2021

Evaluation of Unconventional Signalized Intersections on Arterial Roads and a Proposition for a Novel Intersection Design

Ma'en Al-Omari
University of Central Florida

STARS Citation

Al-Omari, Ma'en, "Evaluation of Unconventional Signalized Intersections on Arterial Roads and a Proposition for a Novel Intersection Design" (2021). *Electronic Theses and Dissertations, 2020-*. 1316.
https://stars.library.ucf.edu/etd2020/1316

EVALUATION OF UNCONVENTIONAL SIGNALIZED INTERSECTIONS ON ARTERIAL ROADS AND A PROPOSITION FOR A NOVEL INTERSECTION DESIGN

By

MA'EN MOHAMMAD ALI AL-OMARI

B.Sc., Jordan University of Science and Technology, 2012
M.Sc., Jordan University of Science and Technology, 2016
M.Sc., University of Central Florida, 2021

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Civil, Environmental, and Construction Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Fall Term
2021

Major Professor: Mohamed Abdel-Aty

ABSTRACT

Several unconventional intersection designs were proposed and implemented to enhance traffic safety and operation at intersections. The efficiency of these intersection designs was not sufficiently evaluated in the previous research because of the limited implementation of such designs. However, with the growing interest in the implementation of unconventional intersections by municipalities and transport agencies, it has become a need for a comprehensive evaluation of their safety and operational benefits. Therefore, this dissertation aims to evaluate the safety and operational aspects of unconventional intersection designs by employing different research approaches: crash analysis, microscopic simulation, and driving simulation. Firstly, this dissertation evaluated the effectiveness of median U-turn crossover-based intersections (median U-turn (MUT) and restricted crossing U-turn (RCUT) intersections), which have the least number of traffic conflicts among other unconventional intersection designs, in enhancing traffic safety by estimating crash modification factors (CMF) for their implementation. The results indicated that MUT and RCUT intersections are safer than the 4-leg conventional intersection. Secondly, A new innovative intersection design, which has been given the name "Shifting Movements" (SM) intersection, was introduced and proposed to replace the implementation of the RCUT intersection under moderate and heavy minor road traffic conditions. Evaluation of the operational benefits of this intersection design was performed in the microscopic simulation environment by assuming different traffic volume levels and left-turn proportions to represent the peak hour with moderate to high left-turn traffic volumes. The results demonstrated that the SM intersection design significantly outperforms conventional and RCUT intersections when they are subjected to high traffic volumes in terms of average control delay and throughput. Finally, A driving simulation experiment was conducted to evaluate the safety aspects of the SM intersection design. Several surrogate safety measures were adopted for the evaluation. The effectiveness of using infrastructure-to-vehicle (I2V) communication for mitigating the confusion at unconventional intersections has been also evaluated in this research. Findings indicated that RCUT and SM intersections have similar safety performance and crossing them is safer than crossing the 4-leg conventional intersection. It was found that using I2V communication is helpful in understanding unconventional movement patterns. This dissertation can be a solid reference for decision-makers regarding the implementation of unconventional intersection designs.

ACKNOWLEDGMENTS

Foremost, I would like to express my sincere gratitude to my advisor Prof. Mohamed Abdel-Aty for the continuous guidance, support, and motivation. I would like to thank my dissertation committee members: Prof. Xin Yan, Dr. Samiul Hasan, and Dr. Lishengsa Yue, for their valuable advice and suggestions.

Last but not the least, I would like to express my deepest appreciation to my family especially my parents and my wife for their unparalleled support. Without them, I would not have accomplished this achievement. I would like also to thank my son. His smile brings happiness to me every day.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Overview

Intersections are the most critical element in the roadway network (less safe than midblock by three to four times [*AustRoads, 2010*]) since they are located where different movements of several transportation modes intersect. This produces a considerable number of conflict points between traffic movements. Therefore, safety and operation weaknesses and sometimes failures in the roadway network are being recorded especially at signalized intersections. The left-turn crash type is one of the most severe crash types at intersections. Therefore, separate phases for left-turn movements (i.e., protected left-turn phases) are provided to minimize such crash type, especially for intensive left-turn traffic. Therefore, longer cycle length and more delay are recorded at intersections. Thus, new countermeasures and treatments are required to enhance traffic safety and operation at the same time. This is achieved at some unconventional intersection designs by rerouting some movements (mainly the left-turn movement) upstream or downstream of the intersection to minimize the number of conflict points and signal phases.

Unconventional intersection designs were proposed due to their expected ability to simultaneously enhance traffic safety and operation at intersections. Traffic movement patterns at unconventional intersections have been reconfigured by mainly eliminating or rerouting the left-turn traffic at the main intersections. The redistribution of the traffic movements reduces the number of conflict points and provides two-phase signalization at unconventional intersections, meaning fewer crashes and less delays. The low number of conflict points is an indication of a safer traffic operation at these intersection designs. Whereas the two-phase signal operation reduces the signal cycle length and traffic delay (*Hughes et al., 2010*).

Most of the unconventional intersection designs have been proposed for a long time. However, their implementation is still limited to few locations in few states. Many research papers and studies have been conducted to evaluate the effectiveness of these intersection designs in the enhancement of traffic safety and operation by utilizing field or virtual data. However, field-based studies depended on limited data from a few unconventional intersections' locations. Recently, municipalities and transport agencies tend to implement these types of intersections. Therefore, data of a sufficient number of unconventional intersections should be used to conduct a comprehensive evaluation of their safety benefits which would strengthen and validate the previous findings.

Not all proposed unconventional intersection designs achieved the desired safety and operational improvements. Furthermore, some of them perform well only under certain traffic volume conditions. Some unconventional intersections have better traffic operational performance than the safety performance, and even some of them are less safe than conventional intersections. While unconventional intersection designs that have a notable low number of conflict points have the best safety performance. Since safety is the priority in the adoption and implementation of these kinds of intersections, median U-turn crossover-based intersections (i.e. median U-turn (MUT) and restricted crossing U-turn (RCUT) intersections), which have the least number of conflict points among other unconventional designs, have been selected for the evaluation in this research.

The RCUT intersection design showed high safety performance. However, its operational effectiveness manifests only at intersections that are subjected to light minor road traffic volume.

Therefore, a new 4-leg intersection design, that it is expected to have better operational performance than the RCUT intersection design when subjected to medium to high minor traffic volumes, has been proposed in this research. This new intersection design has been given the name “Shifting Movement” (SM) intersection. The number of conflict points at this design is equal to the least number of conflict points at previously proposed unconventional intersection designs (i.e. 14 conflict points at the RCUT intersection design). The SM intersection design allows for two-phase signalization. Therefore, it is expected that traffic safety and operation will be simultaneously improved at the SM intersection design. The safety and operational effectiveness of the SM intersection implementation were evaluated in this research by employing microscopic and driving simulations.

Since many drivers are still unfamiliar with unconventional intersections and the implementation of the infrastructure-to-vehicle (I2V) communication has the potential ability to mitigate driver confusion, evaluation of the effectiveness of implementing this technology at unconventional intersections was accomplished in this research.

1.2 Research Data and Tools

Crash, traffic, and geometric data have been gathered at MUT and RCUT intersections in Michigan, North Carolina, and Ohio states. Figure 1.1 shows the states from which the data was collected.

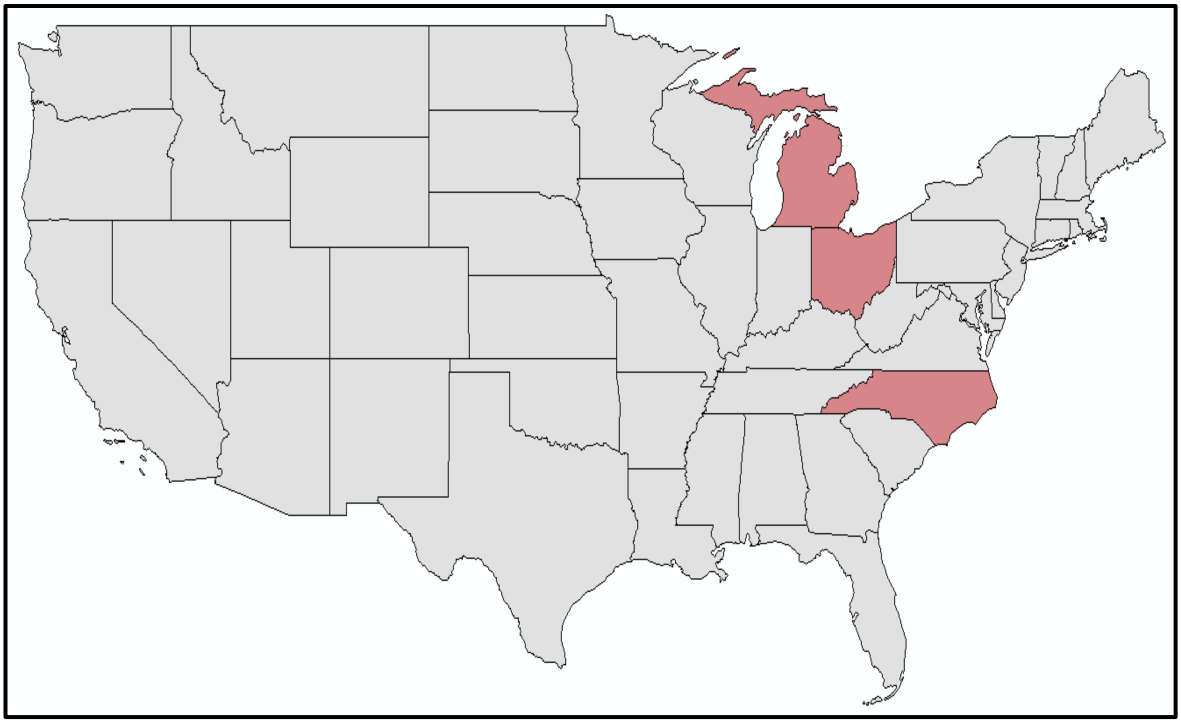


Figure 1.1: States of data source

Different microscopic simulation software programs have been employed to achieve different objectives in this research. PTV Vissim software was used for the microscopic simulation of conventional, RCUT, and SM intersection designs to evaluate their traffic operational performance. Synchro software has been used for signal-timing optimization at conventional, RCUT, and SM intersections. The National Advanced Driving Simulator (NADS) minisim^{TM} at the University of Central Florida (UCF) (Figure 1.2) along with Tile Mosaic Tool (TMT), Interactive Scenario Authoring Tools (ISAT), and NADS minisim^{TM} software were utilized for the safety evaluation of the SM intersection design in the driving simulation environment and for the evaluation of the effectiveness of implementing I2V communication on confusion mitigation at unconventional intersections designs.

Figure 1.2: NADS minisim^{TM} at UCF

1.3 Research Objectives

This research aims to attain three main objectives: safety evaluation of median U-turn crossover-based intersections, proposition, and evaluation of a new intersection design as an alternative to the 4-leg conventional intersection, and evaluation of the effectiveness of implementing I2V communication on driving behavior and confusion reduction at unconventional intersection designs. To this end, five sub-objectives have been identified to achieve that:

1. Evaluation of safety benefits of implementing median U-turn crossover-based intersections (MUT and RCUT intersections) by developing safety performance functions (SPF) and estimating crash modification factors (CMF) for the different crash severities and types. (This was addressed in Chapter 3)

2. Proposition; description of traffic movement patterns; explanation of the expected safety and operational benefits; and investigation of the optimum spacing, lane configuration, and signalization of a new 4-leg unconventional intersection design (i.e. the SM intersection). (This was addressed in Chapter 4)

3. Evaluation of the operational performance of the SM intersection design compared to conventional and RCUT intersection designs in terms of intersection, roads, and movements average control delay and throughput in the microscopic simulation environment. (This was addressed in Chapter 4)

4. Investigation of driving behavior at unconventional intersection designs and evaluation of the safety performance of the SM intersection design compared to conventional and RCUT intersection designs in terms of several surrogate safety measures in the driving simulation environment. (This was addressed in Chapter 5)

5. Evaluation of the effectiveness of implementing I2V communication on driver confusion mitigation at unconventional intersections. (This was addressed in Chapter 5)

1.4 Dissertation Organization

The dissertation is organized as the following: Chapter two presents a general brief about unconventional intersection designs and a detailed literature review about median U-turn crossover-based intersection designs. In addition, a literature review about using microscopic and driving simulation for evaluating the safety and operational effectiveness of implementing unconventional intersections has been also presented. Chapter three evaluates the safety effectiveness of median U-turn crossover-based intersections based on crash data for several years at a considerable number of MUT and RCUT intersection locations from multiple states. Chapter four introduces the SM intersection and evaluates its operational performance compared to conventional and RCUT intersections. Chapter five evaluates the safety aspects of the SM intersection implementation and the I2V communication usefulness. Chapter six provides a summary of findings in this research and its implications.

CHAPTER 2: LITERATURE REVIEW

2.1 Unconventional Intersection Designs

Unconventional intersection designs were defined and applied due to their expected ability to simultaneously enhance traffic safety and operation. The redistribution of the traffic movements (by mainly prohibiting or relocating left-turn movements at the main intersection) provides a two-phase signal operation and a low number of conflict points at unconventional intersections. The low number of signal-phases reduces cycle length and delay, whereas the low number of conflict points is an indication for a potentially lower number of crashes at these intersection designs (*Hughes et al., 2010*).

Throughout the previous four decades, several unconventional intersection designs have been proposed to enhance traffic safety and operation. However, few of them were widely adopted, while others have been only implemented at few locations in the USA. Several intersection configurations have been proposed as alternatives to the 4-leg conventional intersection such as bowtie intersection, displaced left-turn intersection, parallel flow intersection, median U-turn (MUT) intersection, restricted crossing U-turn (RCUT) intersection, quadrant roadway intersection, Jughandle intersection, split-phasing intersection, upstream signalized crossover intersection, symmetric intersection, hamburger or through-about intersection, and synchronized split-phasing intersection. Certain types are most popular in specific states. For example, the median U-turn intersection has been widely adopted in Michigan. The RCUT intersection is more popular in North Carolina, while the Jughandle intersection is commonly implemented in New Jersey.

In this research, Median U-turn crossover-based intersections (i.e., MUT and RCUT intersections) (Figure 2.1) have been considered for evaluation because they have the lowest number of conflict points among the other unconventional intersections. They are the types of unconventional intersections that contain median U-turn crossover areas. Thus, the basic designs of these two unconventional intersections are similar despite some differences.

At MUT intersections, the through and right-turn movements are made the same way as at conventional intersections, while the left-turn movement are completed by using the median U-turn crossover downstream of the main intersection. The main variation between MUT and RCUT intersections is the different traffic movement patterns. At RCUT intersections, the essential movements from the major road (i.e., through; right-turn; and left-turn movements) are made at the main intersection like conventional intersections. While all movements form the minor road are made by turning right first, then median U-turn crossover lanes downstream of the main intersection are used to complete through and left-turn movements (*Hughes et al., 2010*).

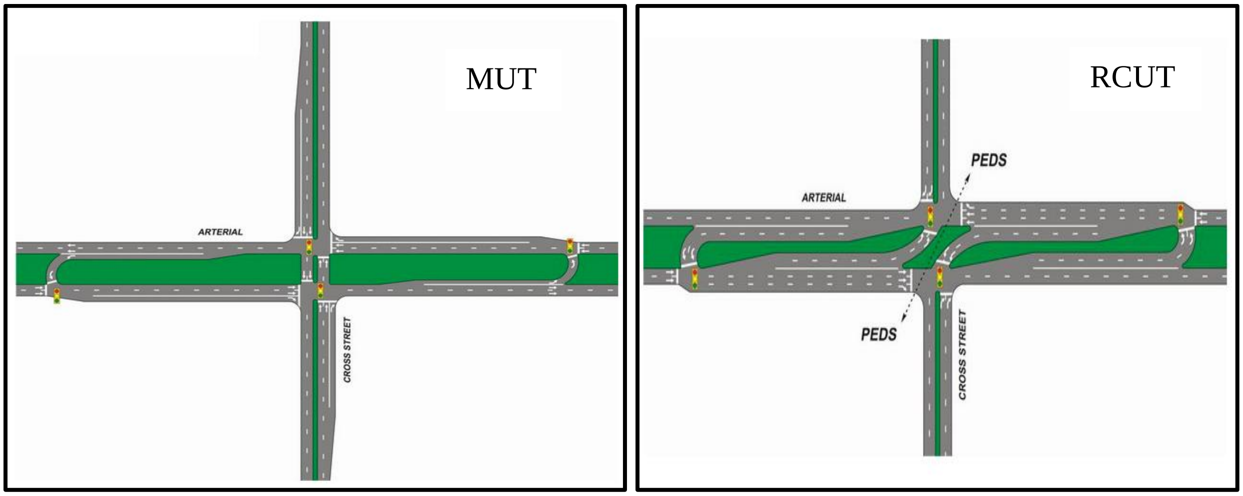


Figure 2.1: Median U-turn crossover-based intersections (*MUID*)

2.2 Evaluation of the Safety Effectiveness of Median U-Turn Crossover-Based Intersections

Several studies have been conducted to evaluate safety performance at MUT and RCUT intersections. This section presents previous efforts that have been done for safety evaluation of median U-turn crossover-based intersections. Many studies indicated that MUT and RCUT intersections are effective in crash reduction. The following paragraphs show a detailed description of these studies.

Kach (1992) concluded that MUT intersections reduce injury crashes by 30% and there is a notable reduction in the most severe crash types such as right-angle, rear-end, left-turn, and head-on crashes at MUT intersections.

Castronovo et al. (1995) performed a study to investigate the relationship between traffic signal density and the crash frequency at MUT intersections. They found that dense segment of MUT intersections has a low crash rate. They concluded that crash rates at MUT intersections are less than at conventional intersections in typical suburban and rural areas by 50% and 36%, respectively.

Maki (1996) concluded that total crashes are reduced by 60% and about 95% reduction in angle crashes are recorded at MUT intersections. This could be because of the low crash rate at median U-turn crossovers since it was found that the crash rate at median U-turn crossovers was reduced by 33% in comparison with it at the two-way left-turn lanes (*Levinson et al., 2000*).

Lu and Dissanayake (2002) conducted a safety evaluation of the right-turn followed by a U-turn (RTUT) procedure for the left-turn traffic. The analysis was based on counting the number of conflict points at several time periods and traffic volume levels. Video recording at seven sites was done at peak and off-peak time periods. The results showed that the number of conflict points at the off-peak, the peak, and overall time periods which resulted from the direct left-turn procedure is more than it for the RTUT procedure by 29%, 76%, and 51%, respectively. The direct left-turn procedure has also 64% more average conflict points per thousand vehicles.

A study by *Zhou et al. (2003)* has developed a regression model to determine the optimum median U-turn crossover spacing. The results showed that safety improvement is associating with the optimum spacing. *PBS and J. (2005)* concluded that implementation of RCUT intersections will reduce the predicted crash rate in comparison with the conventional intersection.

Jagannathan (2007) found that MUT intersections reduced crashes by 60%, and injury crashes were particularly reduced by 75%. He also found that angle and sideswipe crashes have been reduced at MUT intersections by 96% and 61%, respectively, while rear-end crashes were slightly reduced by 17%.

A study by *Kim et al. (2007)* has evaluated safety benefits of the unsignalized RCUT intersection design based on the number of conflicts between movements by using the surrogate safety assessment model (SSAM) software. They found that the total number of conflict points at the RCUT intersection with one U-turn lane decreased by 79% compared to the conventional unsignalized intersection. On the other hand, it increased by 78% at RCUT intersections with two U-turn lanes.

Hummer and Jagannathan (2008) and *Hochstein et al. (2009)* found that the RCUT intersection is effective in crash reduction.

Hummer et al. (2010) evaluated the safety benefits of signalized RCUT intersections in North Carolina. They found that only one signalized RCUT intersection showed safety improvement among the three studied intersections.

Azizi et al. (2012) have evaluated the safety performance of the unconventional MUT implementation in Tehran, Iran. Negative binomial regression for crash count prediction has been employed to determine geometric and traffic conditions that are associating with the crash occurrence at crossovers. They also conducted a comparison between using this common statistical model (i.e. negative binomial regression) and the Artificial Neural Network (ANN) approach for crash prediction. The results indicated that using the ANN approach gives better statistical performance than the negative binomial regression model. They also found that the number of crossovers' crashes decreases by increasing loon's radius.

A study by *Inman and Hass (2012)* has evaluated the safety efficiency of stop controlled RCUT intersections based on lag availability as a measure of conflicts between movements. Furthermore, crash modification factors (CMF) for implementing RCUT intersections have been estimated for different crash severities by using the Empirical Bayes before-after method. They concluded that RCUT intersections reduce total crashes by 44%. They also found by employing the simple before-after analysis that fatal, injury, and property damage only (PDO) crashes have been reduced by 70%, 42%, and 21%, respectively.

Ott et al. (2012) confirmed that a significant reduction in crash frequency and severity will be achieved after implementation of the unsignalized RCUT intersection. They concluded this after employed the Empirical Bayes method to analyze crashes at 13 unsignalized RCUT intersections in North Carolina.

Azizi and Sheikholeslami (2013) evaluated safety aspects of implementing the unconventional MUT intersections (MUT intersection with prohibited minor through traffic at the main intersection). The Empirical Bayesian analysis showed a 13.2% increase in the crash count at this intersection design. However, they found that the crash count is reduced by increasing median U-turn crossovers' spacing and radius of turning at them.

Inman et al. (2013) have concluded after crash analysis at five RCUT intersections by using before-after with empirical Bayes control group method that RCUT intersections have 44% fewer crashes compared to conventional intersections with 9% reduction in the probability of fatality and injury occurrence when crashes happen.

Safety evaluation of RCUT intersections based on field data from Missouri has been conducted by *Edara et al. (2013)*. Crash analysis at five RCUT intersection locations by using the empirical Bayes method indicated that total, fatal and injury, disabling injury, minor injury crashes were significantly reduced by 34.8%, 53.7%, 86%, and 50%, respectively. Rear-end crashes have been also reduced. While, fatal and left-turn, right-angle crashes have been eliminated at RCUT intersections.

Zhang et al. (2013) deduced after conducting crash analysis at 35 unsignalized RCUT intersections that the crash frequency at RCUT intersections with acceleration lanes increases as long as median U-turn crossovers' spacing is less than 1500 ft. However, it decreases at RCUT intersections with spacing greater than 2000 ft.

Edara et al. (2015) performed a comparison between unsignalized RCUT and two-way stop controlled (TWSC) intersections by utilizing empirical Bayes before-after procedure to analyze crashes at five RCUT intersection locations in Missouri. The results showed that total, fatal-and-injury, disabling injury, and minor injury crashes at RCUT intersections were reduced by 31.2 %, 63.8%, 91.6%, and 67.9%, respectively. A Significant reduction (90.2%) were also recorded for right-angle crashes, while left-turn, right-angle crashes have been eliminated at RCUT intersections. It was found in this research that the mean time-to-collision measure for the turning movements from the minor road at the TWSC intersection is four times less than it at the RCUT intersection. This confirms the safety benefits of the RCUT intersection design.

Claros et al. (2017) examined the role of providing acceleration lanes at unsignalized RCUT intersections and median U-turns crossovers' spacing on crash reduction. This is to determine the optimum design and spacing that achieve the safety effectiveness of this intersection design. Crash data at 12 unsignalized RCUT intersections has been analyzed. The results showed that acceleration lanes have a significant impact on crash reduction. Lack of acceleration lanes for the minor right-turn traffic increases the crash frequency by 33%, while lack of them after U-turn lanes increases the crash count by 393%. The results also indicated that there is an inverse relationship between the spacing and the number of crashes. They also verified by using the SSAM software that the provision of acceleration lanes reduces conflicts at the unsignalized RCUT intersection. A similar conclusion that the short spacing has a negative safety effect at unsignalized RCUT intersections has been drawn by *Xu et al. (2017)*. However, they found that there is no significant safety improvement for increase crossover' spacing more than 1100 ft.

A driving simulation experiment has been conducted by *Sun et al. (2017)* to investigate the effect of providing acceleration and deceleration lanes at the unsignalized RCUT intersection design indicated that the presence of acceleration lanes in addition to deceleration lanes improves the safety by 66.3%.

Hummer and Rao (2017) utilized data at eleven signalized RCUT intersections to evaluate their safety efficiency. They only estimated CMFs for total and injury crashes. The CMFs' values were 0.85 and 0.78, respectively.

Sun et al. (2019) studied six (two signalized and four unsignalized) RCUT locations in Louisiana to investigate the safety benefits of RCUT intersection implementation. Two levels of analysis were conducted in this study: RCUT intersection (i.e. the main intersection) and RCUT system (i.e. the main intersection and the crossovers). The results showed a significant reduction in crashes after the RCUT intersection implementation, especially at the main intersection. 28%, 100%, and 42% reductions were recorded for total, fatal, and injury crashes at the main intersection, while 13%, 100%, and 13% reductions were recorded for the RCUT system level for the same crash types respectively.

2.3 Evaluation of the Operational Effectiveness of Median U-Turn Crossover-Based Intersections

Several studies have been conducted to evaluate the operational performance of MUT and RCUT intersections by using field or virtual data.

Reid and Hummer (1999) found that converting the conventional intersection to RCUT intersection significantly reduces the travel time by 10% and increases the average speed by 15%. They employed CORSIM software in the study.

A research study has been performed by *Reid and Hummer (2001)* to evaluate the operational performance of the RCUT intersection. RCUT and conventional signalized intersections have been simulated in the CORSIM environment with different traffic volume levels at specific conditions. Four and two seconds have been set for yellow and red times, respectively. Heavy vehicles' proportion was 3% on the major road and 2% on the minor road. 50 mph and 40 mph have been proposed as travel speeds at major and minor roads, respectively. The simulation results indicated that RCUT intersections experience less travel time than conventional intersections.

Henderson and Stamatiadis (2001) evaluated MUT intersection operational performance along arterials. TSIS and CORSIM software has been used for the microscopic simulation, while TRANSYT-7F software was used for the optimization of signal timing. They found that travel time and delay have been reduced by 32% and 35%, respectively, at peak time.

Bared and Kaisar (2002) performed a study to evaluate the operational performance of the signalized 4-lanes MUT intersection. They utilized CORSIM software to simulate MUT and conventional signalized intersections with deferent traffic volumes and left-turn proportions, while TRANSIT-7F software has been used to optimize signal times. It was found that average travel and stop times of the median crossovers' traffic (left-turn traffic) are higher than they at the conventional intersection by 20-30 s/veh and 10-18 s/veh, respectively. Nevertheless, the network travel time has been reduced for MUT intersections with high traffic volume and moderate to high left-turn percentages (10% and 20%) compared to its value at conventional intersections.

Yang and Zhou (2004) used CORSIM software to compare between two left-turn procedures; the direct left-turn at conventional intersections and the right-turn followed by a U-turn. Intersection models have been calibrated by using field data from six locations. The results indicated that the right-turn followed by a U-turn procedure performs better than the direct left-turn procedure only at high major through-traffic volumes.

A study conducted by *Kim et al. (2007)* stated that the average delay at unsignalized RCUT intersections could be reduced by 28-31% compared to conventional all-way stop control (AWSC) intersections. This resulted in a 12-23% increase in intersection’s throughput.

A microscopic simulation study has been conducted by *Bared (2009)* showed that the RCUT intersection with a low minor road traffic volume level (less than 20% of total entering vehicles [TEV]) has 30% higher throughput and 40% lower network travel time than the conventional signalized intersection.

Hummer et al. (2010) performed a study to evaluate the operational efficiency of signalized RCUT intersections in North Carolina. They used Vissim microscopic software to simulate the RCUT intersection. The model has been calibrated by utilizing a GPS unit installed on a testing vehicle that drove at three RCUT intersections. The results indicated that the RCUT intersection reduces average travel time.

