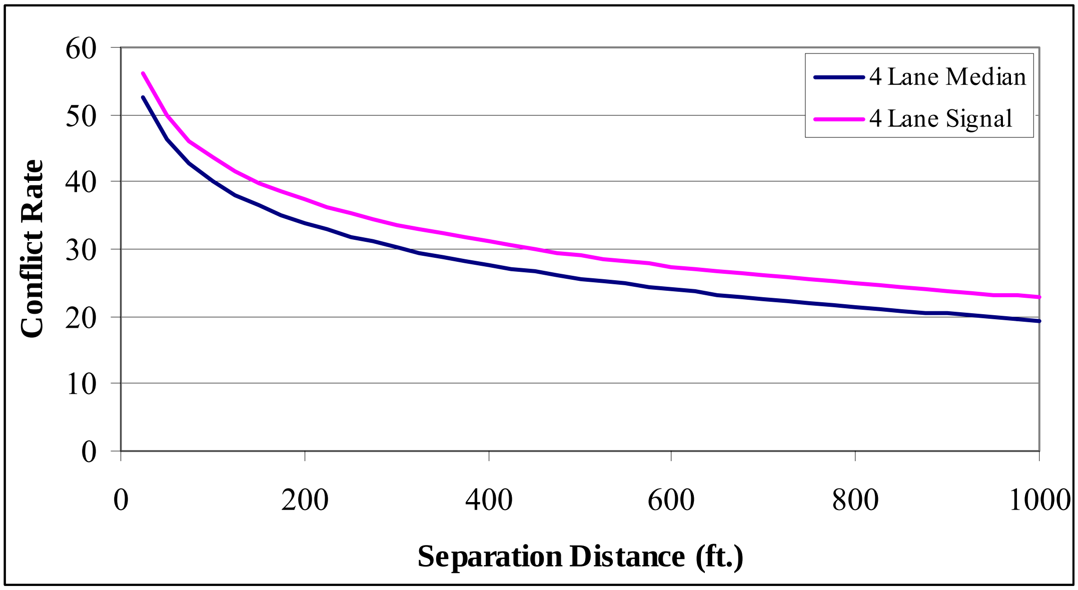


Figure 6.4 Four Lane Arterial Separation Distance vs. Conflict Rate

Recommendations were given for the minimum separation distances under different roadway conditions based on the critical separation distances. If a U-turn bay is located at a median opening on a 4-lane divided roadway with 2 lanes in each direction the minimum separation distance is found to be 420 feet between the driveway exit and the downstream median opening. The minimum separation distance is found to be 600 feet if the U-turn bay is located at a signalized intersection. Additionally, if a U-turn bay is located at a median opening on a 6 or 8 lane divided roadway the minimum separation distance is found to be 690 feet between the driveway exit and the downstream median opening. The minimum separation distance is found to be 1000 feet if a U-turn bay is located at a signalized intersection. Recommended critical separation distances under different roadway conditions are given in Table 6.3.

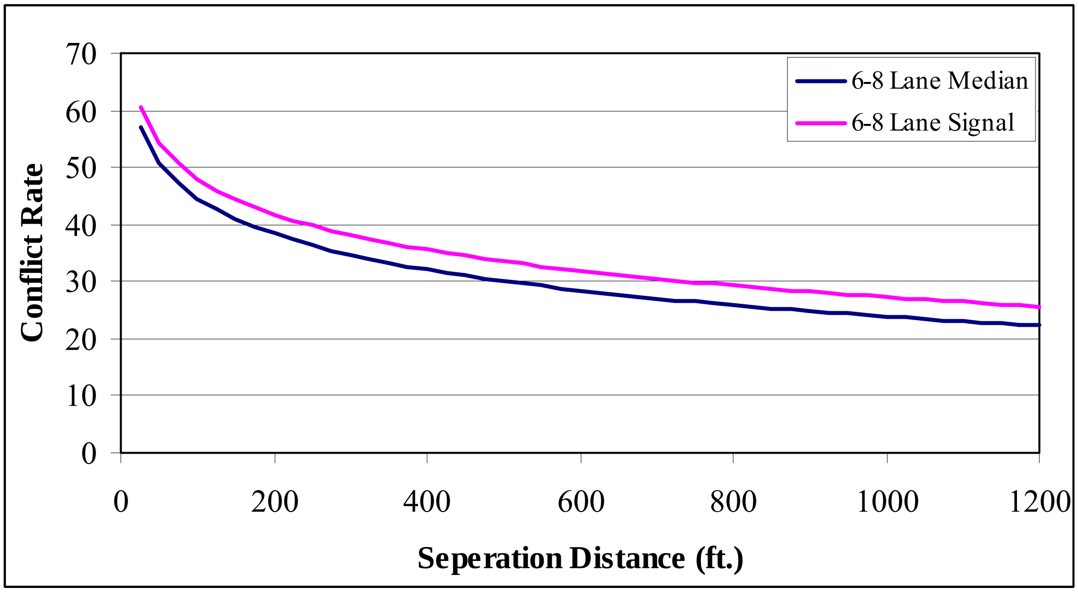


Figure 6.5 Six- Eight Lane Arterial Separation Distance vs. Conflict Rate

Table 6.3 Recommended Separation Distance Values

Location of U-turn Bay	Number of Lanes	Critical Separation Distance	Recommended Separation Distance
Median Opening	4 Lane	419	400
Median Opening	6-8 Lane	687	700
Signalized Intersection	4 Lane	614	600
Signalized Intersection	6-8 Lane	1005	1000

6.5 Summary

Safety performance of vehicles making RTUT is impacted by length of separation distance between driveway and downstream U-turn location. This chapter presented the results of analysis, which investigated impacts of separation distance on safety of right turn followed by U-turn movements. A regression model was developed to identify the impacts of U-turn locations, number of lanes on main arterials and separation distance on conflict rates. Based on model results, recommendations were given for minimum separation distance requirements under different geometric conditions.

CHAPTER 7

U-TURN ANALYSIS

7.1 Introduction

Location U-turns is an important factor for driver choice of making right-turns followed by U-turns maneuvers and safety of left turn alternatives. It is essential to evaluate how the separation distances between driveways and U-turn locations impact the safety performance of vehicles making right-turns followed by U-turns. Based on determined criteria, conflict data were collected at 61 locations. Three types of conflicts are selected for conflict data analysis. These conflicts include right-turn out of the driveway conflict (RTUT1), slow-vehicle same-direction conflict (RTUT2), lane change conflict (RTUT3). In this chapter, conflict data analysis results are presented and minimum separation distance recommendations are provided based on analysis results.