Hughes et al. (2010) conducted a simulation study to evaluate signalized RCUT intersection efficiency under different traffic conditions. Vissim software was used for microscopic simulation and Synchro software has been employed for signal timing optimization. Different traffic volume levels with 5% percent of heavy vehicles were used to simulate traffic at RCUT and conventional signalized intersections. Crossovers have been installed on a 40 ft. width median at 450 ft. from the main intersection. 45 mph and 25 mph travel speeds have been assumed at major and minor roads, respectively. The results indicated that there is a significant effect of the ratio between the minor road traffic and the intersection volumes on the operational performance of RCUT intersections. RCUT intersections experienced higher throughput than conventional intersections for ratios less than 0.2. Identical throughputs have been recorded for RCUT and conventional intersections for ratios between 0.2 and 0.25. However, for ratios higher than 0.25, conventional intersections performed better. The ratio had more influence on travel time at RCUT intersections. It was found that travel time at RCUT intersection would be less than it at conventional intersections only for ratios below 0.15.

A study has been performed by *Haley et al. (2011)* to compare between signalized RCUT and conventional intersections to investigate the operational benefits of RCUT implementation by simulation 3 RCUT locations in North Carolina. Two separated RCUT locations and one RCUT corridor have been simulated in the Vissim environment for this study. The research results indicated that overall average travel time has been reduced at RCUT intersections.

El Esawey and Sayed (2011) simulated MUT and unconventional MUT intersections in the Vissim environment to conduct a comparison with the conventional 4-leg signalized intersection. Traffic movements at the unconventional MUT intersection are the same at MUT intersection except for the minor through movement which is done by using median U-turn crossovers. The results indicated that the unconventional MUT intersection has the lowest capacity among other intersection designs. Its capacity is 27% lower than the conventional 4-leg intersection which in turn its capacity is lower than signaled and unsignalized MUT intersections by 9% and 7%, respectively.

Kivlins and Naudzuns (2011) found that MUT and RCUT intersections perform better at intersection of heavy traffic arterials with light minor traffic.

Inman and Hass (2012) evaluated the operational characteristics of the stop controlled RCUT intersection by holding field monitoring in Maryland. The results indicated that the average travel time of minor through and left-turn movements at the RCUT intersection increased by 64 and 52 seconds compared to the conventional TWSC intersection, respectively. It was recommended to implement acceleration lanes for right and U-turns at the RCUT intersection.

A simulation research study has been conducted in the CORSIM environment by *Naghawi and Idewu (2014)* to compare the operational performance of RCUT and conventional intersections. Different traffic volumes and left-turn proportions were set in this comparison. They concluded that the RCUT intersection reduces the delay and the queue length of the major through traffic. They also pointed out that minor left-turn proportion plays a significant role in delay increase.

Taha and Abdelfatah (2015) conducted a comparison between the conventional direct left-turn and unconventional left-turns at median crossovers in the Vissim environment. Synchro software has been used for signal timing optimization. They concluded that in spite of that unconventional left-turn procedures increase the traveled distance they recorded lower delays than the conventional direct left-turn.

Holzem et al. (2015) compared the travel time at unsignalized RCUT and conventional AWSC intersections. They found that the RCUT intersection reduces the average travel time resulting in a lower average intersection delay although that minor left and through movements are subjected to more delay.

Hashim et al. (2017) have evaluated the operational performance of 3-leg MUT intersections in the Vissim environment. Balanced and unbalanced traffic scenarios with low and high traffic volumes and different left-turn proportions were proposed in this evaluation. The results indicated that this design has a lower delay than the conventional 3-leg intersection at balanced traffic volume approaches up to 1250 v/h. However, the average delay is directly increased at MUT intersections by traffic volume increases. They also found that high proportions of left-turn and heavy vehicle volumes increase the delay at 3-leg MUT intersections especially at high traffic volume.

A research performed by *Naghawi et al (2018A)* to evaluate the operational performance of MUT and RCUT intersections implementation. The researchers selected a congested conventional signalized intersection in Amman, Jordan as the base case in this study. They used

Synchro 8 software to simulate MUT and RCUT intersections. Two analysis levels have been utilized: intersection and corridor levels. The results indicated that MUT and RCUT intersections do not have a good performance under intensive traffic volumes. A similar conclusion has been drawn by *Naghawi et al. (2018B)* even though the RCUT intersection reduced the average intersection delay by 70% at the selected conventional signalized intersections in the study.

Rahman et al. (2019) have employed the Agent-Based modeling simulation to determine the operational performance of the MUT intersection. Even though that the results indicated that the average number of stops has been increased by 5.5% at the MUT intersection compared to the conventional 4-leg intersection, the average travel time has been reduced by 16.8%. The results also indicated that the MUT intersection shows better operational benefits at medium to high traffic volume levels.

2.4 Microscopic Simulation

Microscopic simulation software programs such as PTV Vissim and CORSIM enable to simulate existed roadway elements where field study is not applicable or possible. Heavy traffic volumes or pedestrians and the weather may impede of conducting a field study. In addition, field studies do not enable to exclude some conditions that may affect the purpose of the study. As well, microscopic simulation provides the ability to simulate new situations that resulted from modifying the geometric design, traffic volume levels, control types, or other conditions. Evaluation of the efficiency of the new designs in the enhancement of traffic safety and operation before implementing them saves a lot of money and effort besides protecting lives.

Many research papers and studies have been conducted by utilizing microscopic simulation software programs to simulate unconventional intersections designs in order to evaluate their safety and operation effectiveness. (*Reid and Hummer, 1999*; *Henderson and Stamatiadis, 2001*; *Bared and Kaisar, 2002*; *Yang and Zhou, 2004*; *Bared, 2009*; *Hughes et al., 2010*; *Haley et al., 2011*; *El Esawey and Sayed, 2011*; *Taha and Abdelfatah, 2015*; *Naghawi et al, 2018*).

2.5 Driving Simulation

Driving simulation provides a simulation of the roadway environment to investigate driving behavior under certain conditions or to compare two deferent situations or designs. It enables to conduct studies for situations when the field study is not possible to conduct such as heavy traffic volume levels, bad weather conditions, or new designs. Using driving simulation to investigate driving behavior and safety challenges under fog condition is a good example of driving simulator abilities comparing to field studies. Furthermore, driving simulation is very useful in studies that concern in drivers' characteristics such as gender and age. Additionally to the previous, driving simulation enables to conduct research under situations that may result in crashes occurrence. Like the microscopic simulation, using driving simulation will save time, money, and efforts and protect lives. However, very few studies have employed the driving simulation to evaluate driving behavior at unconventional intersection designs and their effectiveness in improving traffic safety. In addition, the best practice of lane configuration, signage, and lane marking at unconventional intersections was rarely investigated.

Inman (2009) conducted a study to evaluate the effectiveness of three signage options (two ground-mounted signage options and one overhead signage option) in guidance of drivers to access the left-turn lanes upstream of the main intersection of the continuous flow intersection (CFI) and the effectiveness of lane marking in preventing the stopping behavior after the stop line on the minor road. Measures of performance in this study to evaluate the signage were failure to perform the major left-turn movement correctly and location of the lane change. While the stop location relative to the minor road stop line was the performance measure for the effectiveness of lane marking. The results indicated that a ground-mounted signage option that involves “keep Left” sign upstream of the crossover, where the driver accesses the left-turn lanes at the main intersection, has similar effectiveness with the overhead signage option. Lane marking treatment was useful in the elimination of stopping behavior after the stop line on minor roads.

Sun et al. (2017) investigated the effects of lane configuration (providing acceleration and deceleration lanes upstream and downstream the crossover or providing only a deceleration lane), crossover spacing (1000 feet or 2000 feet), and signage style (diagrammatical or directional styles) factors on the safety effectiveness of the RCUT intersection design. Speed variation (speed difference between the subject vehicle and the nearest vehicle to the subject vehicle at the moment of lane-change maneuver) and time to collision (TTC) have been measures of performance in this study. The results indicated that providing acceleration and deceleration lanes reduces the speed variation between vehicles and increases TTC values. The crossover spacing factor was having no significant effect at the RCUT intersection which only has a deceleration lane. However, it was found that providing 2000 feet spacing for the RCUT intersection's crossover that has acceleration and deceleration lanes improve traffic safety in comparison with the 1000 feet spacing. No significant difference was recorded for using diagrammatical or directional signage styles.

Stephens et al. (2017) evaluated the effectiveness of two innovative intersection designs (Cut-Through and Squircle intersections) in reducing speed at intersections. Both intersections eliminate performing the through movement in a straight line by providing small islands at the center of the main intersection. Drivers must deviate from the straight track as they do at roundabouts. While right-turn and left-turn movements are performed as usual. The results indicated that speed of through movement at Cut-Through and Squircle intersections was significantly lower than the speed at the conventional signalized intersection. On the other hand, speed of the left-turn movement at the Cut-Through intersection was significantly higher than its value at the conventional intersection, while three was no significant difference between speed values of the left-turn movement at Squircle and conventional intersections. Generally, Cut-Through and Squircle intersection designs reduce speed by approximately 30% to 40% in comparison with the conventional intersection.

2.6 Implementation of Connected Vehicle Technology at Unconventional Intersection Designs

Only one study has been conducted to evaluate the efficiency of the implementation of connected and automated vehicle technology at unconventional intersection designs (*Zhong et al., 2018*). This evaluation was based on a survey. The authors believe that implementation of unconventional intersections within a connected and automated vehicle environment will reduce driver confusion at these new intersection configurations.

2.7 Literature Gaps

Although that several studies have been conducted for safety evaluation of MUT and RCUT intersections, very limited number of MUT and RCUT intersections ware considered in these studies such as three (*Hughes et al., 2010*), four (*Hummer and Jagannathan,2008*; *Hochstein et al., 2009*), and five (*Edara et al., 2013*) RCUT intersections and four MUT intersections (*Maki,1996*). Only *Hummer and Rao (2017)* utilized eleven RCUT intersections to conduct crash analysis after RCUT intersections' implementation. They estimated CMFs for total and injury crashes only. In addition, the new intersection-related areas at MUT and RCUT intersections (i.e., median U-turn crossovers) were not considered in previous studies.

No previous study has been conducted to develop safety performance functions (SPF) and estimate CMFs for the different crash severities and types by using data from both the main intersection and the median crossovers of a considerable number of signalized MUT and RCUT intersections.

Since the RCUT intersection design, which has the least number of conflict points among other proposed unconventional intersection designs, has an efficient operation performance only as long as minor road traffic is light and its operational benefits fade at medium to high minor road traffic volumes (*Bared, 2009; Hughes et al., 2010*), there is a need for a new intersection design has the same number of conflict points and performs better than the RCUT intersection under medium to high minor road traffic conditions.

Driving behavior at unconventional signalized intersection designs and evaluation of the effectiveness of implementing I2V communication on driver confusion mitigation at unconventional intersections is still unknown.

2.8 Summary

Tables 2.1 and 2.2 summarize all studies that have been conducted for the safety and operation evaluation of median U-turn crossover-based intersections.

Table 2.1: Studies that evaluated the traffic safety at MUT and RCUT intersections

Study	Tools	Method	Number of Sites	Findings
Kach (1992)	-	-	-	MUT intersections reduce injury crashes by 30%, and there is a notable reduction in the most severe crash types such as right-angle, rear-end, left-turn, and head-on crashes at MUT intersections.
Castronovo et al. (1995)	-	-	-	The dense segment of MUT intersections has a low crash rate. They concluded that crash rates at MUT intersections are less than at conventional intersections in typical suburban and rural areas by 50% and 36%, respectively.
Maki (1996)	-	-	4	Total crashes are reduced by 60% and about 95% reduction in angle crashes are recorded at MUT intersections.
Levinson et al. (2000)	-	-	-	The crash rate at median U-turn crossovers is 33% less than at the two-way left-turn lanes.
Lu and Dissanayake (2002)	Video recording	-	7	The number of conflict points at the off-peak, the peak, and overall time periods which resulted from the direct left-turn procedure is more than it for the RTUT procedure by 29%, 76%, and 51%, respectively. The direct left-turn procedure has also 64% more average conflict points per thousand vehicles.
Zhou et al. (2003)	-	Regression model	6	The safety improvement is associating with the optimum spacing.
PBS and J. (2005)	-	-	-	The implementation of signalized RCUT intersections will reduce the predicted crash rate in comparison with the conventional signalized intersection.
Jagannathan (2007)	-	-	-	MUT intersections reduced crashes by 60%, and injury crashes were particularly reduced by 75%. He also found that angle and sideswipe crashes were reduced at MUT intersections by 96% and 61%, respectively, while rear-end crashes were slightly reduced by 17%.

Study	Tools	Method	Number of Sites	Findings
Kim et al. (2007)	SSAM software	Microscopic simulation	NA	The total number of conflict points at the RCUT intersection with one U-turn lane decreased by 79% compared to the conventional unsignalized intersection. On the other hand, it increased by 78% at RCUT intersections with two U-turn lanes.
Hummer and Jagannathan (2008)	-	-	4	RCUT intersections are effective in crash reduction.
Hochstein et al. (2009)	-	-	4	RCUT intersections are effective in crash reduction.
Hummer et al. (2010)	-	Naïve and comparison group analysis	3	Only one signalized RCUT intersection showed safety improvement.
Azizi et al. (2012)	-	Negative binomial regression and ANN approach	3	The ANN approach gives better statistical performance than the negative binomial regression model. They also found that the number of crossovers' crashes decreases by increasing loon's radius.
Inman and Hass (2012)	-	Empirical Bayes before-after	5	RCUT intersections reduce total crashes by 44%.
Inman and Haas (2012)	-	Simple before-after	9	Total, fatal, injury, and PDO crashes are reduced by 33%, 70%, 42%, and 21%, respectively.
Ott et al. (2012)	-	Empirical Bayes before-after	13	A significant reduction in crash frequency and severity will be achieved after implantation of the unsignalized RCUT intersection.
Azizi and Sheikholeslami (2013)	-	Empirical Bayes before-after	6	A 13.2% increase in the crash count at the unconventional MUT intersection design unless median U-turn crossovers' spacing and radius of turning at them are increased.
Inman et al. (2013)	-	Empirical Bayes before-after	5	RCUT intersections have 44% fewer crashes compared to conventional intersections with 9% reduction in the probability of fatality and injury occurrence when crashes happen.

Study	Tools	Method	Number of Sites	Findings
Edara et al. (2013)	-	Empirical Bayes before-after	5	Total, fatal and injury, disabling injury, minor injury crashes at RCUT intersections were significantly reduced by 34.8%, 53.7%, 86%, and 50%, respectively. Rear-end crashes have been also reduced. While, fatal and left-turn, right-angle crashes have been eliminated.
Zhang et al. (2013)	-	-	35	The crash frequency at unsignalized RCUT intersections that contain acceleration lanes increases as long as median U-turn crossovers' spacing is less than 1500 ft. However, it decreases at RCUT intersections with spacing greater than 2000 ft.
Edara et al. (2015)	-	Empirical Bayes before-after	5	Total, fatal-and-injury, disabling injury, minor injury, right-angle and left-turn, right-angle crashes at RCUT intersections were reduced by 31.2 %, 63.8%, 91.6%, 67.9%, 90.2%, and 100%, respectively. The mean time-to-collision measure for the turning movements from the minor road at the TWSC intersection is four times less than it at the RCUT intersection.
Claros et al. (2017)	-	-	12	Acceleration lanes have a significant impact on crash reduction. Lack of acceleration lanes for the minor right-turn traffic increases the crash frequency by 33%, while lack of them after U-turn lanes increases the crash count by 393%. There is an inverse relationship between the spacing and the number of crashes.
Xu et al. (2017)	-	-	-	There is an inverse relationship between the median U-turns crossovers' spacing and the number of crashes at the unsignalized RCUT intersection. But there is no significant safety improvement for increasing the spacing more than 1100 ft.

Study	Tools	Method	Number of Sites	Findings
Sun et al. (2017)	Driving simulator	Driving simulation	NA	The existence of acceleration and deceleration lanes improves the safety at unsignalized RCUT intersections by 66.3%. Providing acceleration and deceleration lanes reduces the speed variation between vehicles and increases TTC values. 1000 ft. spacing is suitable for unsignalized RCUT intersections with only deceleration lanes, while 2000 ft. spacing is recommended for RCUT intersections which also have acceleration lanes.
Hummer and Rao (2017)	-	-	11	The CMFs values for total and injury crashes at signalized RCUT intersections are 0.85 and 0.78, respectively.
Sun et al. (2019)	-	Empirical Bayes before-after	6	There is a significant reduction in crashes after the RCUT intersections implementation, especially at the main intersection. 28%, 100%, and 42% reduction were recorded for total, fatal, and injury crashes at the main intersection, while 13%, 100%, and 13% reductions were recorded at the RCUT system level for the same crash types respectively.

Note: MUT: median U-turn intersection, RCUT: restricted crossing U-turn intersection, SSAM: surrogate safety assessment model, ANN: artificial neural network, PDO: property damage only.

Table 2.2: Studies that evaluated the traffic operation at MUT and RCUT intersections

Study	Tools	Method	Number of Sites	Findings
Reid and Hummer (1999)	CORSIM software	Microscopic simulation	NA	The travel time at RCUT intersections has been reduced by 10% while the average speed has been increased by 15% compared to conventional intersections.
Reid and Hummer (2001)	CORSIM software	Microscopic simulation	NA	RCUT intersections experience less travel time than conventional intersections.
Henderson and Stamatiadis (2001)	TSIS, CORSIM, and TRANSYT-7F software	Microscopic simulation	NA	The travel time and the delay at the MUT intersection have been reduced by 32% and 35%, respectively, at peak time.
Bared and Kaisar (2002)	CORSIM and TRANSYT-7F software	Microscopic simulation	NA	The average travel and stop times of the median crossovers' traffic (left-turn traffic) are higher than they at the conventional intersection by 20-30 s/veh and 10-18 s/veh, respectively. Nevertheless, the network travel time has been reduced for MUT intersections with high traffic volume and moderate to high left-turn percentages (10% and 20%) compared to its value at conventional intersections.
Yang and Zhou (2004)	CORSIM software	Microscopic simulation	6	The right-turn followed by a U-turn procedure performs better than the direct left-turn procedure only at high major through-traffic volumes.
Kim et al. (2007)	-	Microscopic simulation	NA	The average delay at unsignalized RCUT intersections could be reduced by 28-31% compared to conventional AWSC intersections. This resulted in a 12-23% increase in intersection's throughput.
Bared (2009)	-	Microscopic simulation	5	The RCUT intersection with a low minor road traffic volume level (less than 20% of TEV) has a 30% higher throughput and 40% lower network travel time than the conventional signalized intersection.
Hummer et al. (2010)	GPS unit and Vissim software	Microscopic simulation	3	The RCUT intersection reduces average travel time.

Study	Tools	Method	Number of Sites	Findings
Hughes et al. (2010)	Vissim and Synchro software	Microscopic simulation	NA	RCUT intersections experienced higher throughput and less travel time than conventional intersections for minor road traffic volume to TEV ratios less than 0.2 and 0.15, respectively.
Haley et al. (2011)	Vissim software	Microscopic simulation	3	The overall average travel time has been reduced at RCUT intersections.
El Esawey and Sayed (2011)	Vissim software	Microscopic simulation	NA	The capacity of the unconventional MUT intersection is 27% lower than the conventional four-leg intersection which in turn its capacity is lower than signaled and unsignalized MUT intersections by 9% and 7%, respectively.
Kivlins and Naudzuns (2011)	Vissim software	Microscopic simulation	-	MUT and RCUT intersections perform better at intersection of heavy traffic arterials with light minor traffic.
Inman and Hass (2012)	-	Field Data	1	The average travel time of minor through and left-turn movements at the RCUT intersection increased by 64 and 52 seconds compared to the conventional TWSC intersection, respectively.
Naghawi and Idewu (2014)	CORSIM software	Microscopic simulation	NA	The RCUT intersection reduces the delay and the queue length of the major through traffic. The minor left-turn proportion plays a significant role in delay increase.
Taha and Abdelfatah (2015)	Vissim and Synchro software	Microscopic simulation	NA	In spite of that the unconventional left-turn procedures increase the traveled distance they recorded a less delays than the conventional direct left-turn.
Holzem et al. (2015)	Vissim software	Microscopic simulation	NA	The unsignalized RCUT intersection reduces the average travel time resulting in a lower average intersection delay although that minor left and through movements are subjected to more delay.

Study	Tools	Method	Number of Sites	Findings
Hashim et al. (2017)	Vissim software	Microscopic simulation	NA	The 3-leg MUT intersection has a lower delay than the conventional 3-leg intersection at balanced traffic volume approaches up to 1250 v/h. High proportions of left-turn and heavy vehicle volumes increase the delay at 3-leg MUT intersections especially at high traffic volume.
Naghawi et al (2018A)	Synchro software	Microscopic simulation	NA	MUT and RCUT intersections do not have a good performance under intensive traffic volumes.
Naghawi et al. (2018B)	Vissim and Synchro software	Microscopic simulation	NA	The RCUT intersection can reduce the average intersection delay by 70%.
Rahman et al. (2019)	-	Agent-Based modeling simulation	NA	The average number of stops has been increased by 5.5% at the MUT intersection compared to the conventional 4-leg intersection. The average travel time has been reduced by 16.8%. The results also indicated that the MUT intersection shows better operational benefits at medium to high traffic volume levels.

Note: RCUT: restricted crossing U-turn intersection, MUT: median U-turn intersection, AWSC: all-way stop control, TEV: total entering vehicles, TWSC: two-way stop controlled.

CHAPTER 3: EVALUATION OF SAFETY AT MEDIAN U-TURN CROSSOVER-BASED INTERSECTIONS [1]

3.1 Introduction

Unconventional intersections mainly differ from conventional intersections by partially or fully prohibition of left-turn movements at the main intersection. Median U-turn crossover-based intersections (i.e., median U-turn (MUT) and restricted crossing U-turn (RCUT) intersections) are the types of unconventional intersections that contain median U-turn crossover areas. Thus, the basic designs of these two unconventional intersections are similar despite some differences.

At MUT intersections, the through and right-turn movements are made the same way as at conventional intersections, while left-turn and U-turn movements are completed by using the median U-turn crossover downstream of the main intersection. The main variation between MUT and RCUT intersections is the different traffic movement patterns. At RCUT intersections, the essential movements from the major road (i.e., through; right-turn; and left-turn movements) are made at the main intersection like conventional intersections. While all movements form the minor road are made by turning right first, then median U-turn crossover lanes downstream of the main intersection are used to complete through and left-turn movements (*Hughes et al., 2010*).

Two types of MUT intersections were defined; Type A which has median U-turn crossovers downstream of the main intersection for both directions, while Type B has additional two reverse U-turn lanes near the main intersection.

---

[1] This chapter has been published in Transportation Research Record: Journal of the Transportation Research Board (*Al-Omari et al., 2020*)

Figures 3.1, 3.2 and 3.3 show satellite images of median U-turn crossover-based intersections, and Figure 3.4 shows their traffic movement patterns.

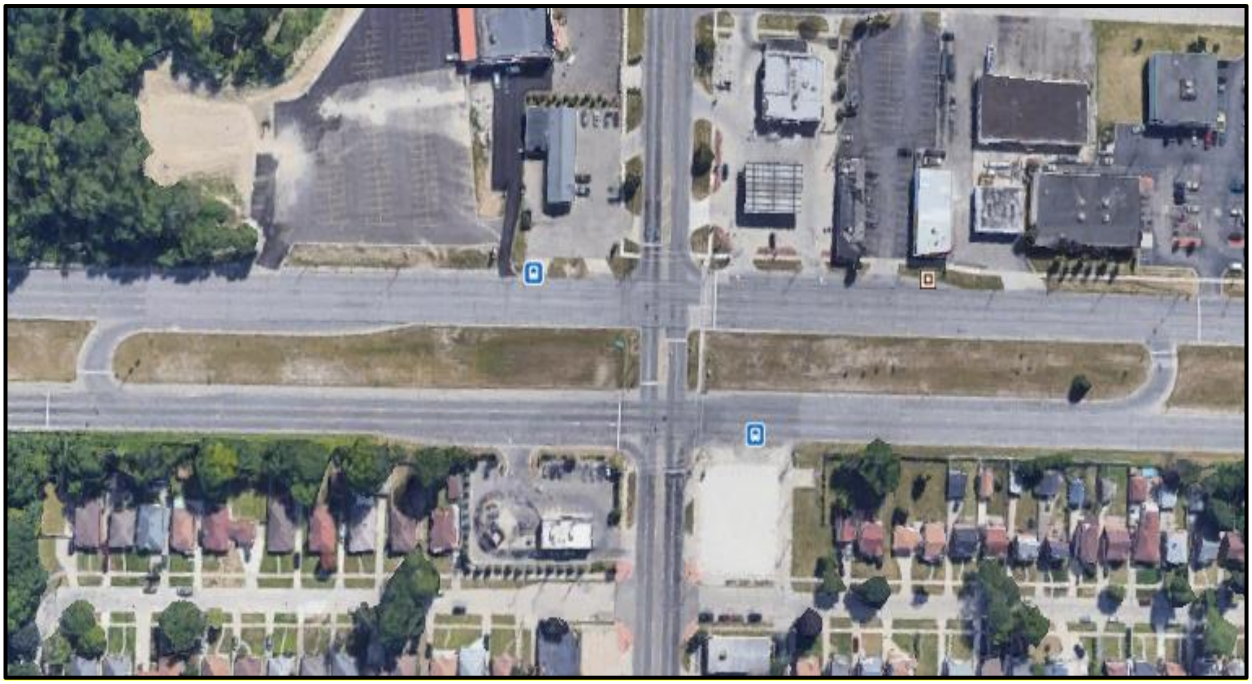


Figure 3.1: MUT type A intersection at US 24 and W Warren St., Detroit, MI (*Google Earth*)

Figure 3.2: MUT type B intersection at E 10 Mile Rd and Gratiot Ave., Eastpointe, MI (*Google Earth*)

Figure 3.3: RCUT intersection at OH-4 Bypass and Symmes Rd, Hamilton, OH (*Google Earth*)

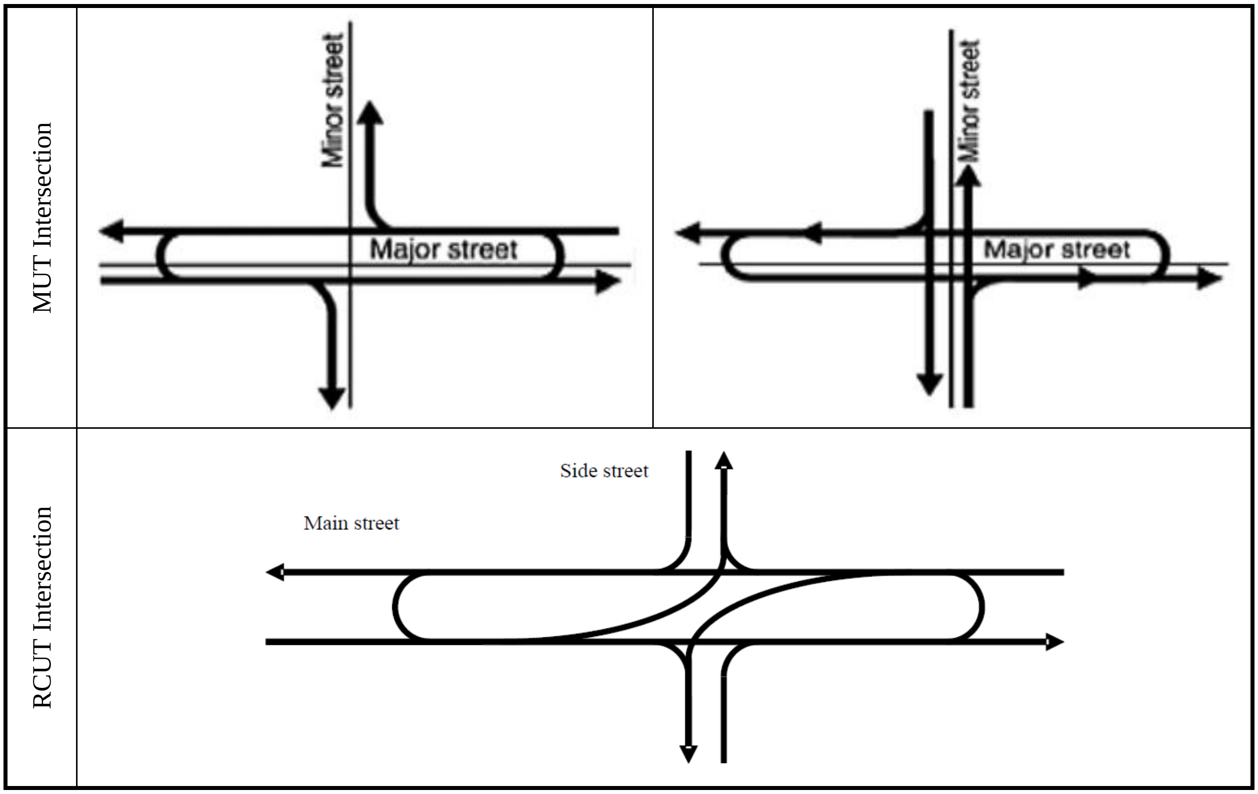


Figure 3.4: Schemes of traffic movements at MUT and RCUT intersections (*Hughes et al., 2010, AASHTO, 2004*)

Although that median U-turn crossovers have been suggested and adopted in the 1970s (*Gluck et al., 1999*) and even as early as the 1960s (*Jagannathan, 2007*), MUT and RCUT intersections' implementation is still limited to few states. For this reason, evaluation of MUT and RCUT intersections' effectiveness in crash reduction is restricted to few research papers and reports. However, most research papers that studied and evaluated MUT and RCUT intersections have showed that implementing them has a significant effect in crash reduction.