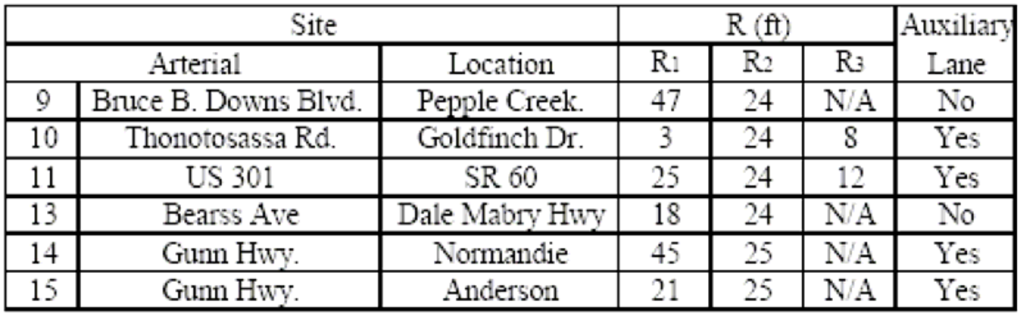
7.2 U-Turn Distribution at Median Openings

In this analysis, additional data other than the conflict data were collected at median opening sites. The data have included types of vehicles and geometric characteristics of median openings. Also, vehicles' U-turn behavior was observed to evaluate the geometric characteristics of median openings. U-turns were classified in three categories; First, vehicles made U-turn onto inner lane of main road. Second, vehicles made U-turn onto outer lane of main road. Finally, vehicles turn onto flare or encroach onto the shoulder in case a flare was not present in geometric design. Vehicles making U-turns at selected sites were classified in five categories. The criteria for classification of the vehicles were length and size of the vehicles. These categories were:

Category 1 PV: Passenger vehicles
Category 2 MV: Minivans, light pick-up trucks and small sport utility vehicles
Category 3 LV: Vans, medium pick-up trucks, large sport utility vehicles
Category 4 MT: Medium trucks and busses
Category 5 LT: Large trucks and busses

The data were collected at six sites. The geometric characteristics of these sites were presented in Table 5.14. Also, Figure 5.53 illustrates a typical median opening with the geometric characteristics.

Table 7.1 Geometric Characteristics of Sites for U-Turn Analysis



Site			R (ft)			Auxiliary Lane
Arterial		Location	R_1	R_2	R_3	
9	Bruce B. Downs Blvd.	Pepple Creek.	47	24	N/A	No
10	Thonotosassa Rd.	Goldfinch Dr.	3	24	8	Yes
11	US 301	SR 60	25	24	12	Yes
13	Bearss Ave	Dale Mabry Hwy	18	24	N/A	No
14	Gunn Hwy.	Normandie	45	25	N/A	Yes
15	Gunn Hwy.	Anderson	21	25	N/A	Yes

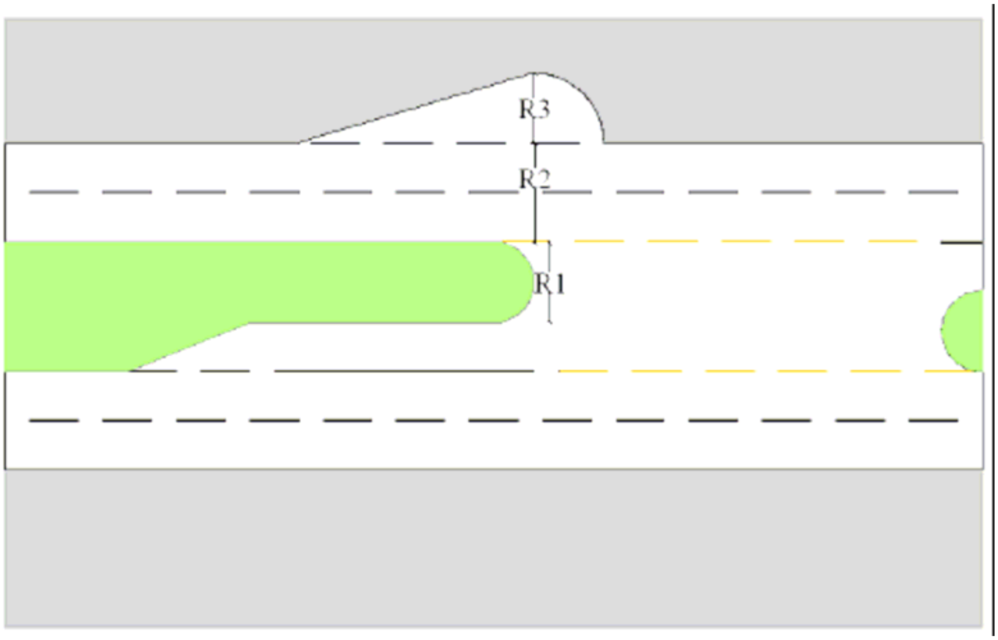


Figure 7.1 Median Opening Geometric Characteristics

Table 7.15 presents the data collected at the field for U-turn distribution at six sites. The geometric characteristics and U-turns distributions at each site are explained in the following paragraphs.

Site 9 has a wide median (47 ft.) without an auxiliary lane. All the vehicles turned on to either inner lane or outer lane of the main road. The vehicles turned on to inner lane were 46 percent of all vehicles while 54 percent of the all vehicles turn onto outer lane. At this site, construction of the auxiliary lane would be beneficial for safety and accommodation of the vehicles making a U-turn.

Site10 has very narrow median (3 ft.) with an auxiliary lane and flare to accommodate U-turns. All of the large vehicles used flare to make U-turns. The vehicles turning on to flare was 73 percent while vehicles turned on to inner and outer lanes were 2 and 25 percent, respectively.

Site 11 has 25-foot median with an auxiliary lane and flare. When this site is compared to Site 10 more vehicles turned on to inner lane to complete U-turns. At this site approximately 72 percent of the vehicles turn on to outer lane while 9 percent and 19 percent turned on to inner lane and flare, respectively.

Site 13 has an 18-foot median without an auxiliary lane and flare. Most of the large vehicles had to go out of road to shoulder to make U-turns. Only 4 percent of all vehicles turned on to inner lane. The vehicles which turned on to outer lane and shoulder were 47 and 49 percent, respectively. Construction of an auxiliary lane is suggested to increase safety at this site.

Site 14 has a wide median (45 ft.) with an auxiliary lane. At this site, road site has a curb which prevents vehicles to encroach on to the shoulder. At this site, 25 percent of vehicles turn on to inner lane while 75 percent used outer lane to make U-turns.

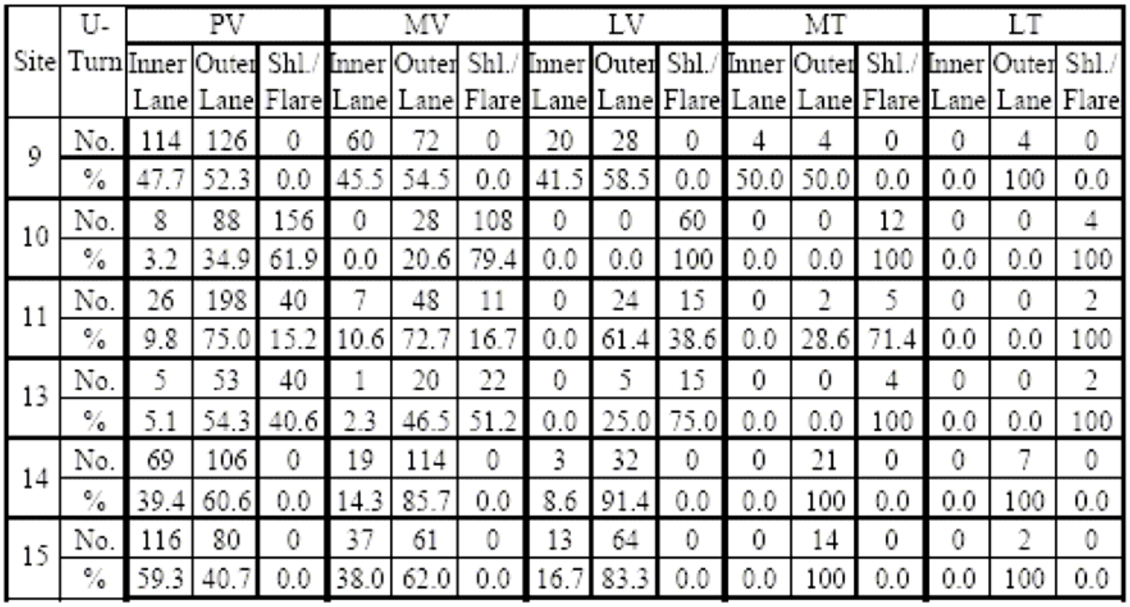
Site 15 This site is very similar to Site 14 except the median width is 25 feet. Also, this site has a curb along the major road. At this site, 23 percent of vehicles turn on to inner lane while 77 percent used outer lane to make U-turns.