In the beginning, evaluation of the effectiveness of MUT and RCUT intersections in crash reduction was based on theoretical inferences rather than actual evaluation by using crash data. The inferences were based on the low number of conflict points at MUT and RCUT intersections (16 at MUT and 14 at RCUT 4-leg intersections) compared with conventional intersections (32 at 4-leg intersection) (*Jagannathan, 2007; Hummer et al., 2014*). Thereafter, several studies were conducted by using crash data. But a very limited number of MUT and RCUT intersections was considered in these studies. In addition, the new intersection-related areas at MUT and RCUT intersections (i.e., median U-turn crossovers) were not considered in the analysis.

In this chapter, a comprehensive evaluation was conducted by using crash data for considerable number of signalized MUT and RCUT intersections from multiple states. A methodology to establish a safety influence area was proposed as it differs than the general 250 ft. used for conventional intersections. The resulting new influence areas were considered in the evaluation of the safety improvements that could be achieved by implementing MUT or RCUT intersections. Safety performance functions (SPF) were developed for MUT intersections and crash modification factors (CMF) were estimated by crash severity and type for MUT and RCUT intersections to quantify their effectiveness in crash reduction. Two methods were used to estimate CMFs: before-after and cross-sectional methods.

3.2 Data Collection and Description

In order to achieve the objectives of this study, data from multiple states were collected. Data from multiple states provides better generalization of the results, therefore wider benefit. Data for 53 MUT Type A and 20 MUT Type B signalized intersections in Michigan and 12 RCUT signalized intersections in North Carolina and Ohio were collected. In addition, data of 151 and 20 conventional signalized intersections were acquired to use in evaluation of MUT and RCUT intersections, respectively. Conventional intersections were selected considering: (1) spatial proximity to the MUT and RCUT intersections, (2) same number of legs (four), (3) same control type (signalized), and (4) similar traffic volume levels. Based on this selection criteria, the available numbers of conventional intersections were different for MUT and RCUT intersections. Thus, approximately two conventional intersections were selected for each MUT and RCUT intersections.

Because of the different geometric designs of MUT Type A and MUT Type B, they were analyzed separately in this study. Since MUT and RCUT intersections have different geometric designs compared to conventional intersections, the new influence areas by the intersection must be considered in the analysis. In the data collection and analysis, three scenarios of the intersection-related areas were studied: (1) 250 ft. (in radius) circular buffer from the center of the main intersection (same as the traditional approach), (2) Large circular buffer that would cover all intersection-related areas (i.e., the main intersection and both median U-turn crossovers), (3) 250 ft. (in radius) circular buffer from the center of the main intersection and 50 ft. (in radius) circular buffer from the center of both median U-turn crossovers. These three scenarios are displayed in Figure 3.5.

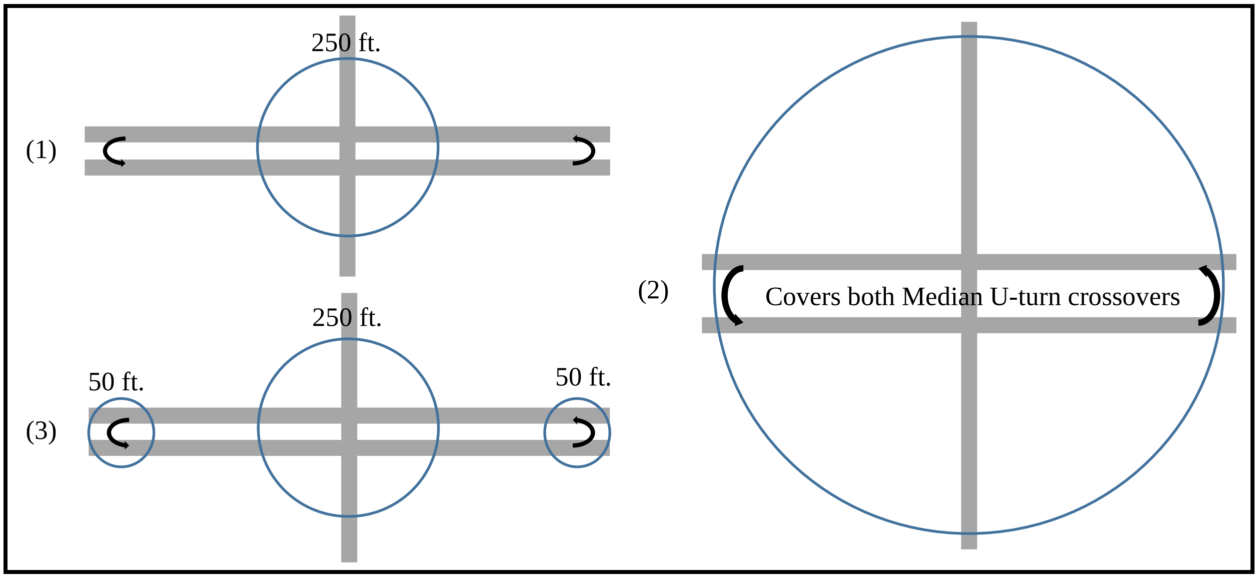


Figure 3.5: Scenarios of influence areas at MUT and RCUT intersections

Crash, traffic, and geometric data were collected for each intersection. Crash data for RCUT intersections were collected from two states. Every state has its own procedure to record crashes, and different crash types are considered among states. Therefore, matching between crash types from different crash reports is sometimes not feasible. In addition, some crash types have not been reported during the selected study periods. Thus, slightly different crash types at MUT and RCUT intersections were considered in this study. For example, Left-turn crashes are combined with angle crashes in Ohio crash reports. Therefore, they were integrated as angle crashes for RCUT intersections. Moreover, there were no non-motorized crashes at RCUT intersections during the selected periods.

The average crash frequencies by crash severity and type of MUT and RCUT intersections for the different scenarios are presented in Table 3.1. Average crash frequency values for the first and the third scenarios are not significantly different from each other. Nevertheless, average crash frequency values for the second scenario are significantly greater than those for other scenarios as it covers an excessively wider area. Tables 3.2 and 3.3 show the descriptive statistics of the prepared data.

Eliminating crashes that occurred at median U-turn crossovers, where several conflict points have been moved, results in low accurate findings. In contrast, the large buffer including both median U-turn crossovers cover too wide area, therefore crashes not related to the intersection could be included in the analysis. The third scenario (250 ft. main buffer + two 50 ft. median U-turn crossover buffers) is considered the most reasonable one because it covers all the intersection-related areas without inclusion crashes not relevant to the intersection. As median U-turn crossovers have only two conflict points and their influence areas are quite limited, a 50 ft. buffer is adequate. In addition, it is enough to cover the road width (up to 4 lanes in each direction) since MUT and RCUT intersections are located on arterials (*Olarte et al., 2011*). This buffer size also guarantees no overlapping will happen between the two buffers since the distance between the center of the main intersection and the center of median U-turn crossover is more than 425 ft. for RCUT intersections and 560-760 ft. for MUT intersections (*Hughes et al., 2010*). Thus, the development of SPFs and estimation of CMFs for median U-turn crossover-based intersections were based on the third scenario.

Daily vehicle miles traveled (DVMT) variables were used along with several other variables for the development of SPFs. DVMT is calculated by multiplying the annual average daily traffic (AADT) by travel distance. Skew angle of each intersection was measured by using Google Maps. It is defined as the degree of deviation from 90˚. The “skewed” is a dummy variable indicating whether an intersection’s skew angle is greater than 5˚ or not. Lighting and pedestrian crossings are variables indicating whether the intersection has lighting and pedestrian crosswalks or not, respectively. The international roughness index (IRI) is a measure of roughness of the pavement. In addition to the abovementioned variables, the number of lanes for each approach were also considered in the analysis.

Table 3.1: Average crash frequency at MUT and RCUT intersections

Intersection Type	Crash Type	Scenario 1	Scenario 2	Scenario 3
MUT Intersections (no. of crash-years: 10, crash-years: 2008-2017)	Total	125.6	590.5	130.0
	Fatal	0.4	1.3	0.4
	Injury	26.8	123.0	27.6
	Single-Vehicle	7.1	46.5	7.4
	Angle	23.2	123.0	24.0
	Head-On	0.4	5.5	0.5
	Head-On Left-Turn	0.9	10.8	0.9
	Rear-End	60.2	237.1	62.2
	Rear-End Left-Turn	1.1	4.2	1.2
	Rear-End Right-Turn	2.3	6.8	2.4
	SD Sideswipe	23.5	102.7	24.4
	OD Sideswipe	0.5	8.1	0.6
	Non-Motorized	3.2	12.1	3.2
RCUT Intersections (no. of crash-years: 2 before and 2 after the implementation, crash-years: 2003-2015)	Total	15.3	35.7	15.4
	Fatal	0.0	0.0	0.0
	Injury	3.9	9.8	4.0
	PDO	11.3	25.5	11.4
	Single-Vehicle	1.8	4.6	1.8
	Angle	2.0	4.8	2.0
	Head-On	0.1	0.4	0.1
	Rear-End	6.7	14.3	6.8
	SD Sideswipe	2.1	4.2	2.1
	OD Sideswipe	0.2	0.4	0.2
	Non-Motorized	0.0	0.4	0.0

Note: MUT: median U-turn intersection, RCUT: restricted crossing U-turn intersection, SD: same direction, OD: opposite direction, PDO: property damage only.

Table 3.2: Descriptive statistics of the conventional and RCUT intersections' crash data

Variable	Conventional Intersections (N=20)				RCUT Intersections (N=12)			
	Mean	S.D.	Min.	Max.	Mean	S.D.	Min.	Max.
Total	20.4	17.0	1	54	15.4	11.5	2	42
Fatal-and-Injury	5.5	4.7	0	19	4.0	2.7	1	9
Fatal	0.0	0.0	0	0	0.0	0.1	0	1
Injury	5.5	4.7	0	19	4.0	2.7	1	9
PDO	14.8	12.9	1	43	11.4	9.1	2	34
Single-Vehicle	1.0	0.8	0	3	1.8	1.6	0	6
Angle	2.9	2.5	0	8	2.0	3.1	0	12
Head-On	0.2	0.3	0	1	0.1	0.3	0	1
Rear-End	10.1	10.4	0	34	6.8	4.8	1	14
SD Sideswipe	2.9	2.4	0	8	2.1	2.7	0	9
OD Sideswipe	0.2	0.2	0	1	0.2	0.2	0	1
Non-Motorized	0.2	0.3	0	1	0.0	0.1	0	1

Note: RCUT: restricted crossing U-turn intersection, S.D.: standard deviation, Min.: minimum, Max.: maximum, PDO: property damage only, SD: same direction, OD: opposite direction.

Table 3.3: Descriptive statistics of the conventional and MUT intersections' data

Crash variables

Variable	Conventional Intersections (N=151)				MUT Type A Intersections (N=53)				MUT Type B Intersections (N=20)			
	Mean	**S.D.**	**Min.**	**Max.**	**Mean**	**S.D.**	**Min.**	**Max.**	**Mean**	**S.D.**	**Min.**	**Max.**
Total	128.4	66.2	9	341	127.3	71.0	40	436	137.2	86.6	16	320
Fatal-and-Injury	26.5	13.8	1	75	28.3	13.5	10	69	27.1	16.2	6	70
Fatal	0.1	0.3	0	2	0.4	0.7	0	3	0.4	0.7	0	3
Injury	26.4	13.7	1	75	27.9	13.4	10	69	26.7	15.9	6	70
PDO	102.0	55.3	8	288	99.0	59.0	28	367	110.2	72.6	10	250
Single-Vehicle	4.2	2.3	0	11	7.3	4.0	1	17	7.5	6.8	1	27
Angle	27.4	17.4	2	86	24.2	15.0	2	78	23.4	11.9	6	54
Head-On	1.1	1.2	0	6	0.4	0.7	0	2	0.7	1.0	0	3
Head-On Left-Turn	9.1	9.0	0	59	0.9	2.2	0	11	0.9	0.9	0	3
Rear-End	58.8	34.2	5	147	62.3	37.2	15	207	62.0	44.8	5	181
Rear-End Left-Turn	1.5	1.6	0	11	1.1	1.9	0	8	1.3	1.8	0	6
Rear-End Right-Turn	1.6	1.7	0	8	2.3	2.4	0	10	2.6	2.3	0	10
SD Sideswipe	17.0	11.2	0	71	22.2	18.2	3	109	30.3	26.6	3	110
OD Sideswipe	1.9	1.6	0	8	0.6	0.9	0	3	0.4	0.8	0	3
Non-Motorized	1.5	1.5	0	6	3.4	3.0	0	14	2.9	3.7	0	16

Explanatory variables

Variable	Conventional Intersections (N=151)				MUT Type A Intersections (N=53)				MUT Type B Intersections (N=20)			
	Mean	**S.D.**	**Min.**	**Max.**	**Mean**	**S.D.**	**Min.**	**Max.**	**Mean**	**S.D.**	**Min.**	**Max.**
Major AADT	32855.1	7973.5	12827	52477	55615.7	13150.7	25512	85076	49310.7	16144.5	19267	72074
Minor AADT	15438.6	8006.1	933	35508	13337.9	7889.0	246	37958	18625.2	14827.5	1204	58591
Total Entering Vehicles	48293.7	11890.4	17681	79749	68953.6	15385.9	29522	99249	67935.9	25203.5	22210	130665
Major DVMT	1555.6	377.5	607	2485	3160.0	747.2	1450	4834	2801.7	917.3	1095	4095
Minor DVMT	731.0	379.1	44	1681	757.8	448.2	14	2157	1058.2	842.5	68	3329
Total DVMT	4573.3	1126.0	1674	7552	7056.4	1565.2	3067	10168	6900.3	2515.1	2300	13056
Skew Angle (°)	5.0	11.3	0	43	15.9	17.1	0	43	21.7	16.5	0	44
Skewed (yes=1, no=0)	0.2	0.4	0	1	0.5	0.5	0	1	0.7	0.5	0	1
Major Speed Limit (mph)	42.0	5.9	25	55	43.3	4.2	35	55	40.8	5.2	30	50
Minor Speed Limit (mph)	38.2	7.0	25	50	35.4	6.6	25	50	35.5	7.2	20	45
Lighting	1.0	0.1	0	1	0.9	0.3	0	1	1.0	0.2	0	1
International Roughness Index (inch/mile)	221.5	139.6	0	943	222.0	149.1	75	705	232.1	117.4	93	514
Pedestrian Crossing	1.0	0.0	1	1	1.0	0.1	0	1	1.0	0.2	0	1
Major Left-Turn Lanes	2.1	0.5	0	4	0.1	0.4	0	2	0.1	0.3	0	1
Minor Left-Turn Lanes	1.9	0.6	0	4	0.0	0.1	0	1	0.2	0.5	0	2
Major Right-Turn Lanes	1.0	1.0	0	4	1.2	0.9	0	2	0.9	0.9	0	2
Minor Right-Turn Lanes	1.0	0.9	0	4	1.3	0.9	0	3	1.2	0.9	0	2
Major Through Lanes	4.2	1.0	1	8	8.0	1.4	4	10	7.0	1.4	4	8
Minor Through Lanes	3.1	1.2	0	6	3.4	1.3	1	7	4.5	1.5	2	9
Major Left + Through Lanes	0.0	0.1	0	1	0.0	0.0	0	0	0.0	0.0	0	0
Minor Left + Through Lanes	0.1	0.4	0	2	0.0	0.0	0	0	0.0	0.0	0	0
Total Left-Turn Lanes	3.9	0.9	1	8	0.1	0.4	0	2	0.2	0.5	0	2
Total Right-Turn Lanes	1.9	1.5	0	4	2.5	1.4	0	5	2.1	1.3	0	4
Total Through Lanes	7.4	1.5	3	12	11.4	2.0	8	17	11.5	2.3	8	17
Total Left + Through Lanes	0.1	0.5	0	2	0.0	0.0	0	0	0.0	0.0	0	0

Note: MUT: median U-turn intersection, S.D.: standard deviation, Min.: minimum, Max.: maximum, PDO: property damage only, SD: same direction, OD: opposite direction, AADT: annual average daily traffic, TEV: total entering vehicles, DVMT: daily vehicle miles traveled.

3.3 Analysis Methodology

Before-after and cross-sectional methods are widely used to estimate CMFs (*Gross et al., 2010*; *Carter et al., 2012*; *Inman et al., 2013*; *Wu et al., 2015*; *Park et al., 2016*; *La Torre et al., 2017*; *Park et al., 2019*). Nevertheless, before-after methods are stronger and preferable than cross-sectional method (*Gross et al., 2010*). Therefore, before-after with comparison group method was utilized to estimate CMFs for RCUT intersections. While cross-sectional method was adopted to develop SPFs and estimate CMFs for MUT intersections. The reason for that is the lack of crash data before the implementation of MUT intersections, as they were implemented in the 1970s (*Gluck et al, 1999*). These two methods are explained in detail in “A Guide to Developing Quality Crash Modification Factors” report (*Gross et al., 2010*).

A CMF is defined as the relative change in number of crashes due to changing one condition while there are no changes in all other conditions (*AASHTO, 2010*). If the estimated CMF is significantly less than one, this results in reduction of the expected number of crashes. As well, a CMF which is significantly greater than one indicates increasing the number of crashes. While, if a CMF is not significantly different from one, then the change has no effect on the number of crashes.

3.3.1 Before-After with Comparison Group Method

Before-after with comparison group analysis has been conducted to estimate CMFs for RCUT intersections. Before-after methods are mostly used to estimate CMFs (*Griffith, 1999; Gross et al., 2010; Inman et al., 2013*; *La Torre et al., 2017*). In order to ensure that the selection of comparison locations was appropriate, average sample odds ratio must be determined (*Hauer, 1997*). Sample odds ratios before implementation of RCUT intersections were calculated by using

Equation 3.1. Average sample odds ratio was equal to 1.277 (close to 1). This shows that there is no evidence that the frequency of crashes that occurred in the before period at RCUT locations and comparison sites were different. Equations 3.2-3.7 were used to calculate the CMF and its confidence interval (*Hauer, 1997*).

$$\mathit{Sample\ Odds\ Ratio} = \frac{\frac{Alternative_{,B} * Comparison_{,A}}{Alternative_{,A} * Comparison_{,B}}}{1+\frac{1}{Alternative_{,A}}+\frac{1}{Comparison_{,B}}} \tag{3.1}$$

Where,

$Alternative_{,B}$: total crashes for the alternative group in year i.
$Alternative_{,A}$: total crashes for the alternative group in year j.
$Comparison_{,B}$: total crashes for the comparison group in year i.
$Comparison_{,A}$: total crashes for the comparison group in year j.

$$N_{expected,A,A} = N_{observed,A,B} * \frac{N_{observed,C,A}}{N_{observed,C,B}} \tag{3.2}$$

Where,

$N_{expected,A,A}$: the expected number of crashes in the after period at the alternative group.
$N_{observed,A,B}$: the observed number of crashes in the before period at the alternative group.
$N_{observed,C,B}$: the observed number of crashes in the before period at the comparison group.
$N_{observed,C,A}$: the observed number of crashes in the after period at the comparison group.

$$Var(N_{expected,A,A}) = {N_{expected,A,\ A}}^{2}\left(\frac{1}{N_{observed,A,B}}+\frac{1}{N_{observed,C,B}}+\frac{1}{N_{observed,C,A}}\right) \tag{3.3}$$

$$CMF = \frac{\frac{N_{observed,A,A}}{N_{expected,A,A}}}{1+\frac{Var\left(N_{expected,A,A}\right)}{{N_{expected,A,A}}^{2}}} \tag{3.4}$$

Where,

$N_{observed,A,A}$: the observed number of crashes in the after period at the alternative group.

$$Var(CMF) = \frac{CMF^2\left[\left(\frac{1}{N_{observed,A,A}}\right)+\left(\frac{Var\left(N_{expected,A,\,A}\right)}{N_{expected,A,\,A}{}^2}\right)\right]}{\left[1+\left(\frac{Var\left(N_{expected,A,\,A}\right)}{N_{expected,A,\,A}{}^2}\right)\right]^2} \tag{3.5}$$

$$SE = \sqrt{Var(CMF)} \tag{3.6}$$

$$Confidence\ Interval\ of\ CMF = CMF \pm ZS * SE \tag{3.7}$$

Where,

ZS: Z score, it is equal to 2.576, 1.96, and 1.645 for 99%, 95%, and 90% confidence levels, respectively.

SE: standard error of the estimated CMF.

3.3.2 Cross-Sectional Method

SPFs including all significant explanatory variables along with DVMT and intersection type variable were developed by using generalized liner model with negative binomial distribution (Equation 3.8). Negative binomial distribution is commonly used to develop SPFs (*Abdel-Aty and Radwan, 2000*; *Lord and Bonneson, 2007*; *Fitzpatrick et al., 2008*; *Manuel et al., 2014*; *Park and Abdel-Aty, 2015*). SAS software was used to develop the SPFs. As we aim to compare between MUT and conventional intersections despite their different intersection-related areas (MUT intersections: 250 ft. buffer from the main intersection and 50 ft. buffer from each median U-turn crossover vs. conventional intersections: 250 ft. buffer from the main intersection), using AADT would lead to biased results. Thus, DVMT was chosen as the exposure variable in this study to control traffic volume more accurately. Equations 3.9 and 3.10 were used to calculate the CMF and its confidence interval.

$$N = exp\ (\beta_0 + \beta_i ln(DVMT_i) + \beta_j IT_j + \beta_k X_k + ln(Y) + \varepsilon) \tag{3.8}$$

Where,

N: predicted average crash frequency at the intersection.
β_0: the intercept.
β_i, β_j, β_k: the estimated parameters.
$DVMT_i$: total DVMT, major DVMT, and minor DVMT.
IT_j: intersection type, it could be MUT Type A, MUT Type B, or conventional (the base condition) intersection.
X_k: a set of independent variables.
Y: number of crash-years.
exp (ε): gamma-distributed error term.

$$CMF = exp\ (\beta_{MUT_i}) \tag{3.9}$$

$$Confidence\ Interval\ of\ CMF = exp\ (\beta_{MUT_i} \pm ZS * SE) \tag{3.10}$$

Where,

β_{MUTi}: the estimated parameter of MUT intersection types; Types A and B.
ZS: Z score, it is equal to 2.576, 1.96, and 1.645 for 99%, 95%, and 90% confidence levels, respectively.
SE: standard error of the estimated parameter of MUT intersection types; Types A and B.

3.4 Analysis Results

A series of CMFs were estimated for RCUT intersections for different crash types by using the before-after with the comparison group method. The results are summarized in Table 3.4. Total, fatal-and-injury, injury, and property damage only (PDO) were significantly reduced at RCUT intersections by 24%, 43%, 43%, and 16%, respectively. This indicates that RCUT intersections are effective in reducing crash severity. Angle, head-on, rear-end, and opposite-direction sideswipe crash types were also significantly reduced after the implementation of RCUT intersections by 41%, 93%, 25%, and 67%, respectively. No significant changes were found for single-vehicle and same-direction sideswipe crashes at RCUT intersections.

Table 3.4: CMFs of the RCUT intersection

Crash Type	CMF	Confidence Interval						P-Value
		99% LL	95% LL	90% LL	90% UL	95% UL	99% UL	
Total	0.7632^{***}	0.5791	0.6232	0.6457	0.8808	0.9033	0.9473	0.0009
Fatal-and-Injury	0.5669^{***}	0.3076	0.3696	0.4013	0.7325	0.7642	0.8262	< 0.0001
Injury	0.5726^{***}	0.3095	0.3724	0.4045	0.7406	0.7727	0.8356	< 0.0001
PDO	0.8414^{*}	0.6032	0.6602	0.6893	0.9935	1.0226	1.0796	0.0863
Single-Vehicle	1.3079	0.3001	0.5411	0.6643	1.9515	2.0748	2.3158	0.4313
Angle	0.5854^{***}	0.2322	0.3167	0.3599	0.8109	0.8540	0.9385	0.0025
Head-On	0.0667^{***}	-0.0263	-0.0041	0.0073	0.1261	0.1374	0.1597	< 0.0001
Rear-End	0.7511^{**}	0.4848	0.5485	0.5810	0.9212	0.9538	1.0175	0.0161
SD Sideswipe	0.9291	0.3028	0.4525	0.5291	1.3290	1.4056	1.5553	0.7704
OD Sideswipe	0.3299^{***}	-0.1595	-0.0424	0.0174	0.6424	0.7022	0.8193	0.0004

Note: CMF: crash modification factor, RCUT: restricted crossing U-turn intersection, LL: lower limit, UL: upper limit, PDO: property damage only, SD: same direction, OD: opposite direction, ***: significant at 99% confidence level, **: significant at 95% confidence level, *: significant at 90% confidence level.

Table 3.5 summarizes the developed SPFs of MUT intersections. For total, fatal-and-injury, injury, and PDO crashes, the following variables have positive effects: log (major DVMT), log (minor DVMT), major speed limit, minor speed limit, and minor through lanes. This indicates that speed limit and number of lanes could increase crash severity. IRI is significant and has a positive coefficient for fatal-and-injury and injury SPFs, which implies that rough pavement could increase fatal and injury crashes. For those crash types, the coefficients for MUT types A and B were found significant and they are negative.

For single-vehicle crashes, neither log (major DVMT) nor log (total DVMT) is significant, only log (minor DVMT) is significant. Beside the exposure variable, minor speed limit and minor through lanes have significant and positive coefficients. The coefficients for MUT Types A and B were found significant and they are positive. About angle crashes, log (major DVMT), log (minor DVMT), and minor through lanes were found significant and the coefficients are positive. MUT coefficients are significant and negative.

Regarding head-on crashes, log (total DVMT) and minor through lanes are significant and have positive coefficients, while MUT coefficients were significant and negative. Concerning head-on left-turn crashes, log (total DVMT), major left-turn lanes, and minor left-turn lanes were found significant, and their coefficients are positive. MUT coefficients are significant and negative.

For rear-end crashes, both exposure variables, log (major DVMT), and log (minor DVMT), were significant. In addition, major speed limit, minor speed limit, and minor through lanes are significant and they have positive coefficients. The MUT coefficients are significant and negative. For rear-end left-turn crashes, both exposure variables log (major DVMT) and log (minor DVMT) are significant. Major speed limit and minor through lanes variables were found significant and they have positive coefficients. The MUT coefficients are significant and negative.

Both rear-end right-turn and same-direction sideswipe crashes have insignificant coefficients for MUT intersections, which implies that there is no significant difference in number of these crash types between MUT and conventional intersections. For opposite-direction sideswipe crashes, log (total DVMT) and minor through lanes were found significant and have positive coefficients. The MUT coefficients were significant and negative. For the abovementioned crash types, speed limits and number of lanes are significantly positive. This indicates that speed limit and number of lanes at the intersection could increase these crash types.

Table 3.5: SPFs for MUT intersections

Variable	Total		Fatal-and-Injury		Injury		PDO		Single-Vehicle		Angle		Head-On	
	EP	SE	EP	SE	EP	SE	EP	SE	EP	SE	EP	SE	EP	SE
Intercept	-3.3366***	0.6387	-2.8855***	0.7338	-2.9741***	0.7326	-4.1196***	0.6761	-0.2145	0.3828	-2.1805**	0.9398	-5.8488**	2.5874
Log (Major DVMT)	0.6733***	0.0943	0.4755***	0.1059	0.4890***	0.1057	0.7221***	0.0998	-	-	0.3682***	0.1298	-	-
Log (Minor DVMT)	0.3069***	0.0362	0.2036***	0.0423	0.2014***	0.0422	0.3343***	0.0388	0.1361**	0.0607	0.3920***	0.0539	-	-
Log (Total DVMT)	-	-	-	-	-	-	-	-	-	-	-	-	0.5990*	0.3105
Major Speed Limit	0.0102*	0.0058	0.0113*	0.0065	0.0113*	0.0065	0.0106**	0.0062	-	-	-	-	-	-
Minor Speed Limit	0.0157***	0.0048	0.0148***	0.0051	0.0147***	0.0051	0.0156***	0.0051	0.0133**	0.0066	-	-	-	-
IRI	-	-	0.0004**	0.0002	0.0004**	0.0002	-	-	-	-	-	-	-	-
Minor Through Lanes	0.0588***	0.0218	0.0603**	0.0238	0.0614***	0.0237	0.0593**	0.0233	0.0650*	0.0354	0.0686**	0.0320	0.2571***	0.0669
MUT Type A	-0.4573***	0.0845	-0.2572***	0.0939	-0.2813***	0.0939	-0.5135***	0.0897	0.3221**	0.1601	-0.3805***	0.1235	-1.3631***	0.2809
MUT Type B	-0.4296***	0.1027	-0.3320***	0.1134	-0.3525***	0.1134	-0.4627***	0.1092	0.3679**	0.1634	-0.4930***	0.1492	-1.0960***	0.3422
Over-Dispersion	0.1178	0.0119	0.1093	0.0138	0.1082	0.0138	0.1305	0.0133	0.1331	0.0311	0.2281	0.0255	0.1647	0.1302

Variable	Head-On LT		Rear-End		Rear-End LT		Rear-End RT		SD Sideswipe		OD Sideswipe		Non-Motorized	
	EP	SE	EP	SE	EP	SE	EP	SE	EP	SE	EP	SE	EP	SE
Intercept	-9.6125***	2.2068	-6.8347***	0.7824	-11.1325***	2.3732	-7.7568***	2.1296	-5.1708***	0.9134	-6.9211***	2.0805	-1.4222	2.3965
Log (Major DVMT)	-	-	1.0542***	0.1131	0.7249**	0.3166	-	-	0.5264***	0.1280	-	-	-	-
Log (Minor DVMT)	-	-	0.2577***	0.0427	0.5547***	0.1386	-	-	0.4441***	0.0545	-	-	-	-
Log (Total DVMT)	1.2654***	0.2589	-	-	-	-	0.7733***	0.2609	-	-	0.8525***	0.2503	-0.0028	0.2438
Major Speed Limit	-	-	0.0124*	0.0069	0.0466***	0.0158	0.0332**	0.0134	-	-	-	-	-	-
Minor Speed Limit	-	-	0.0200***	0.0058	-	-	-	-	-	-	-	-	-	-
Pedestrian Crossing	-	-	-	-	-	-	-	-	-	-	-	-	1.8748*	1.1205
Major Left-Turn Lanes	0.3164**	0.1559	-	-	-	-	-	-	-	-	-	-	-	-
Minor Left-Turn Lanes	0.2485*	0.1376	-	-	-	-	-	-	0.2485***	0.0639	-	-	-	-
Minor Right-Turn Lanes	-	-	-	-	-	-	0.2306***	0.0738	0.1314***	0.0387	-	-	-	-
Major Through Lanes	-	-	-	-	-	-	-	-	0.0966***	0.0315	-	-	-	-
Minor Through Lanes	-	-	0.0488*	0.0263	0.1652***	0.0638	-	-	0.0611**	0.0295	0.1182**	0.0523	-	-
MUT Type A	-1.7609***	0.4360	-0.6428***	0.1006	-0.9310***	0.2892	-0.0660	0.1760	-0.0883	0.1888	-1.5291***	0.2183	0.8079***	0.1865
MUT Type B	-1.7214***	0.5045	-0.6620***	0.1240	-0.9315***	0.3480	0.2100	0.2357	0.1236	0.1877	-2.0641***	0.3848	0.6717***	0.2414
Over-Dispersion	0.6341	0.0847	0.1599	0.0169	0.3391	0.1053	0.2984	0.0844	0.1746	0.0228	0.0925	0.0786	0.4746	0.1020

Note: SPFs: safety performance functions, MUT: median U-turn intersection, EP: estimated parameter, SE: standard error of the estimated parameter, PDO: property damage only, SD: same direction, OD: opposite direction, LT: left-turn, RT: right-turn, DVMT: daily vehicle miles traveled, IRI: international roughness index, ***: significant at 99% confidence level, **: significant at 95% confidence level, *: significant at 90% confidence level.

Lastly, the non-motorized crash model has a negative coefficient for log (total DVMT) and positive for pedestrian crossing. This confirms that intensive pedestrian rates at the intersection increase non-motorized crashes. The MUT coefficients were found significant and positive.

By using the developed SPFs, CMFs for MUT intersections types A and B were estimated (Tables 3.6 and 3.7). MUT Type A intersections have significantly reduced total, fatal-and-injury, injury, and PDO crashes by 37%, 23%, 25%, and 40%, respectively. Angle, head-on, head-on left-turn, rear-end, rear-end left-turn, and opposite-direction sideswipe crashes were also significantly reduced at MUT Type A intersections by 32%, 74%, 83%, 47%, 61%, and 78%, respectively. On the other hand, they have significantly larger number of single-vehicle and non-motorized crashes by 38% and 124%, respectively. Similar safety effects were noticed for MUT Type B intersections despite slight differences. MUT Type B intersections have significantly reduced total, fatal-and-injury, injury, and PDO crashes by 35%, 28%, 30%, 37%, respectively. While, angle, head-on, head-on left-turn, rear-end, rear-end left-turn, and opposite-direction sideswipe crashes were significantly reduced by 39%, 67%, 82%, 48%, 61%, and 87%, respectively. Otherwise, MUT Type B intersections have significantly increased single-vehicle and non-motorized crashes by 44% and 96%, respectively.

No significant change was recorded for rear-end right-turn and same-direction sideswipe crash types at MUT intersections. Figures 3.6 and 3.7 show percentages of change for each crash severity and type at RCUT and MUT intersections.

Table 3.6: CMFs of MUT type A intersections

Crash Type	**CMF**	**Confidence Interval**					
		99% LL	**95% LL**	**90% LL**	**90% UL**	**95% UL**	**99% UL**
Total	0.6330***	0.5092	0.5364	0.5508	0.7274	0.7470	0.7869
Fatal-and-Injury	0.7732***	0.6069	0.6432	0.6625	0.9024	0.9295	0.9852
Injury	0.7548***	0.5927	0.6279	0.6468	0.8809	0.9073	0.9613
PDO	0.5984***	0.4750	0.5019	0.5163	0.6935	0.7134	0.7539
Single-Vehicle	1.3800**	0.9138	1.0083	1.0605	1.7958	1.8887	2.0841
Angle	0.6835***	0.4973	0.5366	0.5579	0.8375	0.8707	0.9394
Head-On	0.2559***	0.1241	0.1475	0.1612	0.4062	0.4437	0.5274
Head-On Left-Turn	0.1719***	0.0559	0.0731	0.0839	0.3522	0.4040	0.5282
Rear-End	0.5258***	0.4058	0.4317	0.4456	0.6204	0.6404	0.6813
Rear-End Left-Turn	0.3942***	0.1872	0.2236	0.2449	0.6343	0.6948	0.8300
Rear-End Right-Turn	0.9361	0.5950	0.6630	0.7008	1.2505	1.3218	1.4729
SD Sideswipe	0.9155	0.5630	0.6323	0.6711	1.2489	1.3254	1.4886
OD Sideswipe	0.2167***	0.1235	0.1413	0.1513	0.3104	0.3325	0.3802
Non-Motorized	2.2432***	1.3877	1.5564	1.6505	3.0486	3.2331	3.6260

Note: CMF: crash modification factor, MUT: median U-turn intersection, LL: lower limit, UL: upper limit, PDO: property damage only, SD: same direction, OD: opposite direction, ***: significant at 99% confidence level, **: significant at 95% confidence level, *: significant at 90% confidence level.

Table 3.7: CMFs of MUT type B intersections

Crash Type	**CMF**	**Confidence Interval**					
		99% LL	**95% LL**	**90% LL**	**90% UL**	**95% UL**	**99% UL**
Total	0.6508***	0.4995	0.5321	0.5496	0.7705	0.7959	0.8478
Fatal-and-Injury	0.7175***	0.5355	0.5745	0.5954	0.8646	0.8961	0.9613
Injury	0.7029***	0.5249	0.5628	0.5833	0.8471	0.8779	0.9413
PDO	0.6296***	0.4753	0.5083	0.5261	0.7535	0.7798	0.8340
Single-Vehicle	1.4447**	0.9485	1.0488	1.1042	1.8902	1.9901	2.2004
Angle	0.6108***	0.4160	0.4559	0.4779	0.7807	0.8183	0.8969
Head-On	0.3342***	0.1385	0.1709	0.1903	0.5868	0.6536	0.8067
Head-On Left-Turn	0.1788***	0.0488	0.0665	0.0780	0.4100	0.4807	0.6555
Rear-End	0.5158***	0.3748	0.4045	0.4206	0.6325	0.6577	0.7099
Rear-End Left-Turn	0.3940***	0.1608	0.1992	0.2222	0.6983	0.7793	0.9652
Rear-End Right-Turn	1.2337	0.6724	0.7773	0.8372	1.8180	1.9581	2.2635
SD Sideswipe	1.1316	0.6979	0.7833	0.8310	1.5409	1.6348	1.8348
OD Sideswipe	0.1269***	0.0471	0.0597	0.0674	0.2390	0.2698	0.3419
Non-Motorized	1.9576***	1.0514	1.2196	1.3160	2.9119	3.1420	3.6448

Note: CMF: crash modification factor, MUT: median U-turn intersection, LL: lower limit, UL: upper limit, PDO: property damage only, SD: same direction, OD: opposite direction, ***: significant at 99% confidence level, **: significant at 95% confidence level, *: significant at 90% confidence level.

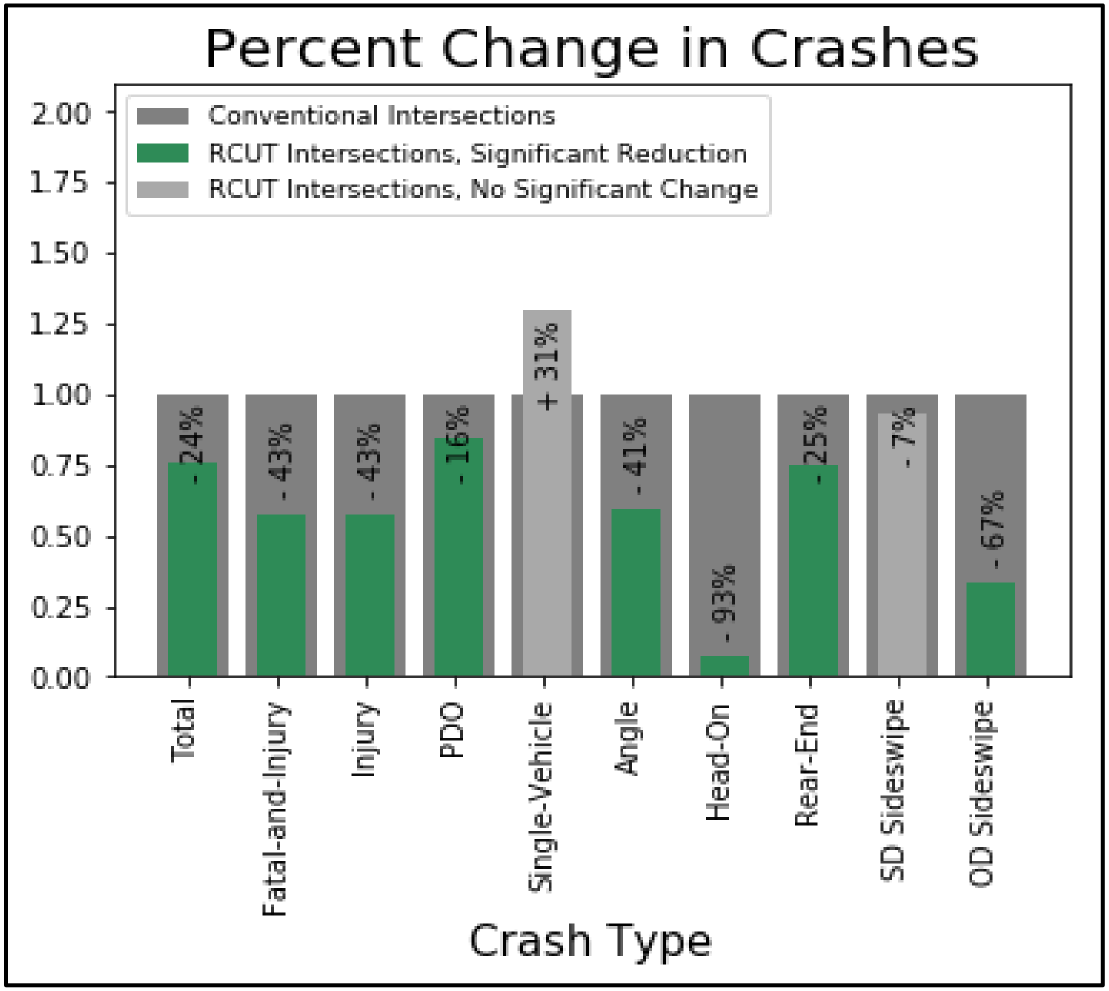


Figure 3.6: Percent change in crashes at RCUT intersections

Note: RCUT: restricted crossing U-turn intersection, PDO: property damage only, SD: same direction, OD: opposite direction.

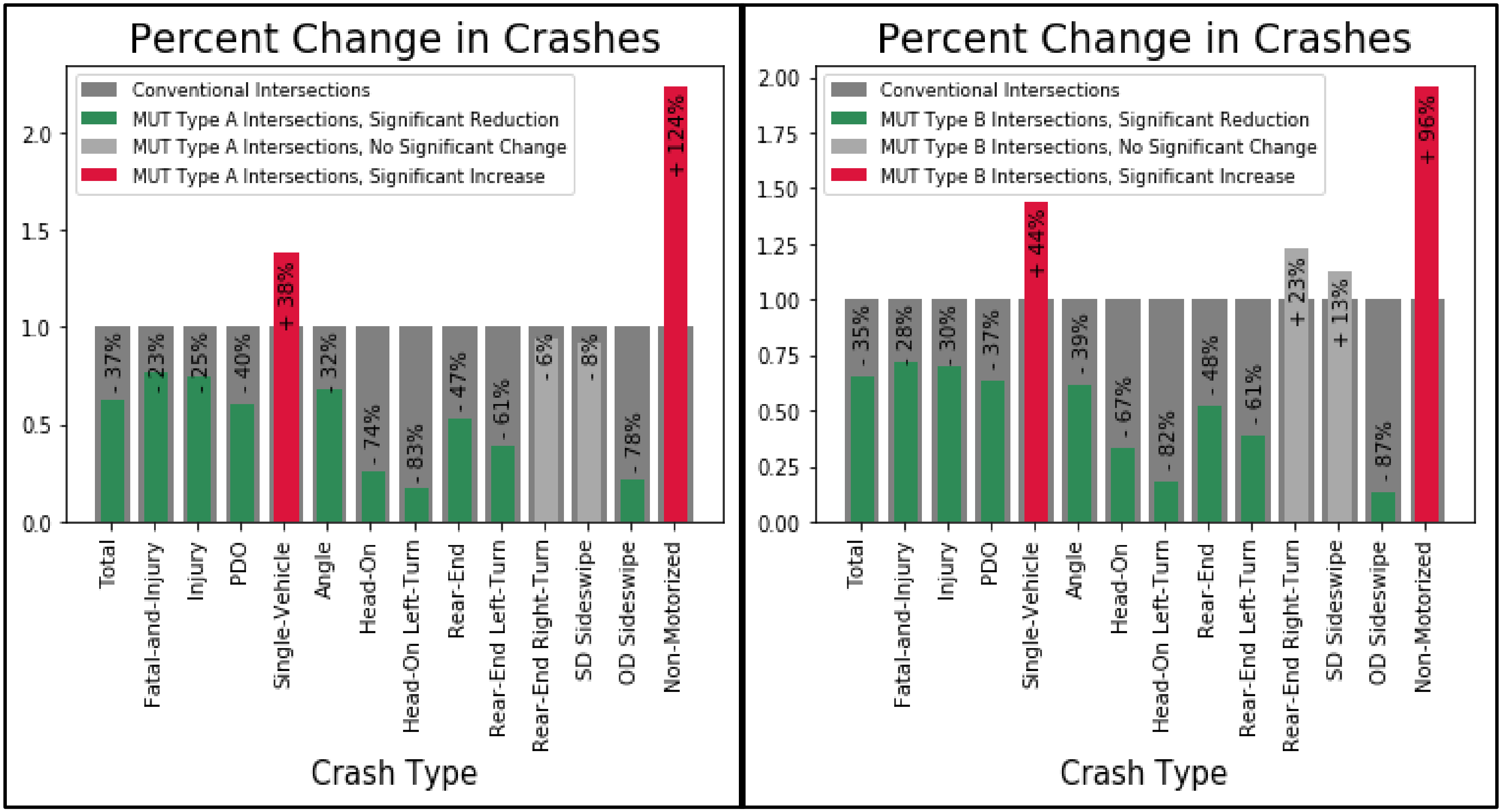


Figure 3.7: Percent change in crashes at MUT type A and type B intersections

Note: MUT: median U-turn intersection, PDO: property damage only, SD: same direction, OD: opposite direction.

3.5 Discussion of Results

MUT and RCUT intersections have similar geometric designs and traffic movement patterns to some extent. Therefore, the safety effect of implementing them is somewhat analogous. MUT and RCUT intersections have been safer than conventional intersections in terms of reducing total, fatal-and injury, injury, PDO, and multi-vehicle crashes. MUT types A and B intersections are more effective than RCUT intersections in reducing total, PDO, rear-end, and opposite direction sideswipe crashes. In contrast, they significantly increase single-vehicle and non-motorized crashes. RCUT intersections showed higher effectiveness in reducing fatal-and-injury, injury, head-on, and angle crashes.

The findings of this study are in line with what was found in the previous studies that the implementation of MUT and RCUT intersections has a significant effect in reducing most crash types. The effectiveness of MUT and RCUT intersections in crash reduction come from prohibition of left-turn movements at the main intersection with the resulted low number of conflict points between the movements at these intersections compared to conventional ones.

On the other hand, it was noticed that single-vehicle crashes and crashes involving non-motorized users are increased at MUT intersections. This could be due to the existence of two signals for through traffic from minor road at some MUT main intersections. This could confuse pedestrians and bicyclists at these intersections. Another reason that could give illustration about increasing single-vehicle and non-motorized crashes at MUT intersections is consideration of median U-turn crossovers as intersection-related areas and inclusion crashes that occurred at them in the analysis. At median U-turn crossovers, the probability of hitting bicyclists or any fixed object could be increased. Also, the presence of signals at median U-turn crossovers could encourage pedestrian and bicyclists to cross the road at them where there are no pedestrian crosswalks.

To improve the safety effectiveness of MUT intersections, there is a need to enhance road users' knowledge and awareness regarding MUT intersections. This is to minimize their negative effect on single-vehicle and non-motorized crashes. Along with that, implementing some countermeasures could be useful. Widening the road near MUT intersections' crossovers (implementing loons) may contribute to reducing single-vehicle crashes. Regulatory and warning signs could be used at MUT intersections to help pedestrians and bicyclists during crossing these types of intersections.

3.6 Conclusions and Recommendations

MUT and RCUT intersections have similar effect in crash reduction. They are safer than conventional intersections due to their effectiveness in reducing most crash types especially left-turn crashes. Head-on left-turn crashes are the most reduced type at MUT intersections by more than 80%. On the other hand, single-vehicle and non-motorized crashes are significantly increased at MUT intersections. MUT intersections are more effective than RCUT intersections in reducing total, PDO, rear-end, and opposite direction sideswipe crashes. While RCUT intersections are more effective in reducing fatal-and-injury, injury, head-on, and angle crashes.

Based on the safety effectiveness of MUT and RCUT intersections, they are recommended for implementation due to their efficiency in crash reduction. MUT intersections (both type A and B) are recommended for implementation to reduce head-on left-turn crashes because they can reduce that most severe crash type by more than 80%. Also, they can reduce rear-end crashes by up to 48%. While RCUT intersections are recommended for implementation if head-on or left-turn (angle) crashes that are the most problematic crash type at the intersection. It can reduce them by 93% and 41%, respectively. Also, RCUT intersection is more recommended for implementation than MUT intersection due to its higher ability to reduce crash severity (i.e., equivalent property damage only value) at the intersection.

Along with enhanced road users' knowledge and awareness, implementing loons near MUT intersections' crossovers and using regulatory and warning signs could be useful in reducing single-vehicle and non-motorized crashes at MUT intersections. Evaluation of the suggested countermeasures at MUT intersections for reducing their negative effect on single vehicle and non-motorized crashes is recommended future research. It is expected that the findings of this study would be useful and helpful for decision makers concerning the conversion from conventional intersections to MUT and RCUT intersections.

CHAPTER 4: PROPOSITION OF A NEW INTERSECTION DESIGN AND EVALUATION OF ITS OPERATIONAL EFFECTIVENESS [2]

4.1 Introduction

Unconventional intersection designs have been proposed to simultaneously improve traffic safety and operation. However, few unconventional intersection designs have achieved the desired purpose. Some of unconventional intersection designs have better operational performance than the safety performance, while the opposite is the case for some others. Most of unconventional intersections have been developed to improve traffic safety and operation at arterials such as the restricted crossing U-turn (RCUT) intersection.

Studies that evaluated the performance of unconventional intersections proved the assumption that the traffic safety at the intersection is improved by reducing the number of conflict points. The RCUT intersection has the least number of conflict points (14 conflict points) among other unconventional intersections (*Hummer et al., 2014*). For this reason, several studies have found that its implementation reduces crash counts and its severity (*Kim et al., 2007; Hummer and Jagannathan, 2008; Hochstein at al., 2009; Inman and Haas, 2012; Inman et al., 2013; Edara et al., 2013; Edara et al., 2015; Hummer and Rao, 2017; Sun et al., 2019*). Punctiliously, it was found in chapter 3 that total, fatal-and-injury, injury, property damage only (PDO), angle, head-on, rear-end, and opposite-direction sideswipe crashes have been significantly reduced at RCUT intersections by 24%, 43%, 43%, 16%, 41%, 93%, 25%, and 67%, respectively.

---

[2] This chapter has been published in Transportation Research Record: Journal of the Transportation Research Board (*Al-Omari and Abdel-Aty, 2021*)

On the other hand, *Hughes et al.* (*2010*) indicated that the optimum operational performance of the RCUT intersection is subject to the ratio between the minor road and the intersection volumes. They found that the RCUT intersection experienced a higher throughput and less travel time than the conventional intersection only at ratios less than 0.2 and 0.15, respectively. Bared (*2009*) found that the RCUT intersection with a low minor road traffic volume level (less than 20% of the total entering vehicles (TEV) to the intersection) has a 30% higher capacity and 40% lower network travel time than the signalized conventional intersection. *Kivlins and Naudzuns* (*2011*) confirmed that RCUT intersections perform better at major heavy-traffic arterial and minor light-traffic road.

In this chapter, we propose a new unconventional intersection design which was given the name "Shifting Movements" (SM) intersection as an alternative to the 4-leg conventional intersection. The SM intersection design has an expected safety and operational benefits since it has only 14 conflict points and provides for two-phase signalization. Moreover, it is expected to perform better than the RCUT intersection design at high minor road traffic volumes. Evaluation of the expected operational benefits of the SM intersection design has been conducted in this study in the microscopic simulation environment. PTV Vissim software is commonly used for the microscopic simulation of unconventional intersections (*Kivlins and Naudzuns, 2011*; *El Esawey, and Sayed, 2011; Haley et al., 2011; Holzem et al., 2015; Hashim et al., 2017*), while Synchro software is mainly used for signal timing optimization (*Hughes at al., 2010; Taha and Abdelfatah, 2015*). Therefore, PTV Vissim software has been employed to simulate RCUT and SM intersection designs along with the conventional 4-leg intersection, while Synchro software has been utilized for the optimization of signal timing.

4.2 Shifting Movements Intersection

4.2.1 Intersection Geometry

Similar to all other unconventional intersections, traffic movement patterns have been rerouted at the SM intersection which resulted in three sub intersections: the central area, the upstream intersection, and the downstream intersection. Figure 4.1 shows our proposed SM intersection scheme along with the RCUT intersection design.

Every stop bar indicates a signal location. Traffic movement patterns at the SM intersection are somehow like those at the RCUT intersection besides two main differences. 1) Left-turn traffic from the major road at the SM intersection is combined with minor road traffic. 2) Major left-turn and minor road traffic moves side by side along the major road downstream of the central area to reach the downstream intersection where it accesses the major road.

Right-turn and through movements from the major road are done as usual. While the major left-turn movement is combined with minor traffic at the central area, then it is completed by turning right at the central area after turning left at the downstream intersection. All traffic from the minor road turn right and move beside the major road reaching to the downstream intersection. Minor right-turn movement is done by turning right, while minor through and left-turn movements are done by turning left at the downstream intersection. Then by turning right at the central area, the through movement is done. Figure 4.2 illustrates traffic movement patterns at the SM intersection design.