The results of the analysis show at most sites, median openings accommodate U-turns without any problems for Category 1 and 2 vehicles which were 85 percent of all the vehicles observed in this analysis. Construction of flares helped the drivers where geometric characteristics of median openings are not sufficient to accommodate U-turns.

7.3 Right Turn and U-Turn Conflict Model

The conflicts related to U-turns and right turns from cross streets were a major concern at signalized intersection sites. Especially, safety evaluation of RTUT and DLT conflicts showed that this type of conflicts has a significant effect on RTUT maneuvers safety. Figure 7.2 shows the conflict type between U-turns and right turns from the cross streets.

Table 7.2 U-Turn Distribution at Median Openings



Site	U-Turn	PV			MV			LV			MT			LT		
		Inner Lane	Outer Lane	Shl./ Flare	Inner Lane	Outer Lane	Shl./ Flare	Inner Lane	Outer Lane	Shl./ Flare	Inner Lane	Outer Lane	Shl./ Flare	Inner Lane	Outer Lane	Shl./ Flare
9	No.	114	126	0	60	72	0	20	28	0	4	4	0	0	4	0
	%	47.7	52.3	0.0	45.5	54.5	0.0	41.5	58.5	0.0	50.0	50.0	0.0	0.0	100	0.0
10	No.	8	88	156	0	28	108	0	0	60	0	0	12	0	0	4
	%	3.2	34.9	61.9	0.0	20.6	79.4	0.0	0.0	100	0.0	0.0	100	0.0	0.0	100
11	No.	26	198	40	7	48	11	0	24	15	0	2	5	0	0	2
	%	9.8	75.0	15.2	10.6	72.7	16.7	0.0	61.4	38.6	0.0	28.6	71.4	0.0	0.0	100
13	No.	5	53	40	1	20	22	0	5	15	0	0	4	0	0	2
	%	5.1	54.3	40.6	2.3	46.5	51.2	0.0	25.0	75.0	0.0	0.0	100	0.0	0.0	100
14	No.	69	106	0	19	114	0	3	32	0	0	21	0	0	7	0
	%	39.4	60.6	0.0	14.3	85.7	0.0	8.6	91.4	0.0	0.0	100	0.0	0.0	100	0.0
15	No.	116	80	0	37	61	0	13	64	0	0	14	0	0	2	0
	%	59.3	40.7	0.0	38.0	62.0	0.0	16.7	83.3	0.0	0.0	100	0.0	0.0	100	0.0

A linear regression model was developed to estimate the relationship between U-turn and right turn volumes, and conflicts rates. Several different regression models were tried and the linear regression model with exponential form was found to have the best goodness of fit to the field data. In the regression model, dependent variable is RT-UT conflict rate, which is the average of conflict rates for the same volume conditions of U-turns and right turns at cross streets. The residual values were plotted against each variable. A bell-shape was observed for the plot of residual values against U-turn volume variable which indicated that a quadratic form was necessary in specifying the model. Therefore, the square of U-turn volume was used instead of U-turn volume in the model. The regression results were presented in Table 7.3.

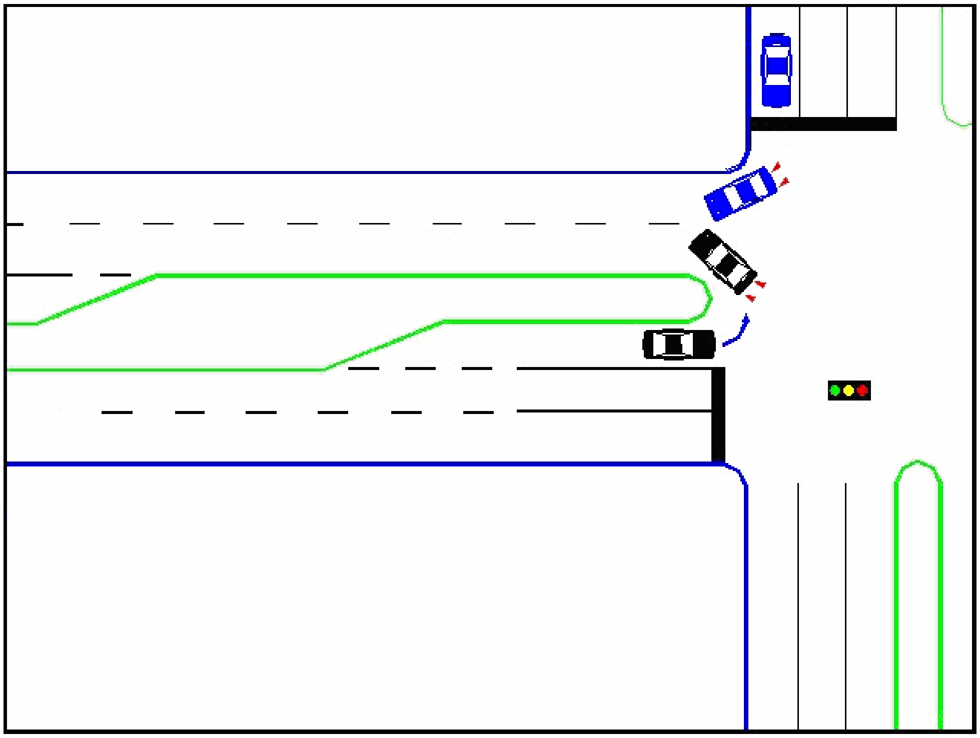
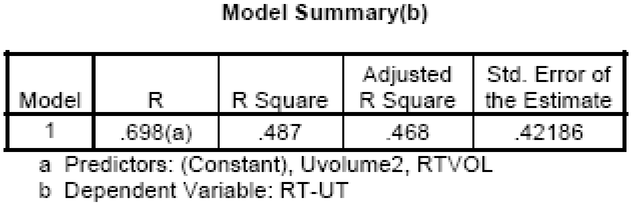


Figure 7.2 RT-UT Conflict

The model shows that the RT-UT conflict rate increases with the increase of U-turn volume and right turn at cross streets. The adjusted R square value is 0.468, which implies that the selected independent variables can explain 46.8% of variations in dependent variable. T-stat indicated that right turn volume is significant at a 95 percent level of confidence, while the U-turn volume was significant at an 80 percent level of confidence. The coefficients of variables were showed that right turn volume at cross streets had higher effect on the RT-UT conflict rate than U-turn volume.