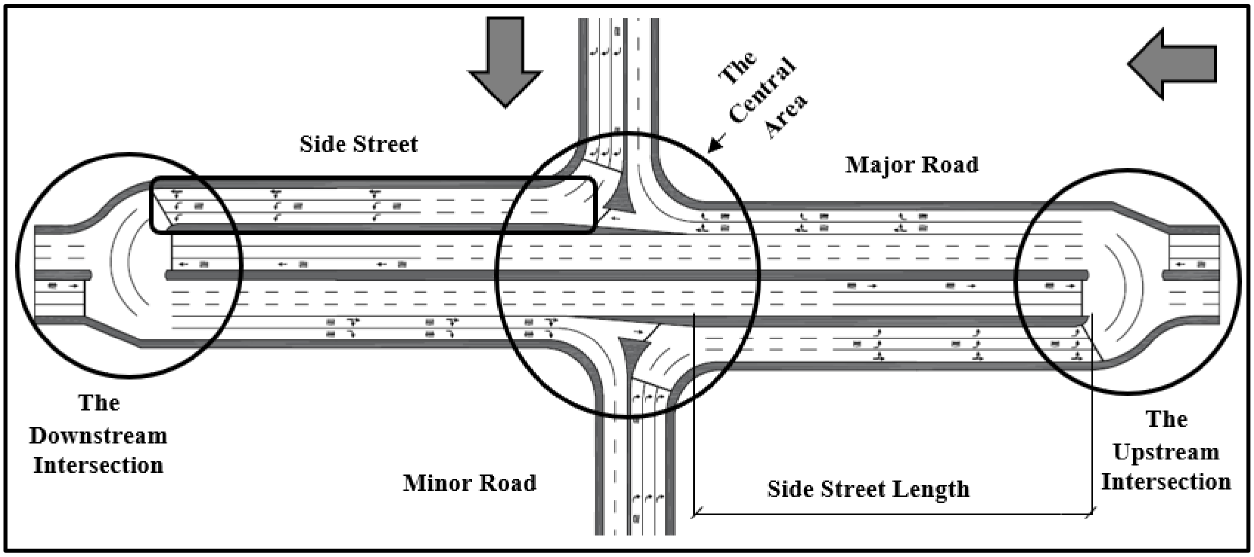


Figure 4.1: The SM intersection

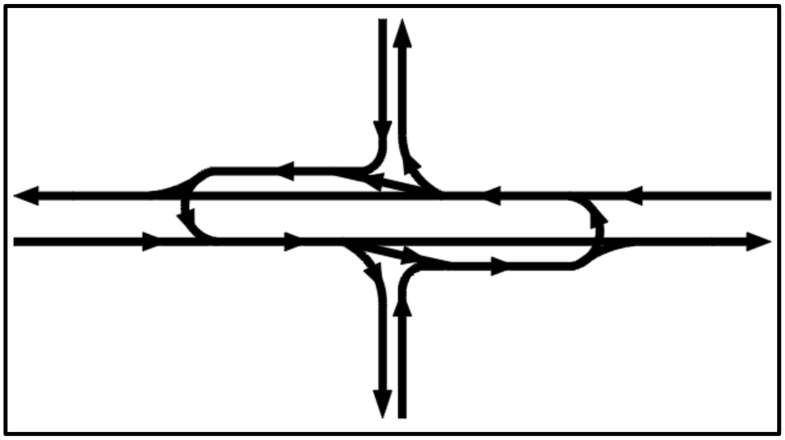


Figure 4.2: Traffic movement patterns at the SM intersection

Access management must be considered in the design and implementation of unconventional intersections because of the presence of unusual traffic movement patterns at these intersection types. To attain this at the SM intersection design, driveways must be eliminated in the area between the upstream and downstream intersections. In addition, the major road and the side street must be physically separated to prevent direct access to the major road in the central area.

4.2.2 Conflict Points

As a result of the reconfiguration of traffic movement patterns at the SM intersection, traffic conflict points have been significantly reduced from 32 conflict points at the conventional intersection to 14 conflict points: 6 diverging points, 6 merging points, and only 2 crossing points. Figure 4.3 shows these conflict points.

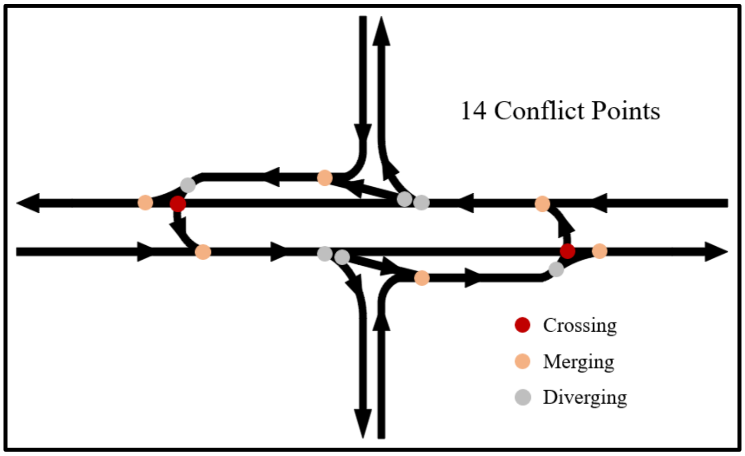


Figure 4.3: Conflict points at the SM intersection

4.2.3 Signalization

The SM intersection can be operated with a two-phase signalization at all the SM intersection's signals (at the central area and upstream and downstream intersections), achieving a two-phase signalization at the whole intersection. The first phase is for major road traffic while the second phase is mainly for minor road traffic. Figure 4.4 illustrates the traffic movements' sequence of each phase. During the first phase, major road traffic starts leaving the upstream intersection heading to the central area where the right-turn movement is completed and left-turn traffic accesses the side road where it is stored for the second phase. Through traffic overrides the central area heading to the downstream intersection. Within the second phase, minor road traffic in the central area starts accessing the side road. Right-turn movement is done at the downstream intersection. Minor through, minor left-turn, and major left-turn movements access the major road by turning left at the downstream intersection. By turning right at the central area, minor through and major left-turn movements are completed. While minor left-turn traffic continues straight to stay on the major road.

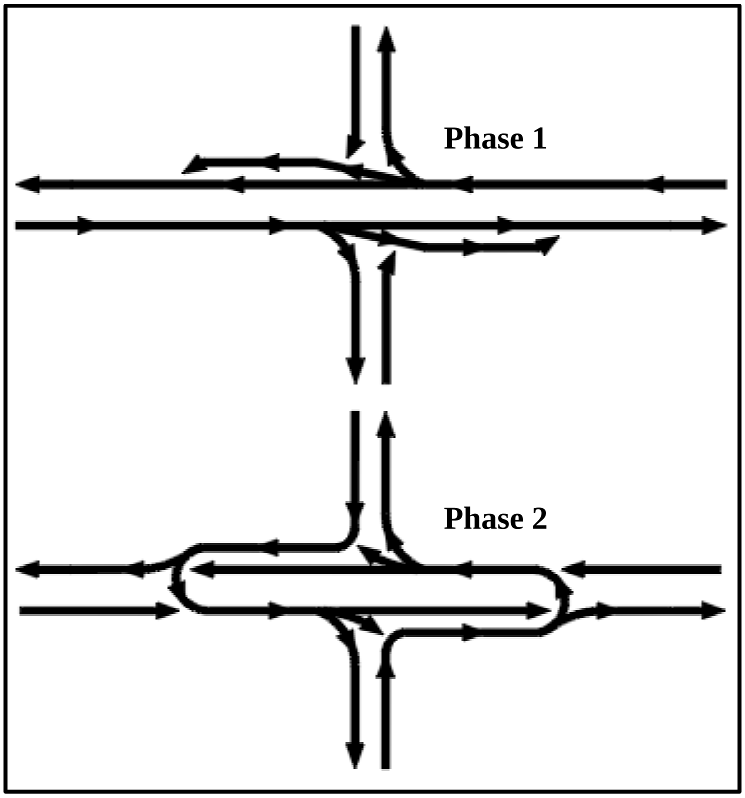


Figure 4.4: SM intersection’s signal phases and movement sequences

4.2.4 Expected Safety and Operational Benefits

Like other unconventional intersections, reducing the number of signal-phases from four (at the conventional intersection) to two phases at the SM intersection design would reduce the average control delay at the intersection. Unlike the RCUT intersections, the SM intersection design is expected to have a notable operational performance when arterial intersects with a minor arterial with moderate to high traffic volume. This is because of reducing the number of stops at the SM intersection. At the RCUT intersection, minor through and left-turn traffic might stop at three signals because it must pass through a median U-turn crossover. Whereas at the SM intersection, minor and major left-turn traffic is subjected to only two potential stops. Only minor left-turn traffic could have additional stop. Moreover, median U-turn crossovers is not adequate for heavy traffic, especially for large vehicles. While providing a side road at the SM intersection to store minor traffic is more adequate for heavy traffic and large vehicles. This guarantee providing a continuous movement on the major road without any potential bottlenecks.

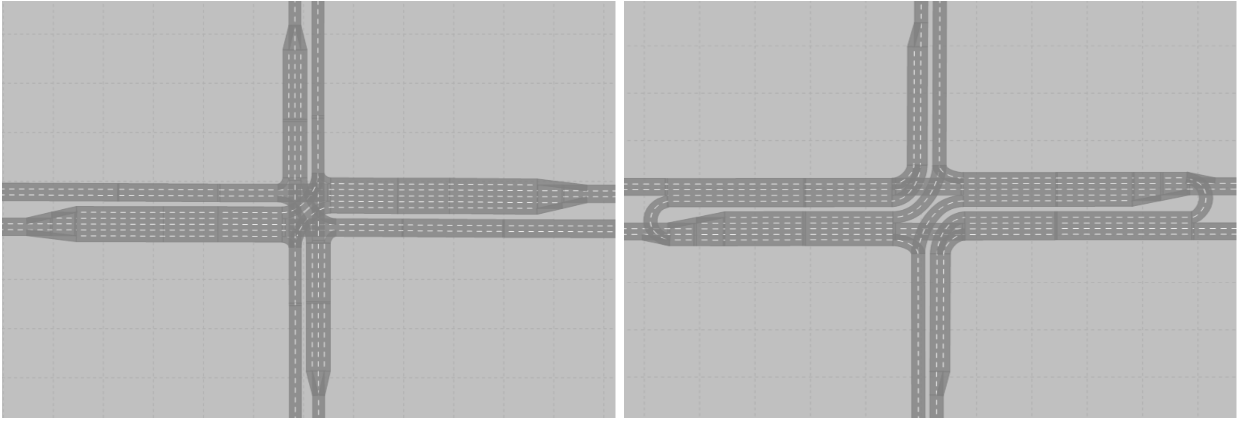
Similar to the RCUT intersections, achieving safety benefits is expected by the implementation of the SM intersection since it only has 14 conflict points. Moreover, accessing the major road from the side road provides a more convenient and safe traffic operation than using median U-turn crossovers.

4.3 Experiment Design

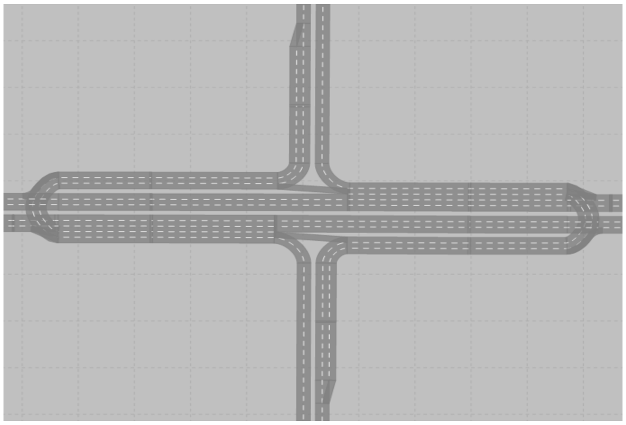
Since pedestrian and bicyclist activities are very limited at arterials and to simplify the comparison, only motorized road users have been considered in this study. Average control delay and throughput have been considered as measures of the effectiveness of the operational performance of the intersection as recommended by the Highway Capacity Manual (HCM) (*2010*). Operational performance is affected by several conditions such as lane configuration, geometric features, traffic volume levels, and signal timing plans. To conduct a fair comparison, lane configuration, geometric features, and traffic volume levels variables were kept compatible for all intersection designs (i.e. conventional, RCUT, and SM intersections). While signal timing plans have been optimized for every intersection design and traffic volume condition to get the optimum operational performance. Average control delay for every movement was calculated by comparing the travel time for every movement at conventional, RCUT, and SM intersections with the free-flow travel time at the conventional intersection with green-light signals. The throughput for every movement was directly obtained from the PTV Vissim outputs. Weighted average delay and throughput have been calculated for intersection, road, and movement levels. The T-test has been employed to determine significant differences at a 95% confidence level between the different values of average delays and throughputs for the three intersection designs at every traffic volume condition.

4.3.1 Lane Configurations

Since most of unconventional intersections aim to improve the traffic operation at arterials, it was assumed that all intersection designs have four approaches and are located where a six-lane road intersects with a four-lane road. The major road has a 400 feet exclusive right-turn lane, while its length is 250 feet at the minor road at all intersection designs. Two 400 feet exclusive left-turn lanes are provided at the major road at conventional and RCUT intersections, while 250 feet exclusive left-turn lane is provided at the minor road at the conventional intersection. Two 400 feet U-turn lanes are provided upstream of the median U-turn crossovers of the RCUT intersection. One 400 feet lane is provided for right-turn and left-turn movements at the major road of SM intersection design, while the side street at the SM intersection has three 400 feet lanes. Figure 4.5 shows the Vissim models of conventional, RCUT, and SM intersections.



(Conventional) (RCUT)



(SM)

Figure 4.5: Vissim models of conventional, RCUT, and SM intersections

Note: RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection.

4.3.2 Geometric Features

The key in RCUT and SM intersection designs is providing the optimum spacing between the main intersection and median U-turn crossovers at the RCUT intersection and between the central area and the upstream/downstream intersection at the SM intersection. Enough spacing is needed to provide a smooth weaving process. Moreover, enough length for the U-turn lanes at the RCUT intersection and for the side street at the SM design is needed for vehicle storage. In contrast, long spacing increases the travel time. For that, 400-600 feet spacing is recommended for signalized crossovers (*AASHTO, 2004*) and 425 feet spacing is specifically recommended for RCUT crossovers (*Hughes at al., 2010*). Therefore, 400 feet length has been selected for the side street at the SM intersection to be compatible with the RCUT intersection design for the operational performance comparison. However, 500 feet length has been also tested and compared with the 400 feet length of the SM intersection’s side street.

4.3.3 Traffic Volume

To represent realistic field conditions where an arterial intersects with a minor arterial or collector, unbalanced traffic volumes (60% of the intersection volume is from the major road while 40% is from the minor road) have been assumed. Five thousand to 8500 v/h intersection volume (TEV) have been assumed to represent the peak hour. Three left-turn proportions have been assumed (10%, 15%, and 20% from the major/minor approach volume) to evaluate intersections’ performance under moderate to heavy left-turn traffic (*Bared and Kaisar, 2002*). Ten percent of the approach volume was set as the right-turn proportion in this evaluation.

4.3.4 Signal Plans

Due to the differences in traffic movement patterns and the number of signal phases between conventional, RCUT, and SM intersections, signal timing must be optimized to get their best performance. Synchro software was used to optimize the cycle length and determine green times of conventional, RCUT, and SM intersections’ signals. Indirect procedure has been conducted to optimize the cycle length and determine green times of the SM intersection’s signals because of three main reasons: 1) the long distance between the upstream and the downstream intersections of the SM intersection that should be considered to get a continuous flow at the arterial (i.e. major through traffic must only stop one time, at the upstream intersection or at the downstream intersection), 2) signals at the central area and the upstream/downstream intersection must be coordinated to avoid any bottlenecks on the major road at the central area, and 3) simulation of left-turn signals at the central area is not applicable since they do not have space to store vehicles.

Signals at the upstream and downstream intersections have been optimized by ignoring traffic in the central area. The travel time that vehicles at the central area and the upstream intersection need to reach the downstream intersection has been added to the cycle length and green times. Eight-seconds offset should be provided between signals at the central area and the upstream/downstream intersection to prevent the accumulation of the major left-turn traffic at the central area. However, ten seconds is recommended for the SM intersection with 500-feet side street. Three-second amber time and two-second red time have been utilized for all signals except at SM upstream and downstream intersections where three-second red time has been used to assure clearing the intersection. Right-turn on red was only allowed at the conventional intersection.

4.3.5 Simulation Models

PTV Vissim software has been employed to simulate intersection designs under the above-mentioned conditions. Sixty-three scenarios have been simulated in this study. Vehicles composition with 2% large vehicles has been used. Fifty mph and 40 mph speeds have been set as the travel speeds at the major and minor roads, respectively. Travel time detectors have been put at a far distance upstream and downstream of intersections where vehicles move without any influence from the intersection in normal conditions. Average control delay and throughput of ten runs for every scenario have been used for the comparison of the simulation results. The first 15-minutes period was considered as a seeding period (results were not recorded in this period), while 75 minutes was the total simulation time. Therefore, the results are based on one-hour simulation.

4.4 Analysis Results

Travel time and throughput of the intersection’s movements have been directly obtained from the PTV Vissim outputs. Average control delay and throughput have been calculated for conventional, RCUT, and SM intersections at three levels of analysis: intersection, road, and movement levels. Tables 4.1 and 4.2 and Figures 4.6, 4.7, 4.8 and 4.9 show average control delays and throughputs of intersection, road, and movement levels with the different left-turn proportions.

The results indicated that the conventional intersection has the lowest average intersection delay as long as the TEV to the intersection is around or below 7400, 7000, and 6625 vehicles with 10%, 15%, and 20% left-turn proportions, respectively. At volumes below these traffic volume levels, average intersection delays at the SM intersection with 10% left-turn proportion are less than the RCUT intersection average delay values, while the RCUT intersection outperforms the SM intersection at high left-turn traffic (20%). On the other hand, higher than the aforementioned TEV levels, the SM intersection significantly outperforms both conventional and RCUT intersections in terms of average intersection delay at the three left-turn proportions. In contrast, the RCUT intersection has higher average intersection delay than the conventional intersection with 10% and 15% left-turn proportions, while it outperforms the conventional intersection with heavy left-turn traffic. Slight differences (most differences are not significant) in intersection's throughput of conventional, RCUT, and SM intersections have been recorded at the low TEV levels with all left-turn proportions. However, the SM intersection's throughput is higher than throughputs of conventional and RCUT intersections at or more than 7250, 7200, and 6250 TEV for 10%, 15%, and 20% left-turn proportions, respectively. Similar trends have been noticed for average minor road delay and throughput at conventional, RCUT, and SM intersections despite slight differences.

For average major road delay, the three intersection designs have close average delay values at or below 6700 TEV with a 10% left-turn proportion. At higher TEV levels, the RCUT intersection has the highest average delay values among both conventional and SM intersections.

Whereas the SM intersection design outperforms the conventional intersection. On the other hand, the RCUT intersection has the lowest average major road delay for all TEV levels with high left-turn proportions (15%-20%) except at 7500 TEV with 15% left-turn proportion where the SM intersection has the lowest average major road delay. The SM intersection outperforms the conventional intersection around 6500 TEV with 15% and 20% left-turn proportions. No considerable differences in major road throughput at conventional, RCUT, and SM intersections have been recorded at the different TEV levels and left-turn proportions except higher than 7500 TEV with 10% left-turn proportion where the RCUT intersection significantly serve less vehicles than SM and conventional intersections.

A similar trend of average intersection delay and throughput has been noticed for average movement delays and throughputs at the different left-turn proportions despite some differences. Average control delay increases while throughput decreases for intersection, road, and movement levels at all intersection designs whenever the proportion of left-turn traffic increases. This is expected because heavy left-turn traffic increases the cycle length at the conventional intersection, while the reason at the RCUT and SM intersection is the relatively long travel distance for this movement. In contrast, an inverse relationship has been noticed at the RCUT intersection that is subjected to heavy traffic. The reason behind this is the large number of vehicles that turn right at the main intersection.

Table 4.1: Average control delays

Analysis Level	Traffic Volume Levels		Average Control Delay (s)								
			Conventional Intersection			RCUT Intersection			SM Intersection		
			10% LT	15% LT	20% LT	10% LT	15% LT	20% LT	10% LT	15% LT	20% LT
Intersection	Total Entering Vehicles (vph)	5000	-	-	$30.7^{R,S}$	-	-	$44^{C,S}$	-	-	$54.9^{C,R}$
		5500	-	$31.8^{R,S}$	$37.3^{R,S}$	-	$45.7^{C,S}$	$47.8^{C,S}$	-	$54^{C,R}$	$57.2^{C,R}$
		6000	$34.3^{R,S}$	$37.8^{R,S}$	$42.2^{R,S}$	$50.6^{C,S}$	$50.5^{C,S}$	$51.6^{C,S}$	$52.8^{C,R}$	$56.2^{C,R}$	$59.5^{C,R}$
		6500	$39.8^{R,S}$	$44.5^{R,S}$	$50.4^{R,S}$	$57.6^{C,S}$	58.6^{C}	$60.2^{C,S}$	$55.3^{C,R}$	59^{C}	$63.2^{C,R}$
		7000	$46.5^{R,S}$	$59.9^{R,S}$	$97.9^{R,S}$	$84^{C,S}$	$72.4^{C,S}$	$75.1^{C,S}$	$59^{C,R}$	$63.2^{C,R}$	$68.8^{C,R}$
		7500	69.8^{R}	$119.3^{R,S}$	$150.9^{R,S}$	$152.8^{C,S}$	$145.1^{C,S}$	$140.6^{C,S}$	65.3^{R}	$71.1^{C,R}$	$89.1^{C,R}$
		8000	$114.7^{R,S}$	$147.2^{R,S}$	-	$217.8^{C,S}$	$186.1^{C,S}$	-	$75.4^{C,R}$	$91.4^{C,R}$	-
		8500	$149^{R,S}$	-	-	$251.3^{C,S}$	-	-	$107.8^{C,R}$	-	-
Major Road	Major Road Volume (vph)	3000	-	-	$28.8^{R,S}$	-	-	$22.4^{C,S}$	-	-	$39^{C,R}$
		3300	-	$30.1^{R,S}$	$35.1^{R,S}$	-	$24.5^{C,S}$	$24.3^{C,S}$	-	$37.3^{C,R}$	$39.2^{C,R}$
		3600	$32.2^{R,S}$	$34.4^{R,S}$	$39.4^{R,S}$	$28.9^{C,S}$	$28.2^{C,S}$	$27.8^{C,S}$	$35.6^{C,R}$	$39.3^{C,R}$	$41.9^{C,R}$
		3900	$36.1^{R,S}$	$39.4^{R,S}$	45.1^{R}	$32.9^{C,S}$	$33.7^{C,S}$	$32.1^{C,S}$	$38.1^{C,R}$	$40.6^{C,R}$	45.6^{R}
		4200	40.4^{R}	$47.6^{R,S}$	$56.1^{R,S}$	$48.2^{C,S}$	$41.4^{C,S}$	$38.8^{C,S}$	39.9^{R}	$44.3^{C,R}$	$51.7^{C,R}$
		4500	$48.2^{R,S}$	$58.8^{R,S}$	68.6^{R}	$80.8^{C,S}$	48.2^{C}	$45^{C,S}$	$43.6^{C,R}$	48.9^{C}	67.8^{R}
		4800	$55^{R,S}$	$69.9^{R,S}$	-	$110.8^{C,S}$	$96.6^{C,S}$	-	$50.4^{C,R}$	$63^{C,R}$	-
		5100	$80.4^{R,S}$	-	-	$160.1^{C,S}$	-	-	$73.3^{C,R}$	-	-
Minor Road	Minor Road Volume (vph)	2000	-	-	$33.6^{R,S}$	-	-	$76.5^{C,S}$	-	-	$78.8^{C,R}$
		2200	-	$34.4^{R,S}$	$40.6^{R,S}$	-	$77.4^{C,S}$	83^{C}	-	$79^{C,R}$	84.3^{C}
		2400	$37.4^{R,S}$	$43^{R,S}$	$46.4^{R,S}$	$83.2^{C,S}$	$84.1^{C,S}$	87.4^{C}	$78.6^{C,R}$	$81.5^{C,R}$	86^{C}
		2600	$45.4^{R,S}$	$52.3^{R,S}$	$58.5^{R,S}$	$94.6^{C,S}$	$95.9^{C,S}$	$102.5^{C,S}$	$81.2^{C,R}$	$86.5^{C,R}$	$89.6^{C,R}$
		2800	$55.7^{R,S}$	$78.4^{R,S}$	$160.5^{R,S}$	$137.7^{C,S}$	$118.9^{C,S}$	$129.6^{C,S}$	$87.6^{C,R}$	$91.7^{C,R}$	$94.4^{C,R}$
		3000	102.2^{R}	$210^{R,S}$	274.4^{S}	$260.7^{C,S}$	$290.3^{C,S}$	284.1^{S}	97.9^{R}	$104.4^{C,R}$	$121^{C,R}$
		3200	$204.1^{R,S}$	$263.1^{R,S}$	-	$378.3^{C,S}$	$320.3^{C,S}$	-	$112.9^{C,R}$	$134.1^{C,R}$	-
		3400	$252^{R,S}$	-	-	$388.2^{C,S}$	-	-	$159.5^{C,R}$	-	-
Right-Turn Movement	Right-Turn Volume (vph)	500	-	-	$8.7^{R,S}$	-	-	$23.1^{C,S}$	-	-	$35.6^{C,R}$
		550	-	$9.6^{R,S}$	$10.3^{R,S}$	-	$25.1^{C,S}$	$24.5^{C,S}$	-	$35^{C,R}$	$38^{C,R}$
		600	$11.8^{R,S}$	$11.4^{R,S}$	$12.3^{R,S}$	$31.4^{C,S}$	$29.2^{C,S}$	$27.9^{C,S}$	$35.1^{C,R}$	$36.9^{C,R}$	$39.8^{C,R}$
		650	$14.2^{R,S}$	$15^{R,S}$	$16.6^{R,S}$	38.3^{C}	$37^{C,S}$	$32.7^{C,S}$	37.1^{C}	$39.9^{C,R}$	$43.1^{C,R}$
		700	$19.9^{R,S}$	$26.8^{R,S}$	56.6	$61.3^{C,S}$	$50.3^{C,S}$	47.5	$40.2^{C,R}$	$43^{C,R}$	48.4
		750	40.8^{R}	$82.9^{R,S}$	104.8^{S}	$129.5^{C,S}$	$111.3^{C,S}$	106.3^{S}	46.1^{R}	$49.4^{C,R}$	$64.7^{C,R}$
		800	$85.8^{R,S}$	$112.9^{R,S}$	-	$186.8^{C,S}$	$161.3^{C,S}$	-	$54^{C,R}$	$66.2^{C,R}$	-
		850	$121^{R,S}$	-	-	$227.3^{C,S}$	-	-	$83.4^{C,R}$	-	-
Through Movement	Through Volume (vph)	5000*TP	-	-	$31^{R,S}$	-	-	$46.9^{C,S}$	-	-	$52.1^{C,R}$
		5500*TP	-	$32^{R,S}$	$37.1^{R,S}$	-	$48.3^{C,S}$	$50.4^{C,S}$	-	$52.3^{C,R}$	$53.4^{C,R}$
		6000*TP	$34.5^{R,S}$	$37.2^{R,S}$	$42^{R,S}$	$52.9^{C,S}$	$53^{C,S}$	54.2^{C}	$52.1^{C,R}$	$54.1^{C,R}$	55.1^{C}
		6500*TP	$39.5^{R,S}$	$43.1^{R,S}$	$50.1^{R,S}$	$60.1^{C,S}$	$61.3^{C,S}$	$62.7^{C,S}$	$54.5^{C,R}$	$56^{C,R}$	$58^{C,R}$
		7000*TP	$45.9^{R,S}$	59.6^{R}	$98.9^{R,S}$	$88.1^{C,S}$	$76.2^{C,S}$	$79.2^{C,S}$	$57.7^{C,R}$	59.8^{R}	$62.6^{C,R}$
		7500*TP	68.4^{R}	$119.4^{R,S}$	151.3^{S}	$157.4^{C,S}$	$150.9^{C,S}$	146.3^{S}	63.4^{R}	$66.9^{C,R}$	$80.3^{C,R}$
		8000*TP	$112.7^{R,S}$	$148.4^{R,S}$	-	$223.5^{C,S}$	$191.4^{C,S}$	-	$73.4^{C,R}$	$86.5^{C,R}$	-
		8500*TP	$148.5^{R,S}$	-	-	$256.8^{C,S}$	-	-	$105.6^{C,R}$	-	-
Left-Turn Movement	Left-Turn Volume (vph)	5000*LTP	-	-	$40.8^{R,S}$	-	-	$44.5^{C,S}$	-	-	$74.5^{C,R}$
		5500*LTP	-	45.9^{S}	$51.4^{R,S}$	-	46.4^{S}	$50.1^{C,S}$	-	$74.9^{C,R}$	$80.3^{C,R}$
		6000*LTP	$55.3^{R,S}$	$58.8^{R,S}$	$58^{R,S}$	$51.2^{C,S}$	$52.3^{C,S}$	$54.4^{C,S}$	$76.1^{C,R}$	$79.5^{C,R}$	$84.9^{C,R}$
		6500*LTP	$67.7^{R,S}$	$71.2^{R,S}$	$68.4^{R,S}$	$56.4^{C,S}$	$59.4^{C,S}$	$65.4^{C,S}$	$80.1^{C,R}$	$86.3^{C,R}$	$91.5^{C,R}$
		7000*LTP	78.1^{S}	$83.7^{R,S}$	$115^{R,S}$	73.7^{S}	$68^{C,S}$	$74.6^{C,S}$	$88.7^{C,R}$	$94^{C,R}$	$100.8^{C,R}$
		7500*LTP	$110.1^{R,S}$	143.1^{S}	$172.7^{R,S}$	$138.9^{C,S}$	138.4^{S}	138^{C}	$100.1^{C,R}$	$106.7^{C,R}$	132^{C}
		8000*LTP	$159.2^{R,S}$	$164.4^{R,S}$	-	$202.5^{C,S}$	$176.2^{C,S}$	-	$112.9^{C,R}$	$132.7^{C,R}$	-
		8500*LTP	$181^{R,S}$	-	-	$231.2^{C,S}$	-	-	$149.4^{C,R}$	-	-

Note: RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, LT: left-turn traffic; TP: through traffic proportion; LTP: left-turn traffic proportion; $^{C/R/S}$: significantly different compared to the conventional/RCUT/SM intersection delay.

Table 4.2: Average throughputs

Analysis Level	Traffic Volume Levels		Throughput								
			Conventional Intersection			RCUT Intersection			SM Intersection		
			10% LT	15% LT	20% LT	10% LT	15% LT	20% LT	10% LT	15% LT	20% LT
Intersection	Total Entering Vehicles (vph)	5000	-	-	5004	-	-	4991 ^{S}	-	-	5033 ^{R}
		5500	-	5507 ^{S}	5497	-	5478	5498	-	5470 ^{C}	5509
		6000	5982 ^{S}	5999	6019	6001	5974 ^{S}	6002	6017 ^{C}	6016 ^{R}	6002
		6500	6507	6504	6506 ^{R,S}	6510	6483	6477 ^{C,S}	6512	6484	6531 ^{C,R}
		7000	7025 ^{R,S}	7011 ^{R,S}	6892 ^{R,S}	6980 ^{C}	6969 ^{C}	6961 ^{C,S}	6972 ^{C}	6953 ^{C}	7026 ^{C,R}
		7500	7442 ^{R,S}	7329 ^{R,S}	7115 ^{R,S}	7240 ^{C,S}	7212 ^{C,S}	7224 ^{C,S}	7496 ^{C,R}	7500 ^{C,R}	7447 ^{C,R}
		8000	7781 ^{R,S}	7585 ^{S}	-	7291 $^{C, S}$	7556 ^{S}	-	8003 ^{C,R}	7899 ^{C,R}	-
		8500	8067 ^{R,S}	-	-	7422 ^{C,S}	-	-	8448 ^{C,R}	-	-
Major Road	Major Road Volume (vph)	3000	-	-	3000	-	-	2990 ^{S}	-	-	3019 ^{R}
		3300	-	3300	3288	-	3290	3299	-	3279	3308
		3600	3554 ^{R,S}	3596	3637 ^{R,S}	3603 ^{C}	3587 ^{S}	3604 ^{C}	3612 ^{C}	3612 ^{R}	3602 ^{C}
		3900	3907	3902	3951 ^{R}	3911	3896	3895 ^{C,S}	3920	3906	3938 ^{R}
		4200	4227 ^{S}	4239 ^{R,S}	4206 ^{S}	4212 ^{S}	4205 ^{C,S}	4205 ^{S}	4176 ^{C,R}	4165 ^{C,R}	4234 ^{C,R}
		4500	4473 ^{S}	4592 ^{R,S}	4502	4461 ^{S}	4506 ^{C}	4505	4505 ^{C,R}	4508 ^{C}	4468
		4800	4811 ^{R}	4810 ^{R,S}	-	4697 ^{C,S}	4744 ^{C}	-	4815 ^{R}	4736 ^{C}	-
		5100	5162 ^{R,S}	-	-	4760 ^{C,S}	-	-	5106 ^{C,R}	-	-
Minor Road	Minor Road Volume (vph)	2000	-	-	2004	-	-	2000	-	-	2014
		2200	-	2207 ^{R,S}	2208	-	2188 ^{C}	2199	-	2190 ^{C}	2201
		2400	2428 ^{R,S}	2403 ^{R}	2382 ^{R,S}	2398 ^{C}	2387 ^{C,S}	2399 ^{C}	2406 ^{C}	2404 ^{R}	2400 ^{C}
		2600	2600	2602 ^{R,S}	2554 ^{R,S}	2599	2586 ^{C}	2582 ^{C}	2593	2578 ^{C}	2593 ^{C}
		2800	2798 ^{R}	2772 ^{S}	2685 ^{R,S}	2768 ^{C,S}	2764 ^{S}	2756 ^{C,S}	2796 ^{R}	2788 ^{C,R}	2792 ^{C,R}
		3000	2969 ^{R,S}	2737 ^{R,S}	2613 ^{R,S}	2779 ^{C,S}	2706 ^{C,S}	2719 ^{C,S}	2991 ^{C,R}	2991 ^{C,R}	2979 ^{C,R}
		3200	2970 ^{R,S}	2776 ^{R,S}	-	2594 ^{C,S}	2812 ^{C,S}	-	3189 ^{C,R}	3163 ^{C,R}	-
		3400	2906 ^{R,S}	-	-	2662 ^{C,S}	-	-	3342 ^{C,R}	-	-
Right-Turn Movement	Right-Turn Volume (vph)	500	-	-	505	-	-	503	-	-	502
		550	-	552	551	-	551	552	-	553	550
		600	600	601	602	600	602	600	600	600	601
		650	643	643	647	643	647	647	645	650	648
		700	695	691	683 ^{R,S}	694	698	696 ^{C}	695	698	695 ^{C}
		750	746 ^{R}	726 ^{S}	714 ^{S}	717 ^{C,S}	717 ^{S}	718 ^{S}	744 ^{R}	745 ^{C,R}	740 ^{C,R}
		800	768 ^{R,S}	756 ^{S}	-	727 ^{C,S}	749 ^{S}	-	792 ^{C,R}	794 ^{C,R}	-
		850	800 ^{R,S}	-	-	735 ^{C,S}	-	-	837 ^{C,R}	-	-
Through Movement	Through Volume (vph)	5000*TP	-	-	3504 ^{S}	-	-	3494 ^{S}	-	-	3526 ^{C,R}
		5500*TP	-	4144 ^{R,S}	3844	-	4106 ^{C}	3849	-	4102 ^{C}	3858
		6000*TP	4775 ^{R,S}	4505 ^{R,S}	4205	4800 ^{C}	4475 ^{C,S}	4205	4815 ^{C}	4522 ^{C,R}	4205
		6500*TP	5222	4910 ^{R,S}	4546 ^{R,S}	5218	4864 ^{C}	4528 ^{C,S}	5215	4872 ^{C}	4578 ^{C,R}
		7000*TP	5624 ^{R,S}	5304 ^{R,S}	4831 ^{R,S}	5588 ^{C}	5225 ^{C}	4864 ^{C,S}	5578 ^{C}	5210 ^{C}	4930 ^{C,R}
		7500*TP	5928 ^{R,S}	5534 ^{R,S}	4933 ^{R,S}	5799 ^{C,S}	5424 ^{C,S}	5067 ^{C,S}	6001 ^{C,R}	5641 ^{C,R}	5225 ^{C,R}
		8000*TP	6253 ^{R,S}	5703 ^{S}	-	5831 ^{C,S}	5686 ^{S}	-	6414 ^{C,R}	5939 ^{C,R}	-
		8500*TP	6451 ^{R,S}	-	-	5950 ^{C,S}	-	-	6769 ^{C,R}	-	-
Left-Turn Movement	Left-Turn Volume (vph)	5000*LTP	-	-	995	-	-	993	-	-	1005
		5500*LTP	-	812	1102	-	821	1098	-	814	1100
		6000*LTP	606	892	1212	600	896	1198	603	894	1196
		6500*LTP	642	951 ^{R}	1312	649	972 ^{C}	1302	652	961	1304
		7000*LTP	706	1016 ^{R,S}	1378 ^{R,S}	698	1046 ^{C}	1400 ^{C}	700	1045 ^{C}	1401 ^{C}
		7500*LTP	768 ^{R}	1070 ^{S}	1469 ^{R}	724 ^{C,S}	1071 ^{S}	1440 ^{C,S}	751 ^{R}	1113 ^{C,R}	1482 ^{R}
		8000*LTP	760 ^{R,S}	1126 ^{S}	-	734 ^{C,S}	1121 ^{S}	-	798 ^{C,R}	1166 ^{C,R}	-
		8500*LTP	816 ^{R,S}	-	-	738 ^{C,S}	-	-	843 ^{C,R}	-	-

Note: RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, LT: left-turn traffic; TP: through traffic proportion; LTP: left-turn traffic proportion; $^{C/R/S}$: significantly different compared to the conventional/RCUT/SM intersection throughput.

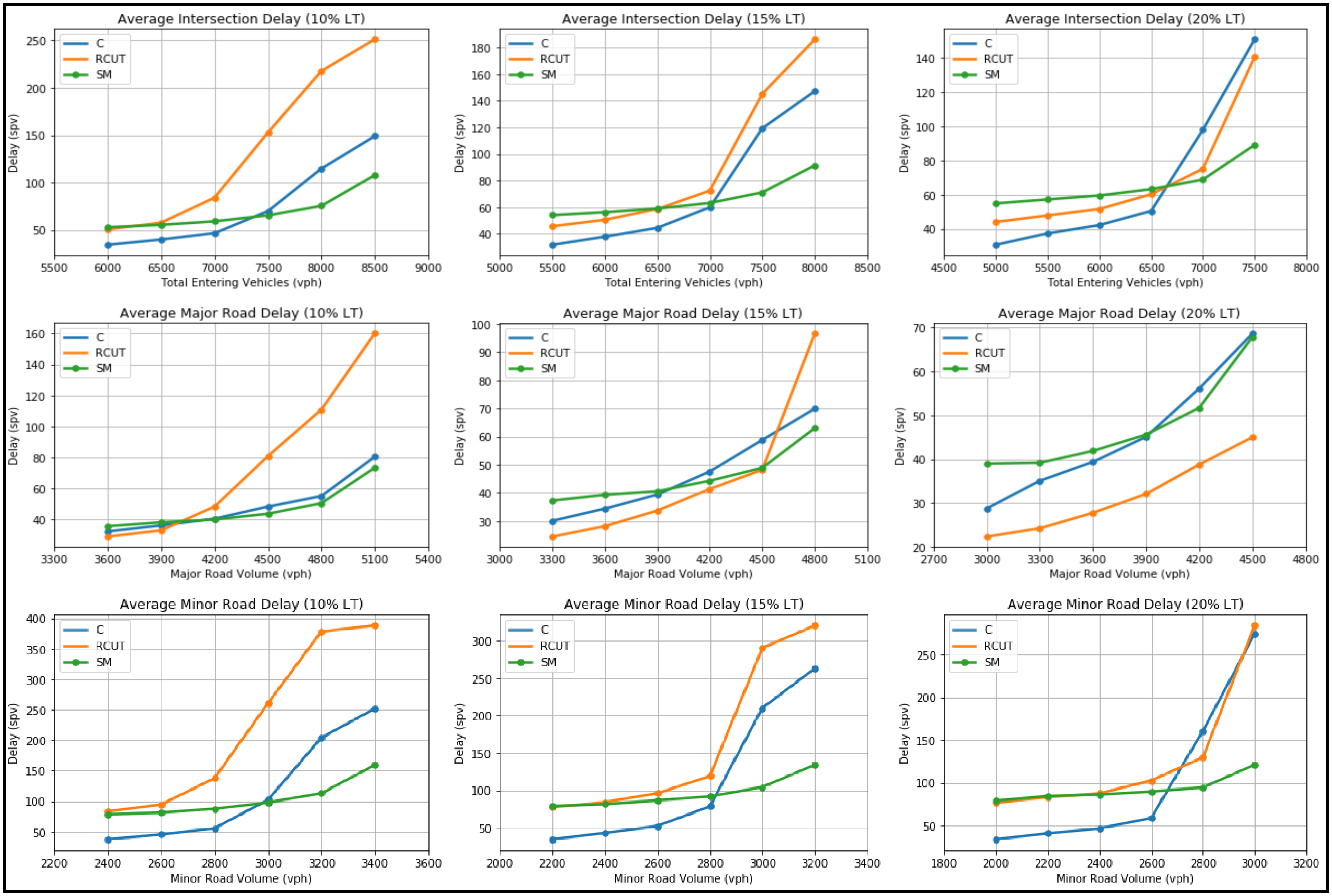


Figure 4.6: Intersection and road average delays

Note: C: conventional intersection, RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, LT: left-turn traffic.

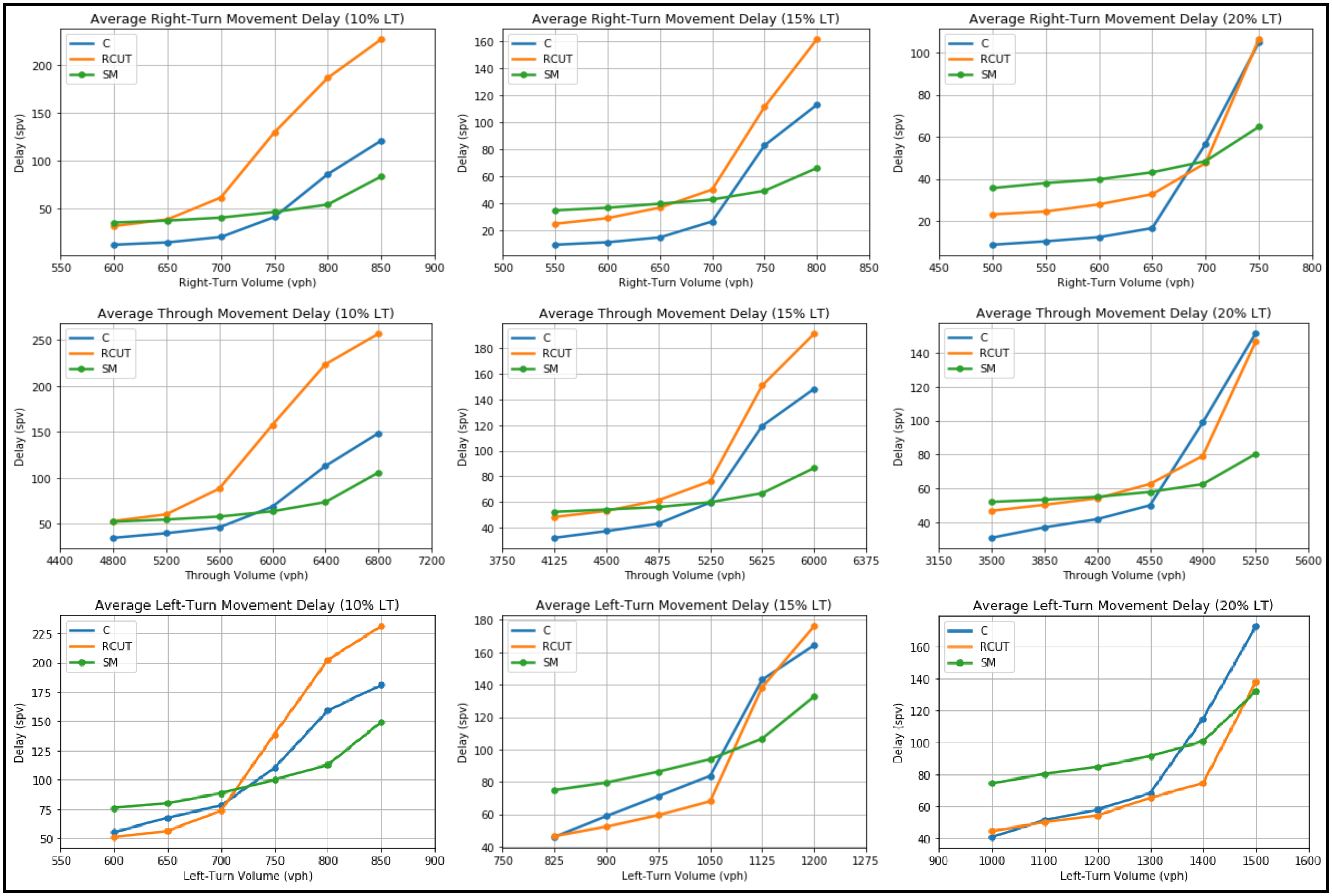


Figure 4.7: Movement average delays

Note: C: conventional intersection, RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, LT: left-turn traffic.

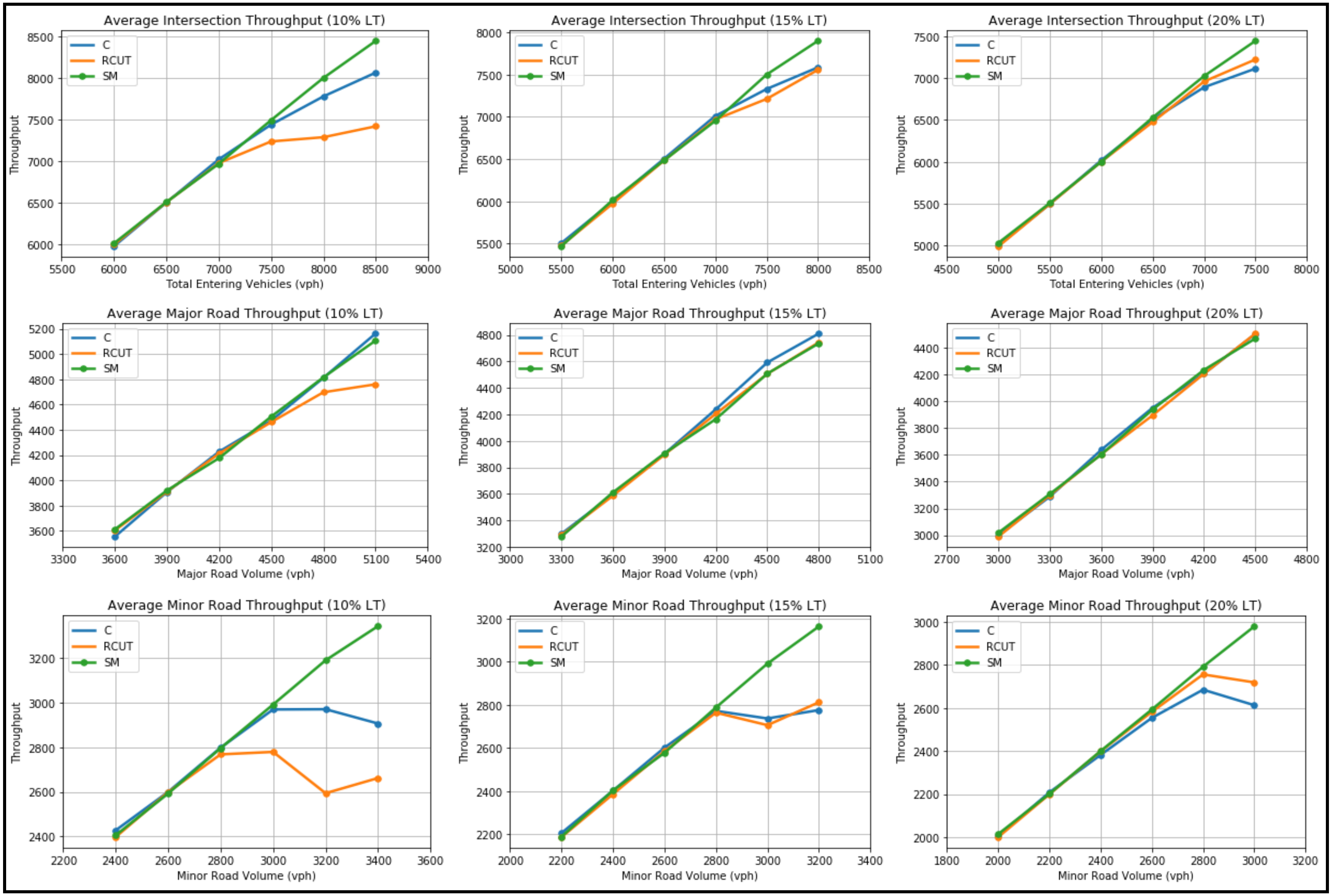


Figure 4.8: Intersection and road throughputs

Note: C: conventional intersection, RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, LT: left-turn traffic.

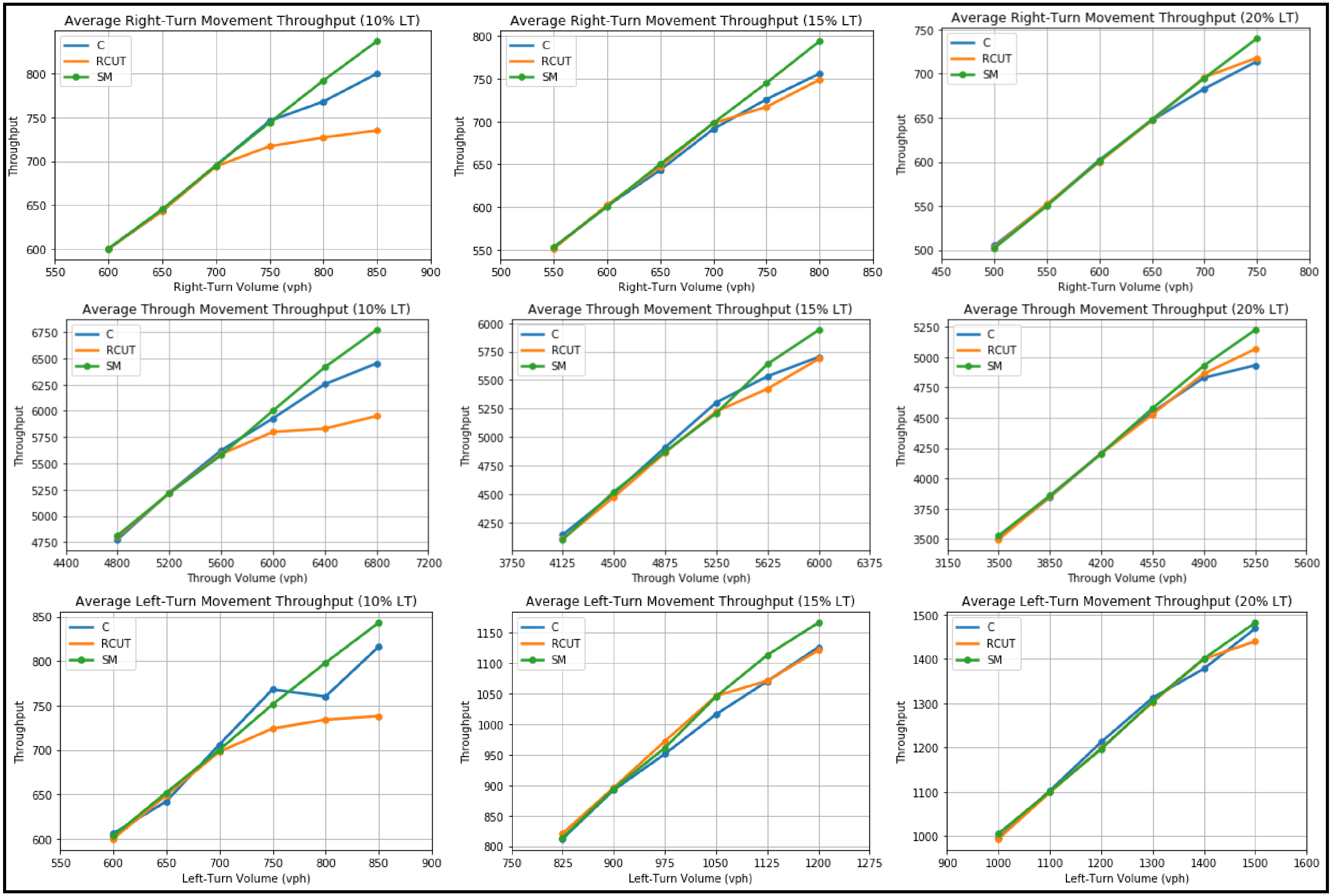


Figure 4.9: Movement throughputs

Note: C: conventional intersection, RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, LT: left-turn traffic.

The results of the comparison between 400- and 500-feet lengths of the side street at the SM intersection design indicated that the 400 feet length has better operational performance in term of average intersection delay whenever the TEV is around or lower than 8200, 7750, and 7250 vehicles with 10%, 15%, and 20% left-turn proportions, respectively. On the other hand, 500 feet length is more effective in delay reduction beyond these traffic volumes. Table 4.3 and Figures 4.10 and 4.11 show average intersection delay and throughput values at the SM intersection with 400-feet and 500-feet side streets with 10%, 15%, and 20% left-turn proportions.

Table 4.3: Average control delays and throughputs of the SM intersection

Measure of Effectiveness	Total Entering Vehicles (vph)	SM Intersection's Side Street					
		400 feet Length			500 feet Length		
		10% LT	15% LT	20% LT	10% LT	15% LT	20% LT
Average Intersection Delay (s)	6500	-	-	63.2 *	-	-	67.7 *
	7000	-	63.2 *	68.8 *	-	67.6 *	73.2 *
	7500	65.3 *	71.1 *	89.1	69.7 *	75 *	85
	8000	75.4 *	91.4	-	78.7 *	89	-
	8500	107.8	-	-	101.8	-	-
Average Intersection Throughputs	6500	-	-	6531 *	-	-	6456 *
	7000	-	6953 *	7026	-	7032 *	7005
	7500	7496	7500	7447	7507	7495	7486
	8000	8003 *	7899 *	-	8070 *	8003 *	-
	8500	8448 *	-	-	8545 *	-	-

Note: LT: left-turn traffic; *: significantly different compared to the 400 feet/500 feet length of the SM intersection's side street delay/throughput.

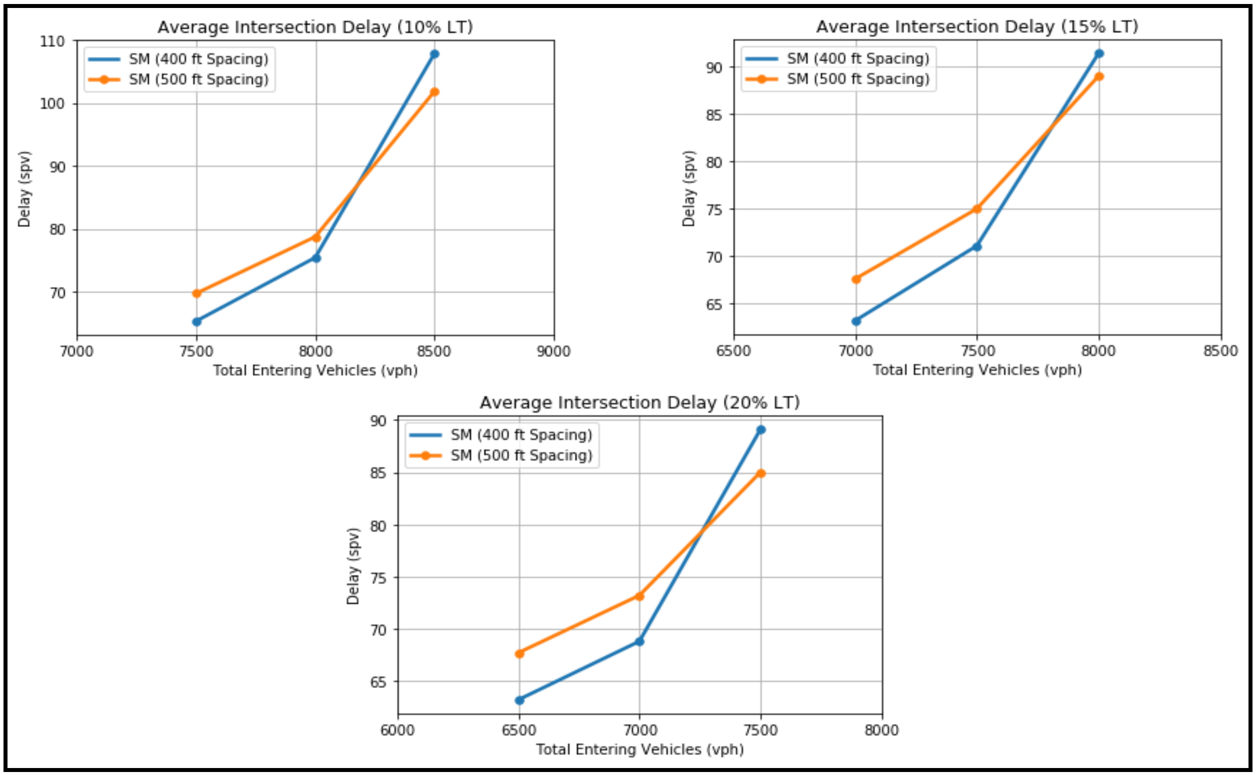


Figure 4.10: Intersection average control delay of 400- and 500-feet side street SM intersections
Note: SM: shifting movements intersection, LT: left-turn traffic.