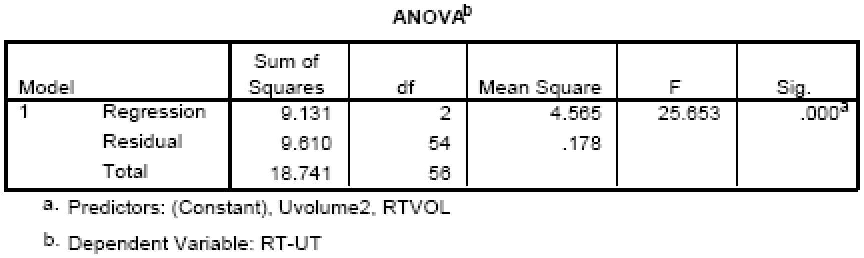
Table 7.3 U-Turn Regression Model Results



Model Summary(b)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.698(a)	.487	.468	.42186

a Predictors: (Constant), Uvolume2, RTVOL
b Dependent Variable: RT-UT

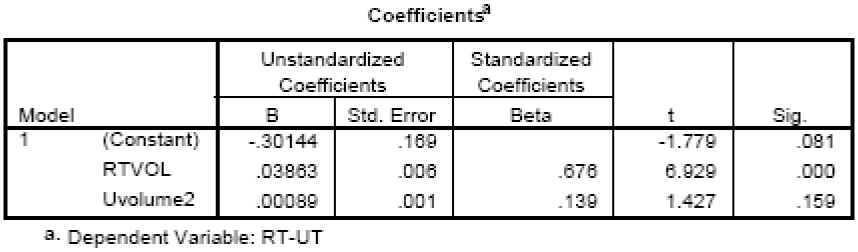


ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	9.131	2	4.565	25.653	.000[a]
	Residual	9.610	54	.178		
	Total	18.741	56			

a. Predictors: (Constant), Uvolume2, RTVOL

b. Dependent Variable: RT-UT



Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.30144	.169		-1.779	.081
	RTVOL	.03863	.006	.676	6.929	.000
	Uvolume2	.00089	.001	.139	1.427	.159

a. Dependent Variable: RT-UT

$$RT\text{-}UT = e^{-0.030+0.0386RTVOL+0.00089UTVOL} \qquad (7.1)$$

where,

RT-UT: Average conflict rate per fifteen minute interval

Uvolume2: The square of U-turn Volume per fifteen minute interval

RTVOL: Right turn volume of cross-street under green arrow time in subject approach per fifteen minute interval

Based on Equation 7.1, curves for the average RT-UT conflict were developed. Figure 7.3 shows a group of curves for average RT-UT conflict rate for the volume values of right turns at cross streets during the green arrow time of subject approach ranges from 10 to 50 vehicles per fifteen minute intervals. The y-axis represents the U-turn volume at signalized intersection. The x-axis represents the average RT-UT conflict rate per fifteen minute interval.

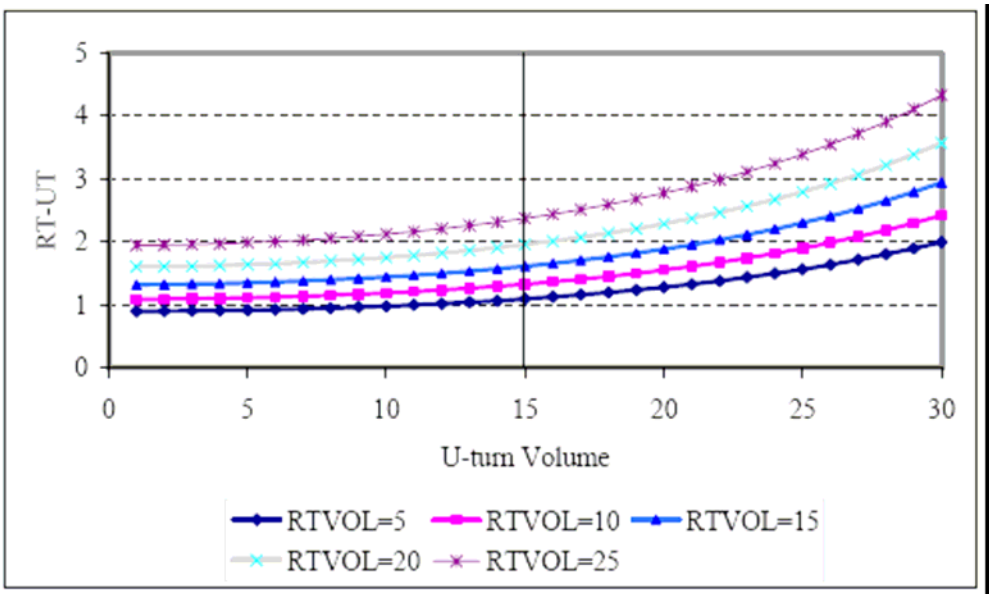


Figure 7.3 RT-UT Conflict Rate Curves Based on Model

According to the curves plotted in Figure 7.3, when U-turn volume and right turn volume at cross street reaches to 30 vehicles per fifteen minute interval, conflict rate is approximately 4.3. Higher rates of RT-UT conflict will cause safety and operational problems at signalized intersections. Median opening closures or conversions in advance of signalized intersections will force the drivers to make right turn followed by a U-turn at signalized intersection. This kind of changes will result in an increase of U-turn volume at signalized intersection and also increase in conflicts between U-turn and right turn vehicles. When the volumes of U-turns at signalized intersections exceed 15 vehicles per fifteen minute interval, RT-UT conflict rate will increase significantly. This volume level can be used as threshold during decision process of median modifications. The designers and planners can use the curves plotted in Figure 7.3 as a guideline for median closures and conversions in advance of signalized intersections.

7.4 Summary

This chapter focused on the analysis of U-turns at median openings and signalized intersections. The data from the analysis shows how unsignalized U-turn bays accommodate U-turns based on width of driveway and median. Additionally, U-turns at signalized intersections were analyzed by a regression model. This model investigated the impact of median modifications which will result in increased volumes of U-turns at signalized intersections. The model results can be used to determine the increase in U-turn conflicts based on changes in U-turn conflicting volumes.

CHAPTER 8

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary

Access management is one of the tools that engineers and planners have used to plan and design the roads to enhance the capacity and safety of road networks. One of the common applications of access management is construction of non-traversable medians. This application results in median closures and construction of restrictive (directional) median openings. In theory, replacing full median openings with directional (restricted) median openings will force the driveway users to make a right turn from the driveway and search for the next possible U-turn movement bay available down-stream of the driveway.

Safety of right turn followed by a U-turn movement was evaluated by several studies. In 2001 and 2004, the research projects sponsored by Florida Department of Transportation (FDOT) was performed by Dr. John Lu and his colleagues in the University of South to evaluate an access management technique: Right turn followed by U-turn at median openings as an alternative to direct left turn from driveways and side streets. These projects evaluated the safety and operational impacts of such an alternative on six-eight lane arterials. The safety impacts were evaluated by crash and conflict analysis. Results from that research indicated that this alternative as compared to direct left turns result in safety benefits and under certain traffic conditions result in operational benefits. Although previous studies stated some safety benefits for the restriction of DLT movements from driveways, there has been a need to compare these movements and quantify the safety benefits under different geometric conditions. This dissertation presents the results of safety evaluation of right turn followed by a turn movement under different geometric conditions.

In order to achieve the objectives of the study, over 1000 hours of conflict data were collected at the field. Data collection locations were classified based on the purpose of data analysis. Conflict analysis was chosen over crash analysis because of several advantages of traffic conflicts over crashes. Eleven types of conflicts were utilized for this study. Seven of the conflict types were related to RTUT movements, while the rest of them were related to DLT movements. Data collection locations were grouped based on analysis purposes. Data collection sites were divided into four sets by geometric criteria depending on U-turn bay locations and number of lanes on major arterial. At selected sites U-turn bays were located either at a median opening or a signalized intersection. Studied driveways were connected to four lane or six-eight lane arterials.

On four lane arterials, RTUT and DLT maneuvers were compared from a safety perspective. To achieve this objective, data were collected at sixteen selected sites. Conflict rates were utilized to compare left turn alternatives. Conflict rates were calculated for both RTUT and DLT movements and compared.

Impacts of separation distance on safety of RTUT movements were investigated by a regression model. The model investigated impacts of U-turn bay locations and the number of lanes on major arterial on separation distance requirements. Regression model results were used to determine minimum required separation distances.

Finally, on four lane arterials U-turn distributions at median openings were analyzed to investigate how U-turns are accommodated at such locations. A U-turn regression model was developed to investigate impacts of median modifications on signalized intersection safety.

8.2 Conclusions

The safety evaluation of right turn followed by U-turns by traffic conflicts resulted in several conclusions. They are explained in the following paragraphs:

- General safety comparison of right turn followed by U-turn movements as an alternative to direct left movements indicated that right turn followed by a turn movement can be considered as a safer alternative to direct left turn.
- When U-turns locations were signalized intersections, direct left turn movements generated two times more conflicts per hour compared to right turn followed by a turn movements. The drivers usually prefers direct left turn movements if this movement is not prohibited. Therefore, high volume of direct left turn movements resulted in higher number of conflicts. When the effects of traffic volumes were taken into consideration, right turn followed by a turn movements had a 5 percent higher conflict rate than direct left turn movements. Prior to a median modification, if possible U-turn bay is located at signalized intersection; U-turns movements at these locations can be regulated by a lane reserved for U-turn movement.

- When U-turns locations were median openings, direct left turn movements generated 10 percent more conflicts per hour than RTUT movements. Furthermore, the other conflict rate, which takes the effect of traffic volumes into consideration, was 62 percent higher for DLT movements as compared to RTUT movements. Median openings located close by signalized intersections did not cause any safety problems because of gaps generated by signalized intersections. However, median openings located where the free flow traffic is present, might cause safety problems especially for U-turn movements if the roadway and the median opening width are not sufficient to accommodate U-turns. U-turns can be prohibited at locations with insufficient geometric conditions until a suitable location or signalized intersection is present.
- Severity analysis of conflicts clearly indicated that right turn followed by a U-turn movement causes less severe conflicts. The average conflict severity score for direct left turn movements were 1.88 and 1.91 for U-turns at signalized intersections and U-turns at median openings, respectively. Direct left turn conflicts occurred between driveway vehicles and main road vehicles had the highest conflict severity scores. These conflicts can only be avoided by restricting the direct left turn movement from the driveways. The average conflict severity score for right turn followed by a turn movements were 1.40 and 1.60 for U-turns at signalized intersections and U-turns at median openings, respectively. The conflict severity score difference between signalized intersection and median opening sites for both right turn followed by a turn and direct left turn movements caused by main arterial traffic speed. Vehicles approaching to signalized intersections usually have reduced speeds resulting in less severe conflicts. Although U-turn movements at signalized intersection cause high

number of conflicts, severity scores of these conflicts had a lower average than other conflict types. On the other hand, U-turns movements at median openings had higher severity scores especially where traffic has free flow speeds. Signalized intersections are recommended to accommodate U-turns when severity scores of conflicts are considered.

- The separation distance between driveway exits and downstream U-turn locations have significant impacts on safety of vehicles making right-turns followed by U-turns. The analysis results indicated that the conflict rate decreases as the separation distance increases for all geometric conditions. Providing longer separations distances are essential to improve safety, however, it is recommended to consider operational aspects of the problem.
- Location of U-turn bays and number of lanes on major arterials significantly impacts minimum required separation distance. In this research, four geometric conditions were analyzed separately. According to the analysis results; on four lane arterials, if U-turn bays are located at a signalized intersection the minimum separation distance found to be 600 feet and if U-turn bays are located at a median opening the minimum separation distance found to be 400 feet. On six or eight lane, if U-turn bays are located at a signalized intersection the minimum separation distance found to be 1000 feet and if U-turn bays are located at a median opening the minimum separation distance found to be 700 feet. Increase in number of lanes on major arterials significantly increases minimum required separation distance. Increased width of roadways makes it difficult for drivers to weave through lanes to reach U-turn bays

downstream of driveways. In addition, signalized intersections located downstream of driveways caused and increase in minimum required separation distance.

- The results of the U-turn distribution analysis at median openings sites indicated that; at most sites, median openings accommodate U-turns without any problems for smaller vehicles which were 85 percent of all the vehicles observed in this analysis. Data analysis results indicated that when flares are present, 95 percent of the vehicles used outer lane or flares. Then again, when flares are not present 68 percent of vehicles used outer lane to complete U-turns at median openings. It is recommended to construct flares at locations where median width is narrow and main arterial has four lanes. Based on field observations, construction of flares helped drivers to complete U-turn maneuvers and clear possible conflict locations faster. Especially, at locations with high U-turn volumes, construction of flares will have safety and operational benefits.
- The conflicts related to U-turns and right turns from cross streets could cause safety problems at signalized intersections. Especially, safety evaluation of RTUT and DLT conflicts showed that this type of conflicts has a significant effect on RTUT maneuvers safety. The analysis results indicated that increase in U-turn volume significantly impacts the conflict rate for this type of conflict. Median modifications across the high volume driveways may result safety and operational problems at downstream signalized intersections. This problem can be solved by defining the right of way for drivers making a U-turn or right turn across the street. Prohibiting the right turn movements on red phase of signal is another solution to prevent any safety problems.

8.3 Recommendations

It would be useful to do a before and after analysis of median closures and median opening conversions which would point out the safety and operational effects such changes. Another issue with right followed by U-turns and direct left turns are accommodation of large vehicles. A study at locations with insufficient geometric conditions focused on large vehicles would be useful.

Geometric conditions of U-turn areas may have impacts on the safety performance of RTUT movements. Median openings without exclusive turn lanes may affect the safety and capacity of the roadways and RTUT movements. Also, the effects of geometric conditions such as median openings with insufficient storage space, and should be considered for a safety evaluation of RTUT movements.

.

REFERENCES

Access Management Manual, Transportation Research Board, 2003.

Brown, G.R. (1994). “Traffic Conflicts for Road Safety Studies”. Canadian Journal of Civil Engineering, Vol. 21, No.1, pp.1-15.

Carter, D., Hummer, J., Foyle, R., and Philips, S.(2004)”Operational and Safety Effects of U-turns at Signalized Intersections” Transportation Research Board 84th AnnualMeeting Proceedings.

Chin, H.C., and Quek, S. T. (1997). “Measurement of Traffic Conflicts”, Accident Analysis and Prevention, Vol.26, No.3, pp.169-185.

D. Cooper and N. Ferguson, 1976. "A conflict simulation model," Traffic Engineering and Control, Vol. 17, pp. 306-309.

Engel, U. (1985). “To What Extent Do Conflict Studies Replace Accident Analysis: Validation of Conflict Studies - An International Review. In Organisme National De Securite Routiere. Proceedings “Evaluation 85”, Paris, France. Vol.2, pp. 324-343.

G. Tiwari, et al., 1995. "Conflict analysis for prediction of fatal crash locations in mixed traffic streams," Proceedings of the 29th Annual Association for the Advancement of Automotive Medicine, Oct 17-18. Chicago, IL.