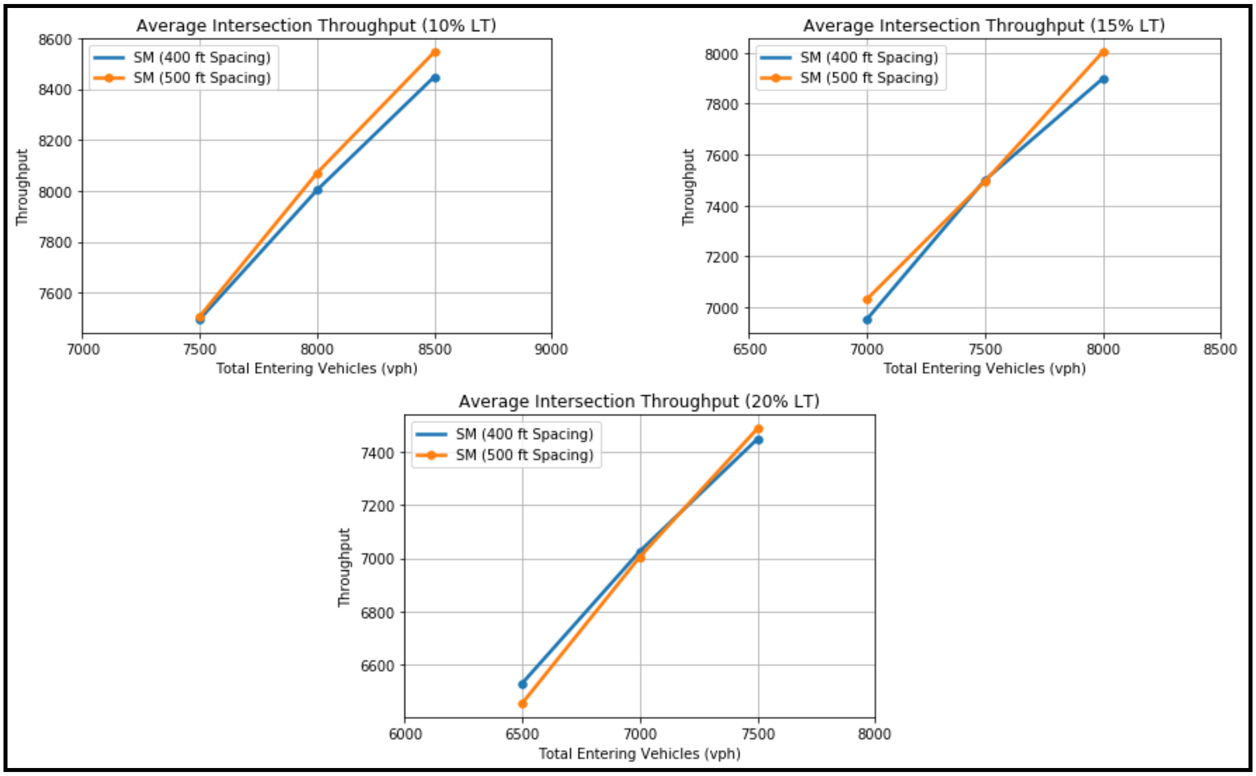


Figure 4.11: Intersection Throughput of 400- and 500-feet side street SM intersections
Note: SM: shifting movements intersection, LT: left-turn traffic.

4.5 Discussion of Results

As expected, the conventional intersection performs better than unconventional intersection designs at low TEV levels and left-turn proportions. The absence of additional travel distance for the left-turn and minor traffic (the distance between the main intersection and the crossover and the distance between the central area and the upstream/downstream intersection at the RCUT and SM intersections, respectively) at the conventional intersection compared to unconventional intersection designs beside the short queues are the main reasons of the high traffic operational performance of the conventional intersection under low to moderate TEV levels and left-turn proportions. However, for high TEV levels and left-turn proportions, long cycle lengths are recorded at the conventional intersection that results in long queues. In contrast, unconventional intersections still have moderate cycle lengths under high TEV levels and left-turn proportions that enable them to perform better than the conventional intersection although a part of the traffic is subjected to additional travel distances.

The results confirm that the RCUT intersection design has weak operational performance at moderate to heavy minor road traffic (more than 20% of TEV). The reason is the high travel time of the minor through and left-turn traffic at the RCUT intersection which could stop three potential times since it must pass through median U-turn crossovers. The SM intersection has achieved the expected operational benefits especially at high TEV levels and left-turn proportions even that the minor left-turn traffic is also subjected to three potential stops. The long spacing between the upstream and downstream intersections and providing a continuous movement of the minor through traffic at the central area prevent any bottlenecks unlike the RCUT intersection. This reduces the travel time at the SM intersection. Therefore, Average delay values have been significantly reduced while throughputs have increased at the SM intersection compared to conventional and RCUT intersections. Sufficient length of the SM intersection’s side street provides more storage space that prevents creation of long queues and traffic bottlenecks. However, it slightly increases the travel distance for minor and major left-turn traffic. Therefore, long length is only recommended at high TEV levels and left-turn proportions.

4.6 Conclusions and Recommendations

A new 4-leg intersection design (i.e., the SM intersection design) has been proposed in this research. The SM intersection has the lowest number of conflict points (similar to the RCUT intersection) among other proposed unconventional intersection designs. Therefore, safety benefits are expected to be achieved by implementing such design. Evaluation of the operational performance of the SM intersection design compared to conventional and RCUT intersections has been conducted in the microscopic simulation environment. Different traffic volume levels and left-turn proportions have been assumed. The results indicated that the conventional intersection with low traffic volumes and left-turn proportions outperforms RCUT and SM intersection designs in terms of average control delay. On the other hand, unconventional intersection designs have a better performance at heavy traffic volumes and left-turn proportions.

The SM intersection design has slightly higher average delay values than the RCUT intersection design at low traffic volumes. However, it outperforms the RCUT design at moderate to heavy traffic volumes. Therefore, the RCUT intersection is recommended when the minor road traffic volume is light. While for locations with moderate and high minor road traffic volume levels, the SM intersection is recommended for implementation. Four hundred feet length of the side street is recommended at the SM intersection design. However, for very heavy traffic volumes 500 feet length is recommended.

It is expected that traffic safety and operation will be enhanced by implementing the SM intersection design at locations with moderate to high traffic volumes.

CHAPTER 5: EVALUATION OF DRIVING BEHAVIOUR AND SAFETY AT THE SHIFTING MOVEMENTS INTERSECTION AND USING INFRASTRUCTURE-TO-VEHICLE COMMUNICATION AT UNCONVENTIONAL INTERSECTIONS

5.1 Introduction

Unconventional intersection designs have been proposed in order to improve traffic safety and operation at intersections. The shifting movement (SM) interstation design which has been introduced in Chapter 4 has a similar number of traffic conflict points to the restricted crossing U-turn (RCUT) intersection. It was found that even though both unconventional intersections (i.e. RCUT and SM intersections) have the same number of conflict points and two-phase signalization, the SM intersection design significantly outperforms the RCUT intersection design in terms of traffic operation (less intersection average control delay by 57% in some traffic conditions, in addition to more throughput) under moderate and heavy traffic volumes.

The low number of conflict points at the SM intersection design is an indication of a safe traffic operation. However, unconventional movement patterns may confuse drivers who do not have any experience with unconventional intersections. For further investigation of the safety aspects of the SM intersection design, a driving simulation experiment was conducted in this study in order to evaluate the traffic safety at the SM intersection design and to determine the extent of confusion that drivers could have while crossing this intersection design in comparison with conventional and RCUT signalized intersections. Furthermore, an evaluation of the effect of implementing the infrastructure-to-vehicle (I2V) communication on driving behavior and traffic safety improvement at unconventional intersections was also accomplished in this study.

5.2 Experiment Design

5.2.1 Geometric Design

Unconventional intersection designs which were considered in this study (i.e. RCUT and SM intersections) have been simulated along with the conventional intersection in the daytime in an urban environment where a divided 6-lanes arterial (the major road) intersects with a divided 4-lanes collector (the minor road). A crossover spacing of 425 feet was adopted at the RCUT intersection (*Hughes, 2010*). Consistent with this, 400 feet spacing between the central area and the upstream/downstream intersection of the SM intersection has been provided. Figures 5.1, 5.2 and 5.3 show the conventional, RCUT, and SM intersections, respectively.

The collector at these intersections has an additional 250-feet exclusive right-turn lane. The arterial at conventional and RCUT intersections have an additional 400-feet exclusive right-turn lane and two additional 400-feet exclusive left-turn lanes. Two 400-feet lanes have been customized for the U-turn movement at the RCUT intersection’s crossovers. At the SM intersection, the arterial has a 400-feet exclusive right-turn lane and a 400-feet multipurpose lane for right-turn movement and for accessing the side street from the major road. The side street at the SM intersection has three 400-feet lanes. A 0.8-mile straight undivided 4-lanes road connects every two intersections. All roads in the simulated roadway network have 12-feet (in width) lanes.

All intersections of RCUT and SM intersections (i.e. the main intersection and crossovers at the RCUT intersection and the central area and upstream/downstream intersections at the SM intersection) have been controlled by traffic signals. Lane marking has been implemented at the intersections to specify the permitted movement(s) that can be done by using any particular lane.

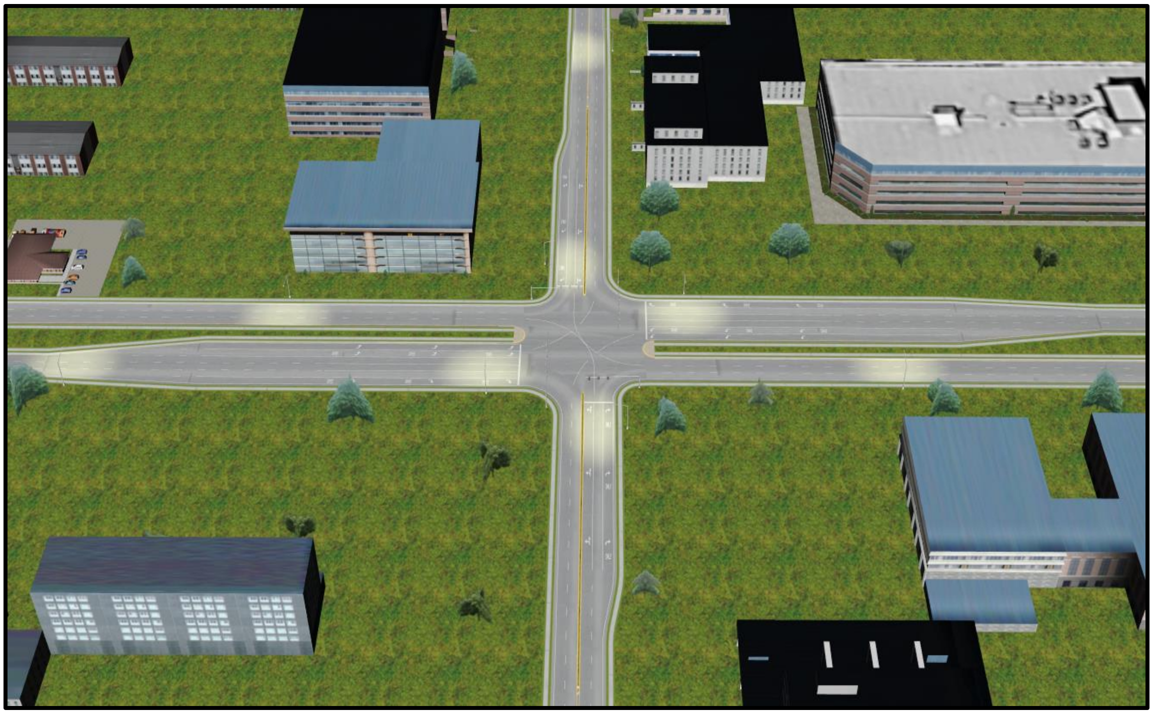


Figure 5.1: The conventional intersection design

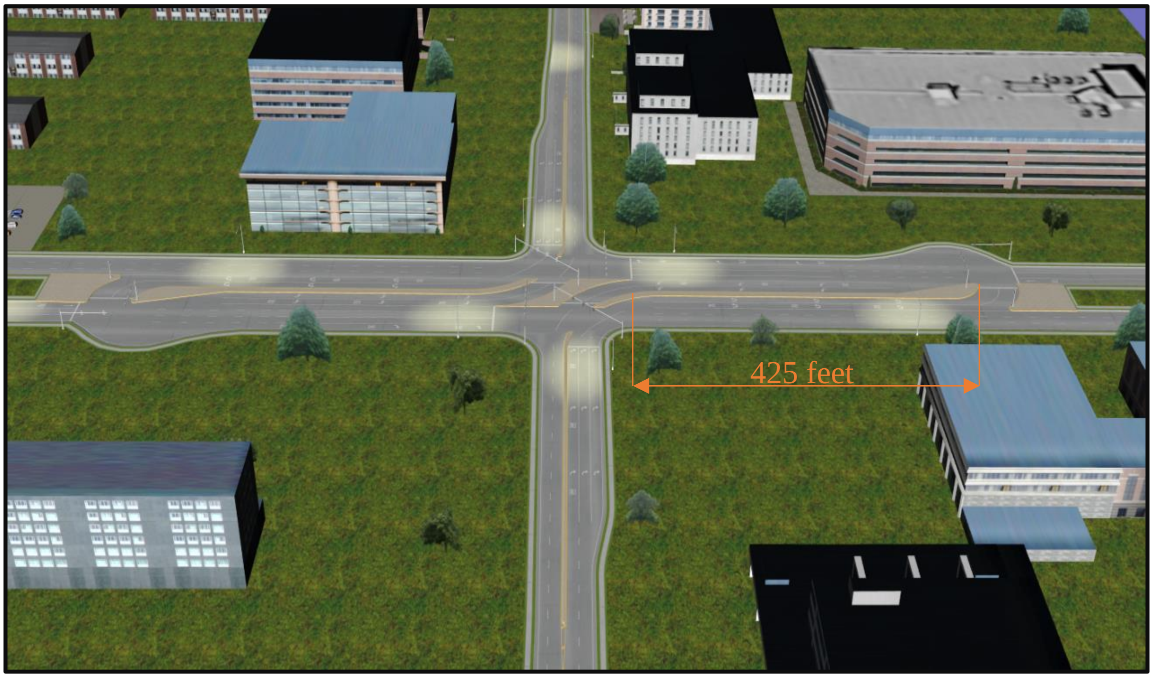


Figure 5.2: The RCUT intersection design

Figure 5.3: The SM intersection design

5.2.2 Signage

Different regulatory and guide signs have been used in this experiment especially at intersections. Most of them already exist in the Manual on Uniform Traffic Control Devices (*MUTCD, 2009*) such as speed limit (40 mph and 50 mph speed limits have been adopted at minor and major roads, respectively) (R2-1), no right-turn (R3-1), no left-turn (R3-2), no U-turn (R3-4), “Left Lane Must Turn Left” (R3-7), “All Turns From Right Lane” (R3-23), “Do Not Enter” (R5-1), and “One Way” (R6-1) signs and others. Moreover, new signs have been designed and installed at unconventional intersections to guide drivers on how to perform unconventional movements at RCUT and SM intersections. Figures 5.4, 5.5, and 5.6 show the used signs at conventional, RCUT, and SM intersections, respectively.

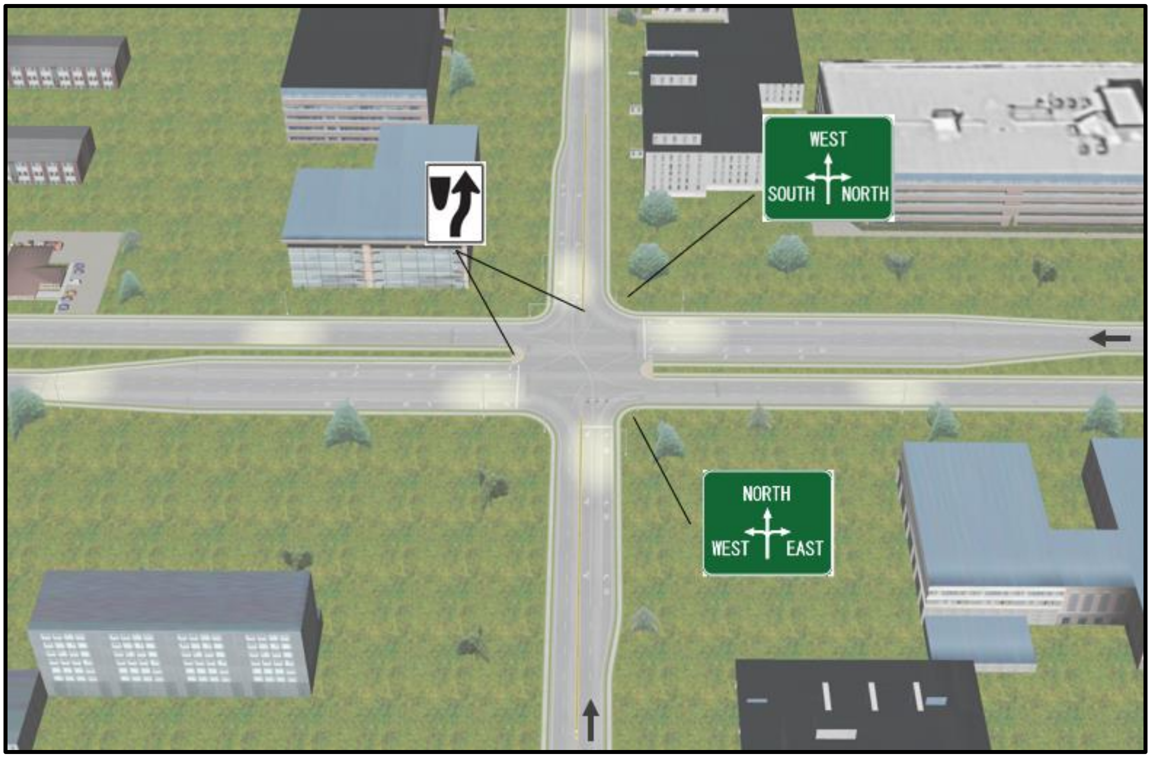


Figure 5.4: The used signs at the conventional intersection

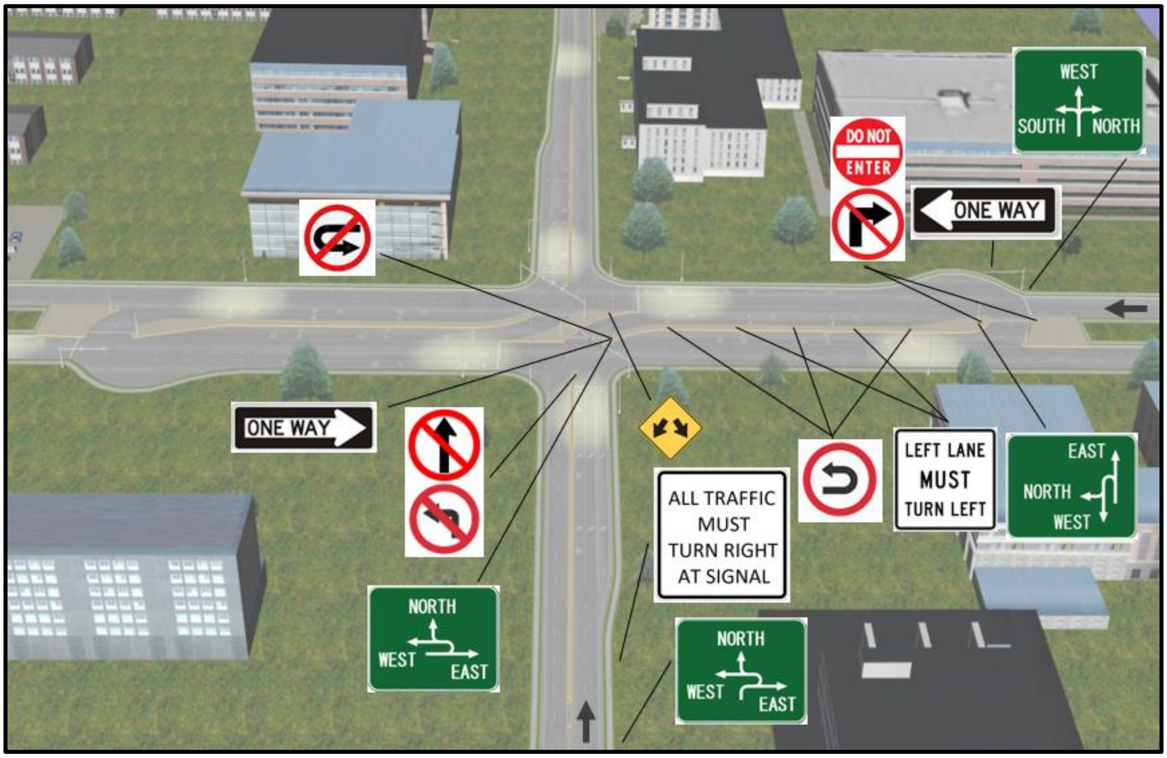


Figure 5.5: The used signs at the RCUT intersection

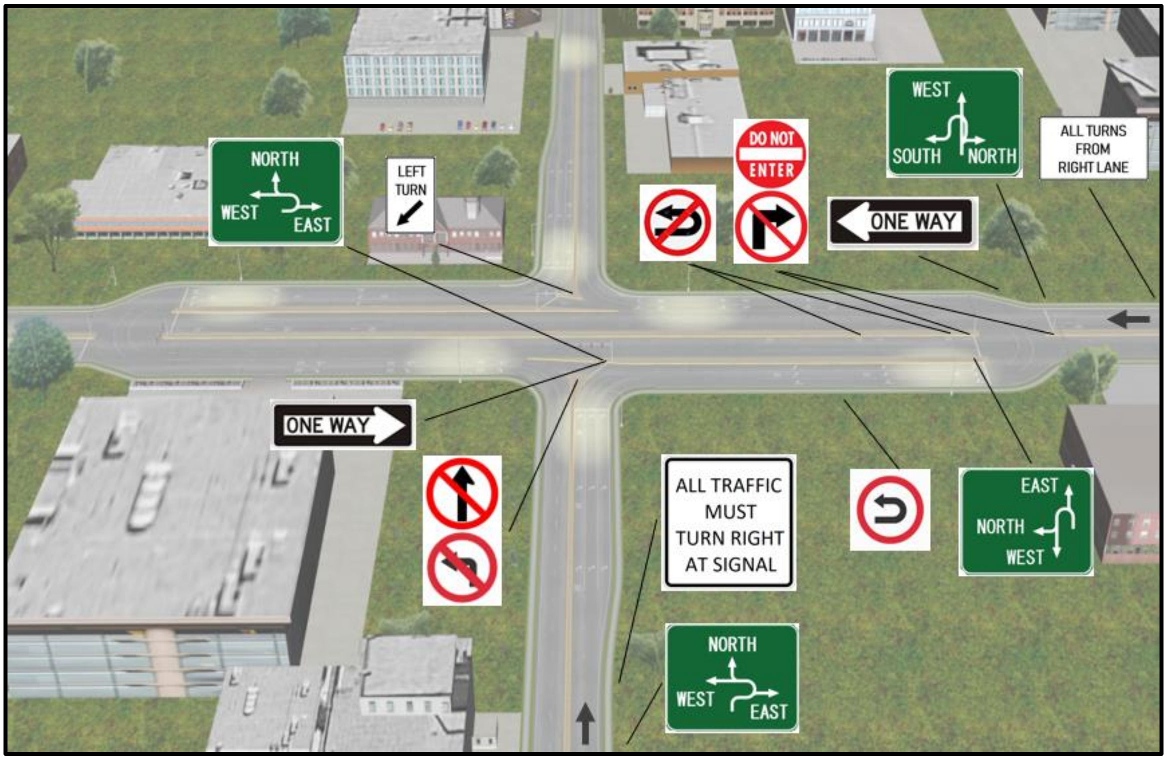


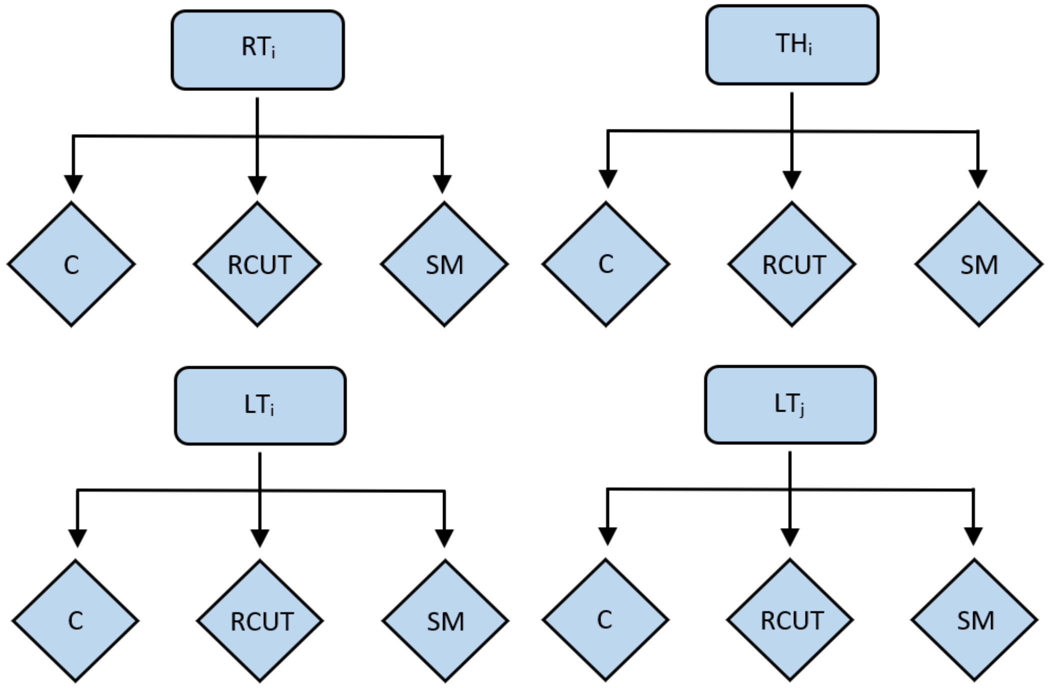
Figure 5.6: The used signs at the SM intersection

5.2.3 Scenario Design

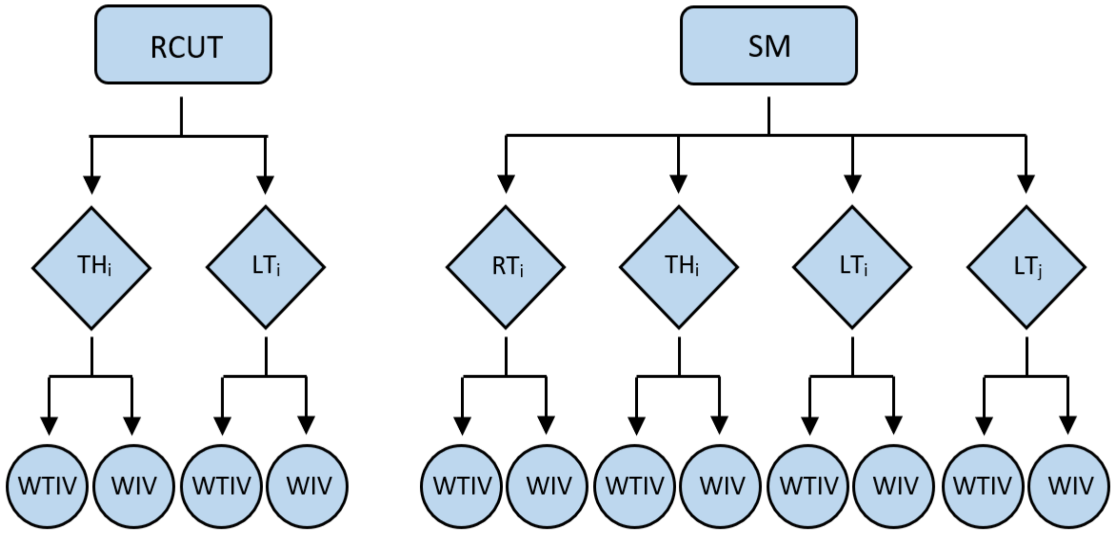
The main objective of this study was to investigate the driving behavior at unconventional intersection designs and to evaluate the safety aspects of the SM intersection. The effectiveness of using I2V communication was also investigated in this study. However, this was analyzed separately because the implementation of I2V communication has been only done for the unconventional movements which their counts are not equal among the intersections. Therefore, two separate experiments were conducted in this study. Both experiments are full factorial design experiments with one within-subject factor. This means that all participants perform all alternatives in the experiment.