Gettman D. and Head L., (2003) Surrogate Safety Measures From Traffic Simulation Models, Final Report, FHWA-RD-03-050, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Gettman D. and Head L., (2003) Surrogate Safety Measures From Traffic Simulation Models, Final Report, FHWA-RD-03-050, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Glauz, W. D., Bauer, B. M., and Migletz, D. J. (1985). “Expected Traffic Conflict Rates and Their Use in Predicting Accidents”, Transportation Research Record 1026, Transportation Research Board, National Research Council, Washington, D.C., pp. 1-12.

Gluck, J., Levinson, H.S. and Stover, V.G. (1999). Impacts of Access Management Techniques, National Cooperative Highway Research Program Report 420, Transportation Research Board, National Research Council, Washington, DC.

Hauer, E., (1978). “Design Considerations on Traffic Conflict Surveys”, Transportation Research Record 667, Transportation Research Board, National Research Council, Washington, D.C., pp.57-66.

Hayward, J.C. (1972). “Near-Miss Determination Through Use of a Scale of Danger”. Highway Research Board Record No. 384, Washington D.C., Highway Research Board, pp. 24-33.

Highway Capacity Manual. (2000). Transportation Research Board, National ResearchCouncil, Washington, D.C.

Ivey, Harris and Walls, “Districtwide Median Evaluation Technical Memorandum: Corridor Land Use, Development & Driver/Business Survey Analysis,” prepared for FDOT District 5, 1995.

J. Darzentas, et al., 1980. "Minimum acceptance gaps and conflict involvement in a single crossing maneuver," Traffic Engineering and Control, Vol. 21, pp. 58-62.

Kach, B., “The Comparative Accident Experience of Directional and Bi Directional Signalized Intersections,” Michigan Department of Transportation (April 15, 1992).

Katamine, N.M. (2000). “Nature and Frequency of Secondary Conflicts at Unsignalized Intersections”. Journal of Transportation Engineering, Vol. 126, No. 2, pp. 129-132.

Koepke, F., and Levinson H. (1992). NCHRP 348: Access Management Guidelines for Activity Center. Transportation Research Board, National Research Council, Washington D.C.

Lu, J., Dissanayake, S, Castillo, N., and Williams, K. Safety Evaluation Of Right Turns Followed By U-Turns as an Alternative to Direct Left Turns - Conflict Analysis, USF 2001.

Lu, J., Pirinccioglu, F, Pernia, J.C. Safety Evaluation Of Right Turns Followed By U-Turns at Signalized Intersections as an Alternative to Direct Left Turns - Conflict Analysis, USF 2004.

Maki, R.E., “Directional Crossovers: Michigan’s Preferred Left-Turn Strategy,” Presented at the 1996 Annual Meeting of the Transportation Research Board.

Migletz, D. J. Glauz, W. D. and Bauer, K.M. (1985). “Relationships Between Traffic Conflicts and Accidents”, Report No. FHWA/RD-84/042, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Migletz, D. J. Glauz, W. D. and Bauer, K.M. (1985). “Relationships Between Traffic Conflicts and Accidents”, Report No. FHWA/RD-84/042, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Opinion survey following Oakland Park Boulevard median reconstruction. Florida Department of Transportation, District 4, Traffic Operations.

Parker, M.R., and Zegeer, C.V. (1989). “Traffic Conflict Technique for Safety and Operations-Engineer’s Guide”, FHWA-IP-88-26, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Parker, M.R., and Zegeer, C.V. (1989). “Traffic Conflict Technique for Safety and Operations-Observer’s Manual”, FHWA-IP-88-27, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Potts, I.B., Levinson, H.S., Harwood, D.W., and Gluck J.(2004) Safety of U-Turns at Unsignalized Median Openings, National Cooperative Highway Research Program Report 17-21, Transportation Research Board, National Research Council, Washington, DC.

Recommended Warrants for the Use of Protected/Permissive Left-Turn Phasing. Technical Committee Project 4A-30, Institute of Transportation Engineers, Washington, DC, 1994.

Robertson, H.D., Hummer, J. E., and Nelson D. C. (1994). “Manual of Transportation Engineering Studies, Chapter 12” Institute of Transportation Engineers. Prentice Hall, NJ.

Salman, N.K., and Al-Maita, K.J. (1995). “Safety Evaluation at the Three-leg, Unsignalized Intersections by Traffic Conflict Technique”, Transportation Research Record 1485, Transportation Research Board, National Research Council, Washington, D.C., pp. 177-185.

Sayed, T., and Zein, S. (1999). “Traffic Conflict Standards for Intersections”, Transportation Planning and Technology, Vol. 22, No.4, pp 309-323.

Sayed, T; Brown, G; and Navin, F. (1994). “Simulation of Traffic Conflicts at Unsignalized Intersections with TSC-Sim”. Accident Analysis and Prevention, Vol.26, No.5, 1994, pp.593-607.

Torbic D., Borkowski J., Elefteriadou L., McFadden J., (1998) “Relationships Between Traffic Operations and Safety at Signalized Intersections” Third International Symposium on Highway Capacity, Copenhagen, Denmark.

Townes, M.S., Boardman, J.H. and Skinner, R.E.(2004). Safety of U-turns at Unsignalized Median Openings, National Cooperative Highway Research Program Report 524, Transportation Research Board, National Research Council, Washington, DC.

Vargas, F.A. and Gautam, Y. (1989), Problem: Roadway Safety vs. Commercial Development Access. Compendium of technical papers, ITE, 59th annual meeting San Diego California.

Weerasuriya SA, Pietrzyk MC (1998) “Development of Expected Conflict Value Tables for Unsignalized Three-Legged Intersections”, Transportation Research Board Issue 1635, pp 121-126.

Zegeer, C.V., Deen, R.C. (1978). “Traffic Conflicts as a Diagnostic Tool in Highway Safety”. Transportation Research Record 667, Transportation Research Board, National Research Council, Washington, D.C., pp. 48-55.

Zhou, H., Hsu, P., and Lu, J., (2003). “Optimal Location of U-turn Median Openings on Roadways.” Transportation Research Record, Transportation Research Board, National Research Council, Washington D.C.

APPENDICES

Appendix A: Study Location Maps

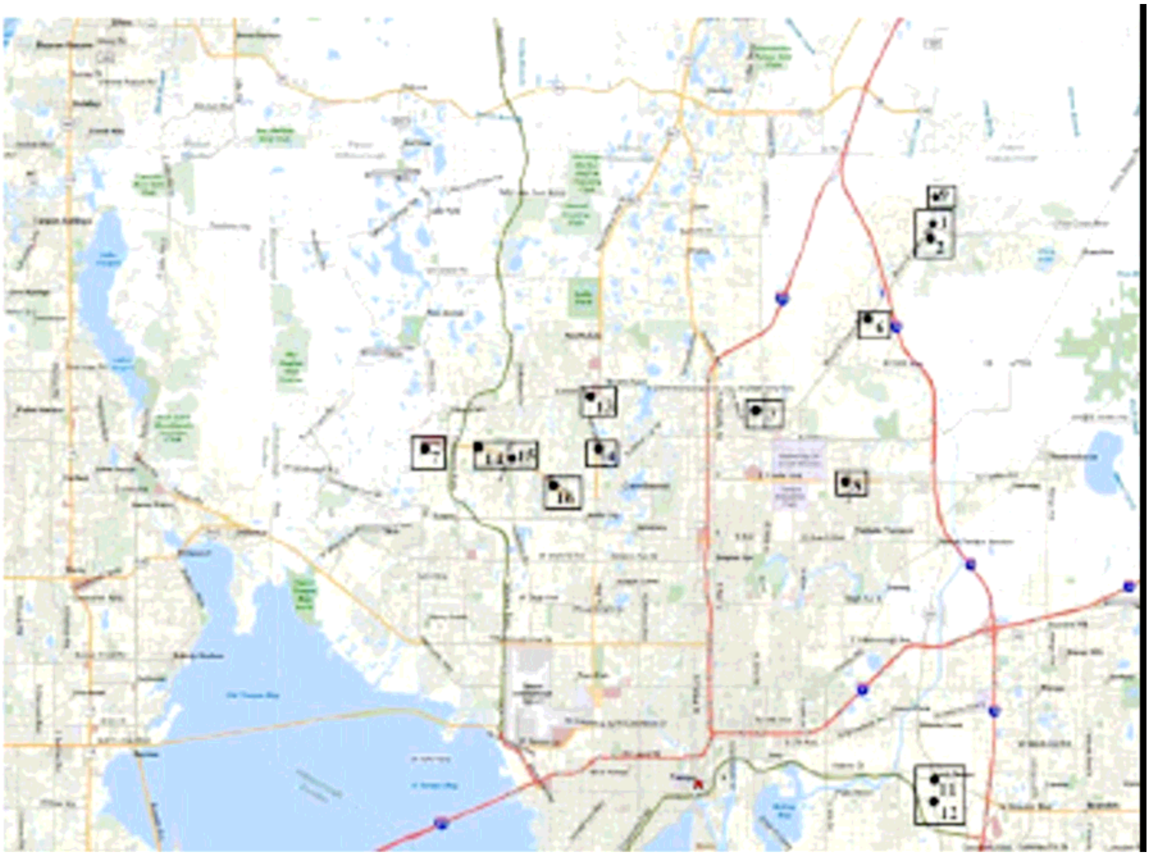
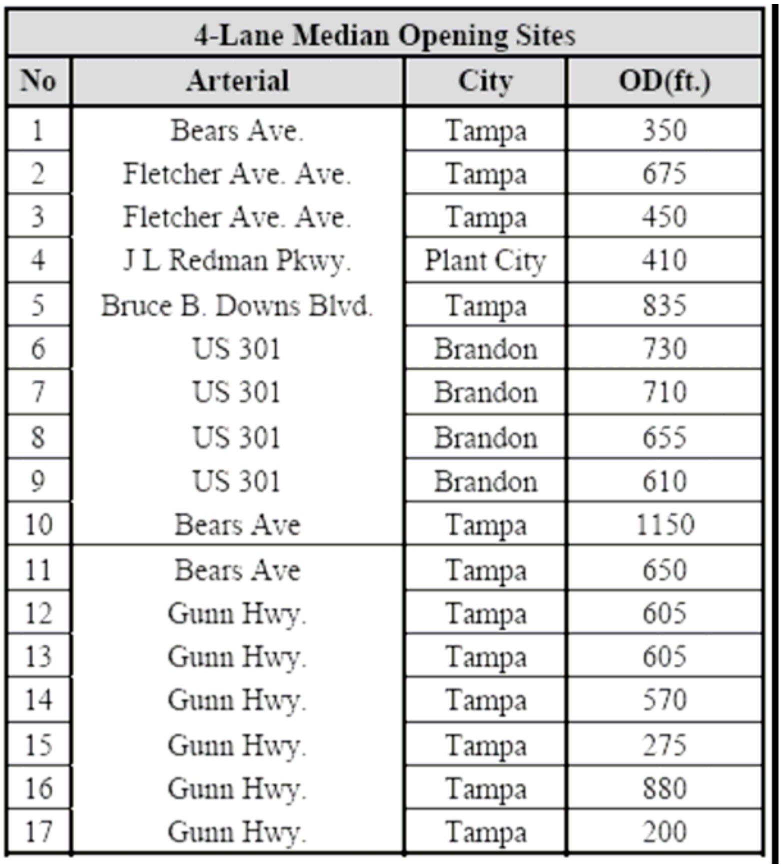


Figure A.1 Tampa Bay Area Sites Map

Figure A.2 Plant City Area Sites Map

Appendix B: Study Locations for Separation Distance

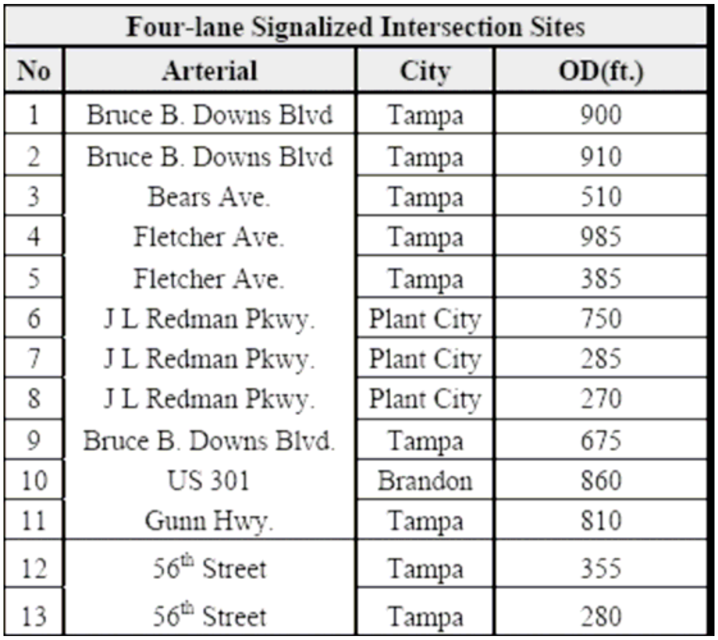
Table B.1 Location and Separation Distance for 4-Lane Median Opening Sites



4-Lane Median Opening Sites			
No	**Arterial**	**City**	**OD(ft.)**
1	Bears Ave.	Tampa	350
2	Fletcher Ave. Ave.	Tampa	675
3	Fletcher Ave. Ave.	Tampa	450
4	J L Redman Pkwy.	Plant City	410
5	Bruce B. Downs Blvd.	Tampa	835
6	US 301	Brandon	730
7	US 301	Brandon	710
8	US 301	Brandon	655
9	US 301	Brandon	610
10	Bears Ave	Tampa	1150
11	Bears Ave	Tampa	650
12	Gunn Hwy.	Tampa	605
13	Gunn Hwy.	Tampa	605
14	Gunn Hwy.	Tampa	570
15	Gunn Hwy.	Tampa	275
16	Gunn Hwy.	Tampa	880
17	Gunn Hwy.	Tampa	200

Appendix B: (Continued)

Table B.2 Location and Separation Distance for 4-Lane Signalized Intersection Sites

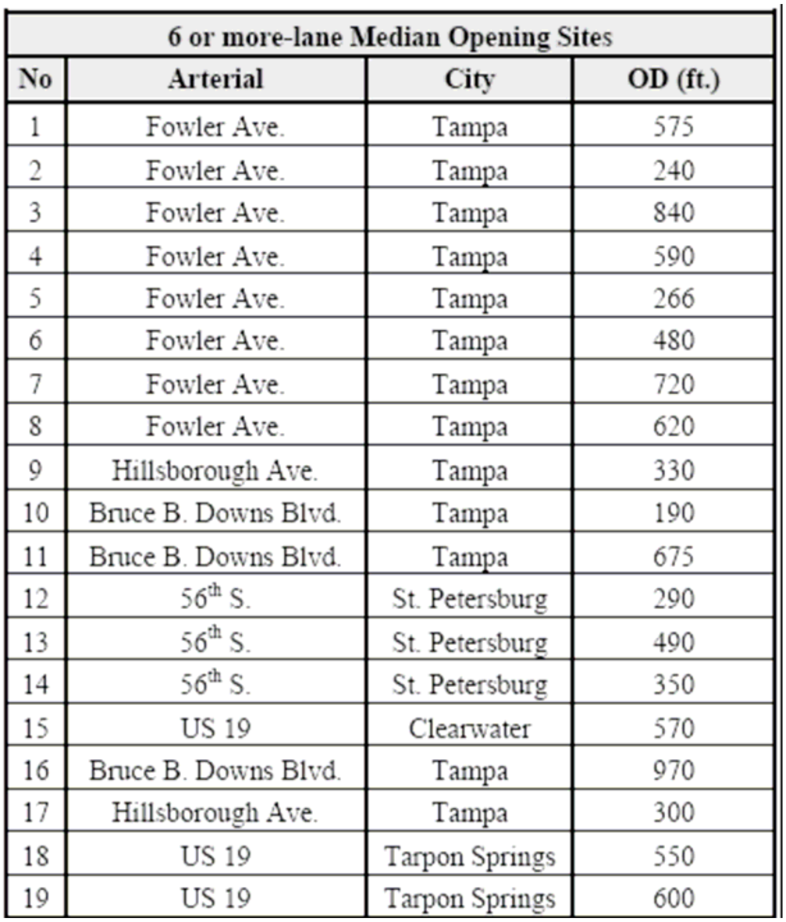


Four-lane Signalized Intersection Sites

No	Arterial	City	OD(ft.)
1	Bruce B. Downs Blvd	Tampa	900
2	Bruce B. Downs Blvd	Tampa	910
3	Bears Ave.	Tampa	510
4	Fletcher Ave.	Tampa	985
5	Fletcher Ave.	Tampa	385
6	J L Redman Pkwy.	Plant City	750
7	J L Redman Pkwy.	Plant City	285
8	J L Redman Pkwy.	Plant City	270
9	Bruce B. Downs Blvd.	Tampa	675
10	US 301	Brandon	860
11	Gunn Hwy.	Tampa	810
12	56th Street	Tampa	355
13	56th Street	Tampa	280

Appendix B: (Continued)

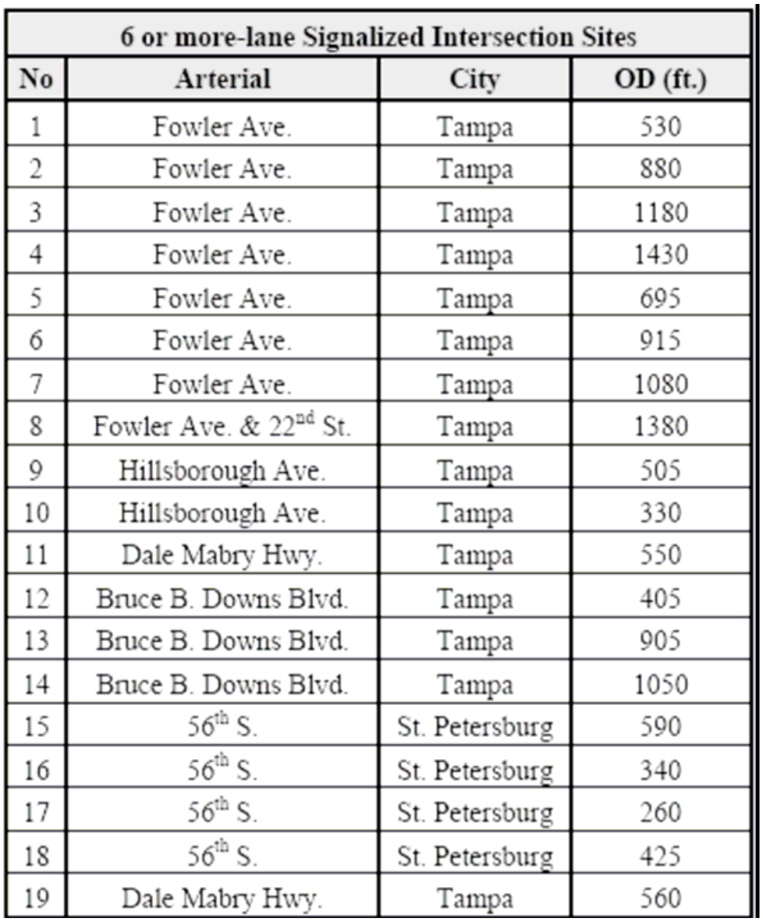
Table B.3 Location and Separation Distance for 6 or More Lane Median Opening Sites



6 or more-lane Median Opening Sites			
No	**Arterial**	**City**	**OD (ft.)**
1	Fowler Ave.	Tampa	575
2	Fowler Ave.	Tampa	240
3	Fowler Ave.	Tampa	840
4	Fowler Ave.	Tampa	590
5	Fowler Ave.	Tampa	266
6	Fowler Ave.	Tampa	480
7	Fowler Ave.	Tampa	720
8	Fowler Ave.	Tampa	620
9	Hillsborough Ave.	Tampa	330
10	Bruce B. Downs Blvd.	Tampa	190
11	Bruce B. Downs Blvd.	Tampa	675
12	56th S.	St. Petersburg	290
13	56th S.	St. Petersburg	490
14	56th S.	St. Petersburg	350
15	US 19	Clearwater	570
16	Bruce B. Downs Blvd.	Tampa	970
17	Hillsborough Ave.	Tampa	300
18	US 19	Tarpon Springs	550
19	US 19	Tarpon Springs	600

Appendix B: (Continued)

Table B.4 Location and Separation Distance for 6 or More Lane Signalized Intersection Sites



6 or more-lane Signalized Intersection Sites			
No	**Arterial**	**City**	**OD (ft.)**
1	Fowler Ave.	Tampa	530
2	Fowler Ave.	Tampa	880
3	Fowler Ave.	Tampa	1180
4	Fowler Ave.	Tampa	1430
5	Fowler Ave.	Tampa	695
6	Fowler Ave.	Tampa	915
7	Fowler Ave.	Tampa	1080
8	Fowler Ave. & 22nd St.	Tampa	1380
9	Hillsborough Ave.	Tampa	505
10	Hillsborough Ave.	Tampa	330
11	Dale Mabry Hwy.	Tampa	550
12	Bruce B. Downs Blvd.	Tampa	405
13	Bruce B. Downs Blvd.	Tampa	905
14	Bruce B. Downs Blvd.	Tampa	1050
15	56th S.	St. Petersburg	590
16	56th S.	St. Petersburg	340
17	56th S.	St. Petersburg	260
18	56th S.	St. Petersburg	425
19	Dale Mabry Hwy.	Tampa	560

ABOUT THE AUTHOR

Fatih Pirinccioglu was born in Ankara, Turkey, in 1977. His father is a mechanical engineer and owner of an engineering company in Turkey. He was named after the great Ottoman Sultan who conquered Istanbul in 1453.

Fatih Pirinccioglu attended Gazi University in 1994 and he received his Bachelor of Science degree in Civil Engineering in 1999. In 2000, he came to United States to attend Wayne State University in Detroit, Michigan. He received his Master of Science degree in Construction Management in 2002. Fatih Pirinccioglu joined University of South Florida in 2003 as a Ph.D. student and a graduate research assistant. He has worked in several research projects funded by various agencies. He is currently involved as a project engineer in construction projects.