The factor in the first experiment was the intersection type with three levels (conventional, RCUT, and SM intersections). All participants were requested to drive and accomplish four movements at the three intersection designs. These four movements that are covering all unconventional movements at RCUT and SM intersections are minor road movements in addition to the major left-turn movement. In the second experiment, the factor was the use of I2V communication at unconventional intersections with two levels (Yes or No). All participants were requested to accomplish all the unconventional movements at RCUT and SM intersections with and without using I2V communication. Figure 5.7 shows a schematic diagram for the two experiments in this study.

The I2V communication has been simulated by sending navigation information for guiding drivers to accomplish the unconventional movements. Visual and voice messages have been sent to drivers before every stage of each unconventional movement at RCUT and SM intersections. For example, to guide the driver to complete the minor through movement at the RCUT intersection, three visual and voice messages have been sent. The first message is sent to the driver 700 feet upstream of the stop line at the main intersection. In this message, the driver is phonetically asked to use the middle lane to turn right. Meanwhile, an illustration diagram that specifies that the driver must be in the middle lane is shown on the middle screen directly at the driver's eye level (Figure 5.8). The second message is sent directly after leaving the stop line at the main intersection stating that the driver must use the second lane from the left to make a U-turn at the downstream median crossover in addition to showing the illustration diagram in Figure 5.9. The last message related to this movement is sent once the driver did the U-turn movement at the crossover. In this message, the driver is asked to use the right lane to turn right at the main intersection. The illustration diagram in Figure 5.10 is also shown at the third stage of this movement.



(first experiment)



(second experiment)

Figure 5.7: Schematic diagram of the first and second experiments’ factor

Note: C: conventional intersection, RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, RTi: minor right-turn movement, THi: minor through movement, LTi: minor left-turn movement, LTj: major left-turn movement, WTIV: without I2V communication, WIV: with I2V communication.

Figure 5.8: An illustration diagram is shown 700 feet upstream the stop line at the main intersection

Figure 5.9: An illustration diagram is shown after leaving the stop line at the main intersection

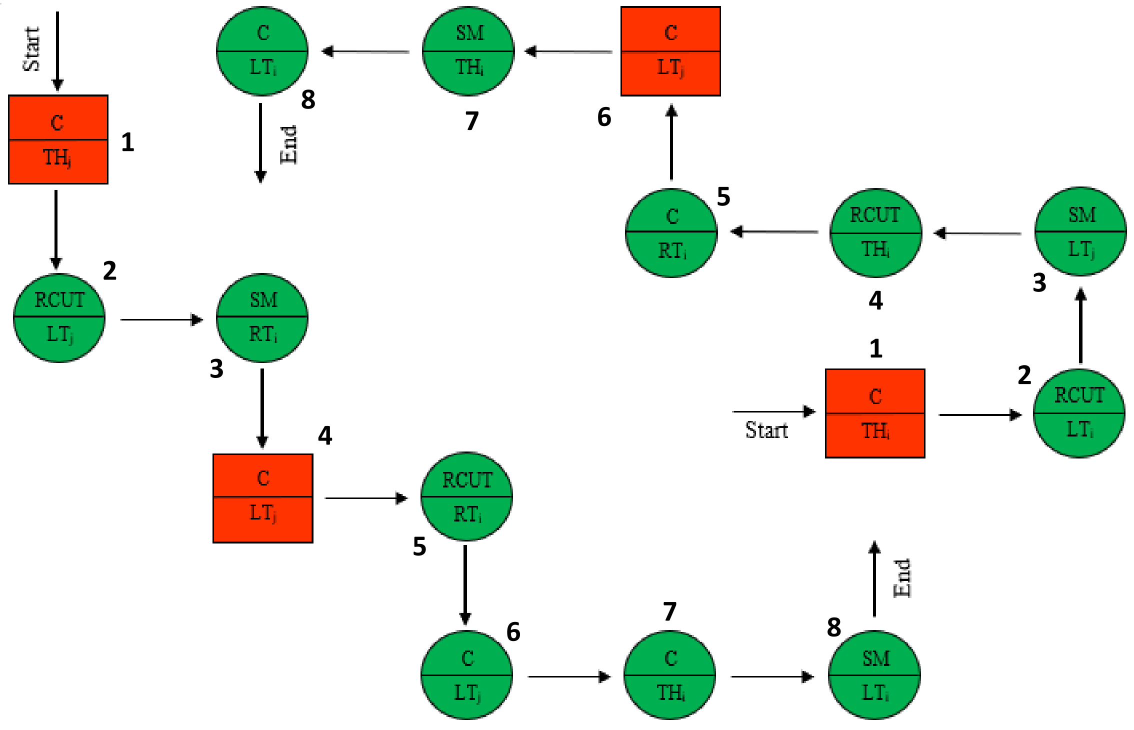
Figure 5.10: An illustration diagram is shown at the RCUT intersection’s crossover.

Three (10-minutes) routes have been designed to perform right-turn, through, and left-turn movements at a combination of conventional, RCUT, and SM intersections. A route that involves a combination of movements and intersections is considered more realistic and efficient than a single movement/intersection route (*Kennedy et al., 2005; Campbell et al., 2008*). To examine the geometric design of the unconventional intersections, the driver must have the freedom to drive at a free-flow speed without impedance with other vehicles. Therefore, light traffic was set in the roadway environment (there are no vehicles moving in the same direction beside the subject vehicle, and vehicles ahead and behind it are far).

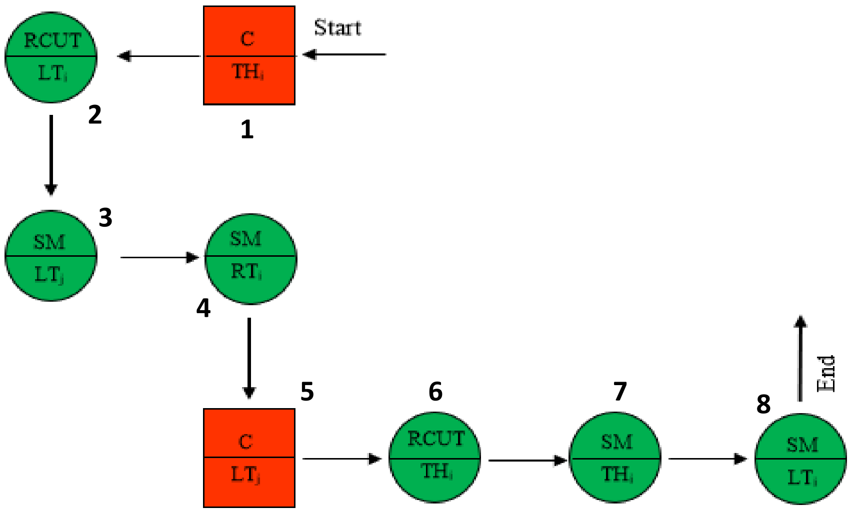
The I2V communication has been only implemented in one route (with-I2V route) while other two routes (without-I2V routes) are without usage of I2V communication. The driver was directed to do the four movements (right-turn, through, and left-turn movements from the minor road and the left-turn movement from the major road) at conventional, RCUT, and SM intersections in the two without-I2V routes. While the driver was asked to perform only the unconventional movements at RCUT and SM intersections in the with-I2V route knowing that this route contains conventional intersections as control intersections.

To give the driver time to engage in driving before considering the data for analysis, the driver was directed in all routes to do a through movement at a conventional intersection where the data of this movement was not accounted for in the analysis. A spacing of 0.8 mile between intersections was provided to give the driver enough time to go back to normal driving behavior before reaching the next intersection.

Traffic signals at all intersections have right-turn and left-turn arrows for right-turn and left-turn movements, respectively. All traffic signals have been triggered to have a green light once the driver is at 800 feet from the intersection except the first and the fourth, the fifth, or the sixth intersections which have red traffic signals to avoid expectation of a green light at every intersection in the route. Data at intersections with red traffic signals were excluded from the analysis. The driver is asked to head in a specific direction at every intersection. Text and voice messages have been sent 1100 feet upstream of the first stop line at the intersection. Figure 5.11 shows the designed routes in this study.



(Without-I2V)



(With-I2V)

Figure 5.11: Without-I2V and with-I2V routes

Note: C: conventional intersection, RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, RTi: minor right-turn movement, THi: minor through movement, LTi: minor left-turn movement, LTj: major left-turn movement, red color: red signal light, green color: green signal light.

5.3 Experiment Development

5.3.1 Scenario Development

The MiniSim^{TM} by the University of Iowa’s National Advanced Driving Simulator (NADS) at the University of Central Florida (UCF) was employed in this experiment. Along with the cockpit, the simulator consists of three screens, audio, and vibration systems, and three cameras. A horizontal 130-degree field of vision has been provided by Full HD screens. A 2.1 channel audio system allows simulating different sounds such as engine, oncoming vehicles, and tire-pavement interaction noise sounds. It also allows sending voice messages during the experiment. The vibration system is located under the driving seat which simulates any vibrations during driving. Two cameras are installed at the top and the bottom of the middle screen to record the driver's eye movements and face reactions, while another camera is installed above the gas and brake pedals to record the driver’s leg actions and reactions and the movement between gas and brake pedals.

Tile Mosaic Tool (TMT) software was used to build the roadway network which connects a combination of the three intersection tiles by a 4-lane road tile. To set traffic, install signs, and trigger traffic signals, Interactive Scenario Authoring Tools (ISAT) software was employed. Many triggers have been designed for sending different types of messages to guide the driver to be on the desired track. Figures 5.12, 5.13 and 5.14 show the graphical user interface (GUI) of TMT, ISAT, and NADS software, respectively.

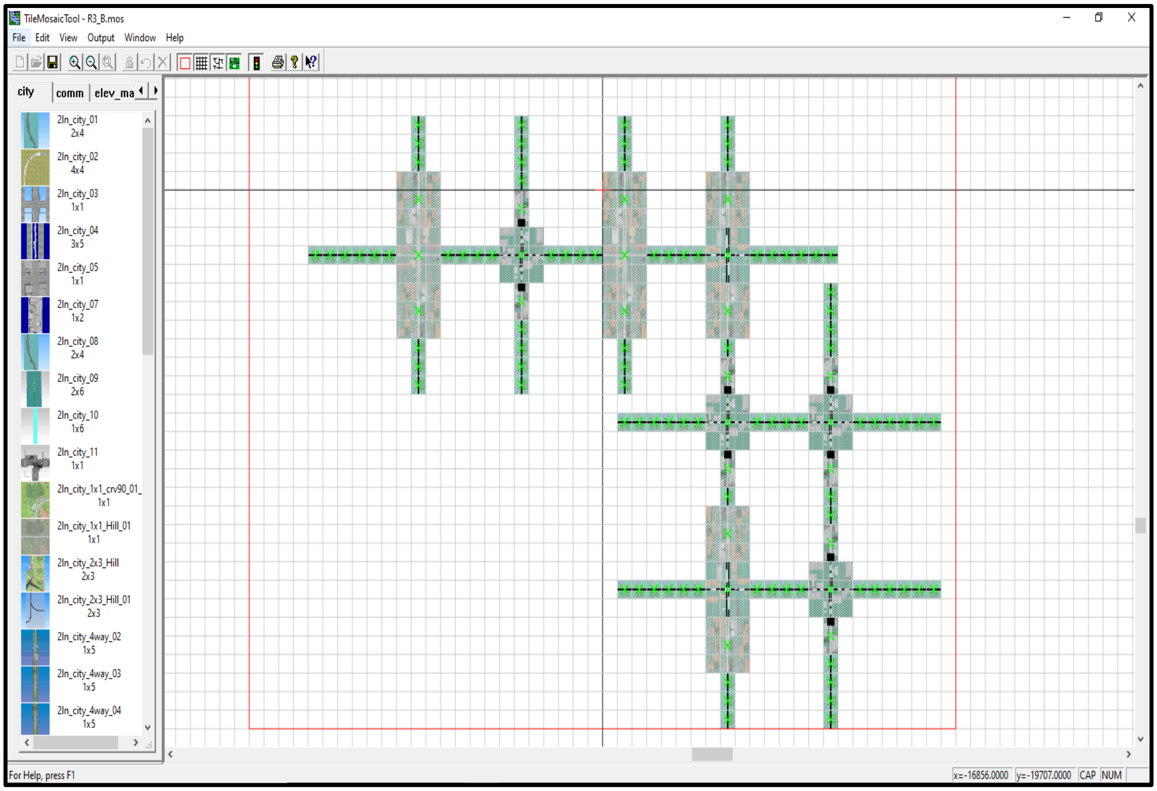


Figure 5.12: GUI of TMT software

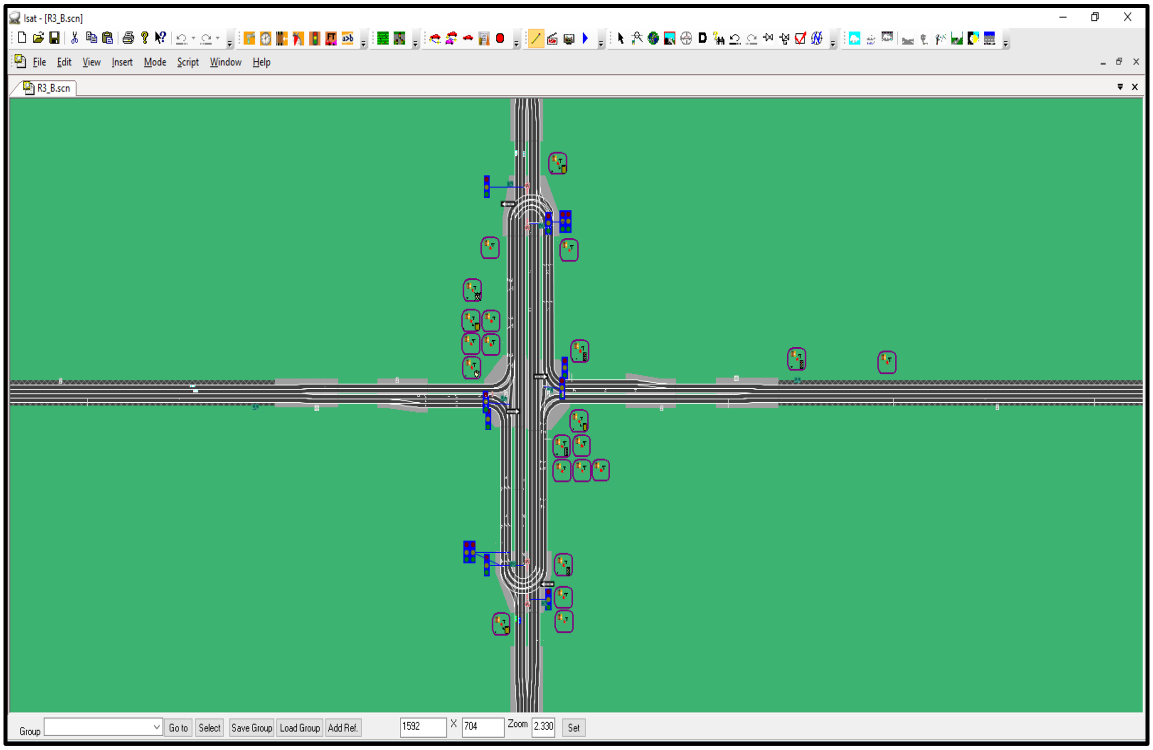
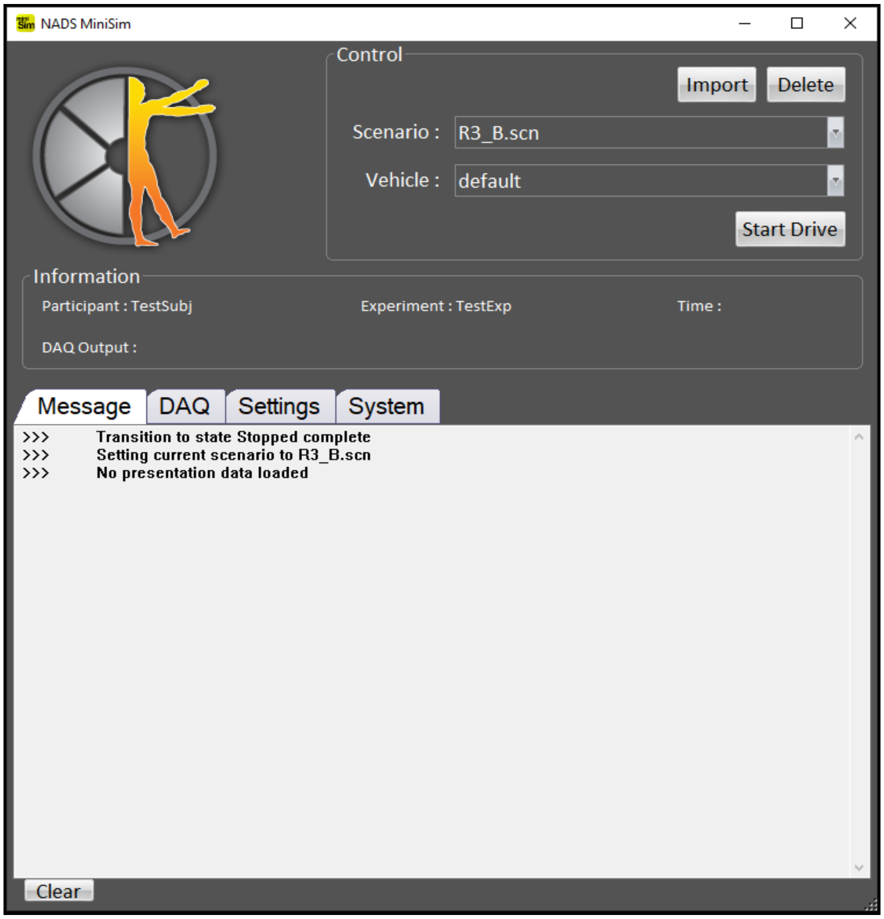


Figure 5.13: GUI of ISAT software



Scenario : R3_B.scn

Vehicle : default

Participant : TestSubj

Experiment : TestExp

Time :

DAQ Output :

```
>>>       Transition to state Stopped complete
>>>       Setting current scenario to R3_B.scn
>>>       No presentation data loaded
```

Figure 5.14: GUI of NADS minisim^{TM} software

Triggers have been developed to guide the driver to go back to the right track if he/she did a mistake and fail to do a certain movement. To counterbalance the random effects, the order of unconventional intersections within every route was changed which resulted in two configurations for every route.

5.3.2 Participants

Thirty-four participants were recruited for this experiment. Requirements for participating in the experiment were owning a valid driving license and absence of alcohol or drug influence and any handicap that may impact driving. Due to the Coronavirus (COVID-19) disease situation and inability to recruit subjects easily, the vast majority of participants were students at the

University of Central Florida. All of them are nonprofessional drivers (i.e. their jobs do not involve driving activities).

Two age groups were noticed for participants: young drivers with ages less than 25 years old (*Wu et al., 2018; Zicat et al., 2018; Yue et al., 2020*) and adult drivers (the majority) with ages between 26 to 42 years old. No elderly drivers with ages more than 65 years old (*Vlakveld et al., 2015; Yue et al., 2019*) have participated in the experiment. The ages ranged between 18 and 42 years. Figure 5.15 shows a histogram of the participants' age.

Two participants experienced motion sickness at the beginning of the experiment, and they could not complete it. Therefore, the data in this study was obtained from 32 participants who had completed the experiment. The G*power 3.1 software is widely used for determining the required sample size (*Faul et al., 2009*). Therefore, it was employed to determine the required sample size that achieves the minimum statistical power of 0.8 (*VanVoorhis and Morgan, 2007; Bujang and Adnan, 2016*). By setting 0.3 and 0.55 values for the effect size parameter (*Faul et al. 2009*), it was found that the minimum required sample size is 20 and 28 for the repeated measures analysis of variance (RM-ANOVA) and the paired T-test, respectively. Since the sample size in the study is greater than the minimum required sample size. Therefore, the sample size in this study has achieved the statistical requirements for the sample size.

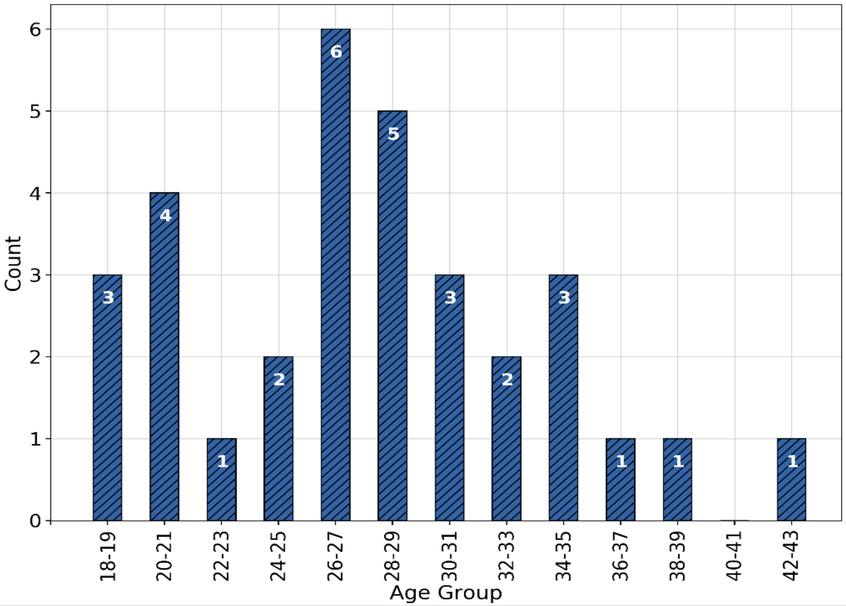


Figure 5.15: Histogram of participants' ages

5.3.3 Experiment Procedure

The experiment was approved by the Institutional Review Board (IRB). The experiment was conducted during March and April of 2021 where the safety measures of Coronavirus (COVID-19) disease must be fulfilled. Therefore, the simulator was cleaned before the participant reaching the driving simulator laboratory. Wearing a face mask was required for both the participant and the researcher along with practicing social distancing. Upon the participant reaching the laboratory, he/she was briefed about the driving simulator and the experiment. The participant also learned about unconventional intersections especially about the two unconventional intersections in this experiment (i.e., RCUT and SM intersections). A presentation that describes the movement pattern for every movement at RCUT and SM intersections was shown before starting the experiment. It also shows examples of the guide signs that direct the driver to go in the target direction. Explanation about using the driving simulator and the instructions that will be provided during the experiment was briefed. Then, the researcher answered any question in the participant's mind to ensure that he/she understood the nature of the experiment and movement patterns at these unconventional intersections.

After that, the participant was asked to complete a questionnaire about his/her driving experience. In the beginning, the participant was subjected to a 5-minutes trafficless practice route. During this route, the driver was asked to increase the speed, stop the vehicle, and make turning movements. The main objective of this route is to familiarize the participant with the simulator car (the gas pedal, the brake pedal, and the steering wheel) and the given instructions during the experiment (text, visual, and voice information). The driver was advised to drive as normal in real conditions and he/she can quit the experiment any time if getting motion sickness or feeling uncomfortable.

The order of unconventional intersections within every route, the order of the with-I2V and without-I2V routes, and the order of without-I2V routes themselves was changed to mitigate the order effect. This produced eight different route combinations. Every participant was randomly assigned a one route combination.

Between every two routes, the participant had a few-minutes break if he/she wanted. After finishing the experiment, the driver was asked to complete another questionnaire. The after-experiment questionnaire reports the participants' feedback about the experiment, the confusion at unconventional intersections, and the extent of signs and I2V communication usefulness.

5.4 Analysis Methodology

To investigate the driver understanding of the unconventional movements at RCUT and SM intersections, the number of accomplished and missed movements for every movement at the three intersection types have been determined. The driver was considered missed the movement if he/she did not accomplish the movement in the right way from the first time. Data of accomplished movements was only utilized for the analysis.

In order to investigate the driving behavior at unconventional intersections especially at the SM intersection and to evaluate the effectiveness of using I2V communication for mitigating the driving confusion at unconventional intersections, four surrogate safety measures related to the subject vehicle were calculated:

1. The Relative Area of Speeding (*Moreno and García, 2013*): the normalized relative area (per unit time) bounded between the speed profile and the speed limit line where speed is above the speed limit.

2. The Relative Area of Sudden Acceleration: the normalized relative area (per unit time) bounded between the acceleration profile and 6.6 ft/s^2 acceleration line (*Silva and Eugenio Naranjo, 2020*) where acceleration is above the 6.6 ft/s^2. The value of 6.6 ft/s^2 was adopted as the threshold of sudden acceleration because low traffic flow was adopted in this experiment.

3. The Relative Area of Sudden brake: the normalized relative area (per unit time) bounded between the deceleration profile and 6.6 ft/s^2 deceleration line (*Silva and Eugenio Naranjo, 2020*) where deceleration is above the 6.6 ft/s^2. The value of 6.6 ft/s2 was adopted as the threshold of sudden deceleration because low traffic flow was adopted in this experiment.

4. Lane Deviation (*Savino, 2009*): the standard deviation of the vehicle position within the lane.

The driver was considered that he/she starts doing a specific movement once getting the direction message (heading north, east, west, or south) until the driver completes the target movement and leave the intersection.

The one-way (RM-ANOVA) was employed for testing whether values of the surrogate safety measure at the three intersection types are significantly different. This was repeated for every movement type in this experiment. The Greenhouse-Geisser corrected (GGC) p-value was adopted if the sphericity assumption (equality of variance of the differences between all groups) was not achieved. However, the Friedman test was employed if the assumption of normality was not achieved. Shapiro-Wilk and Mauchly’s tests have been used to check the normality and sphericity assumptions, respectively. The Paired T-test Post-Hoc test was employed if the one-way RM-ANOVA model indicated that there is a significant difference between the values at the 95% confidence level (p-value or GGC p-value < 0.05) to determine which values are significantly different from each other. While the Wilcoxon Signed-Rank Post-Hoc test was employed for non-normal data. Figure 5.16 shows a flowchart for the analysis methodology of the first experiment.

To evaluate the effectiveness of using I2V communication at unconventional intersections the Paired T-test was utilized. The Shapiro-Wilk test was used to check the normality of the data. If the normality assumption was not achieved, the Wilcoxon Signed-Rank test was used to determine whether the values with and without using I2V communication are significantly different at the 95% confidence level. Figure 5.17 shows a flowchart for the analysis methodology of the second experiment.

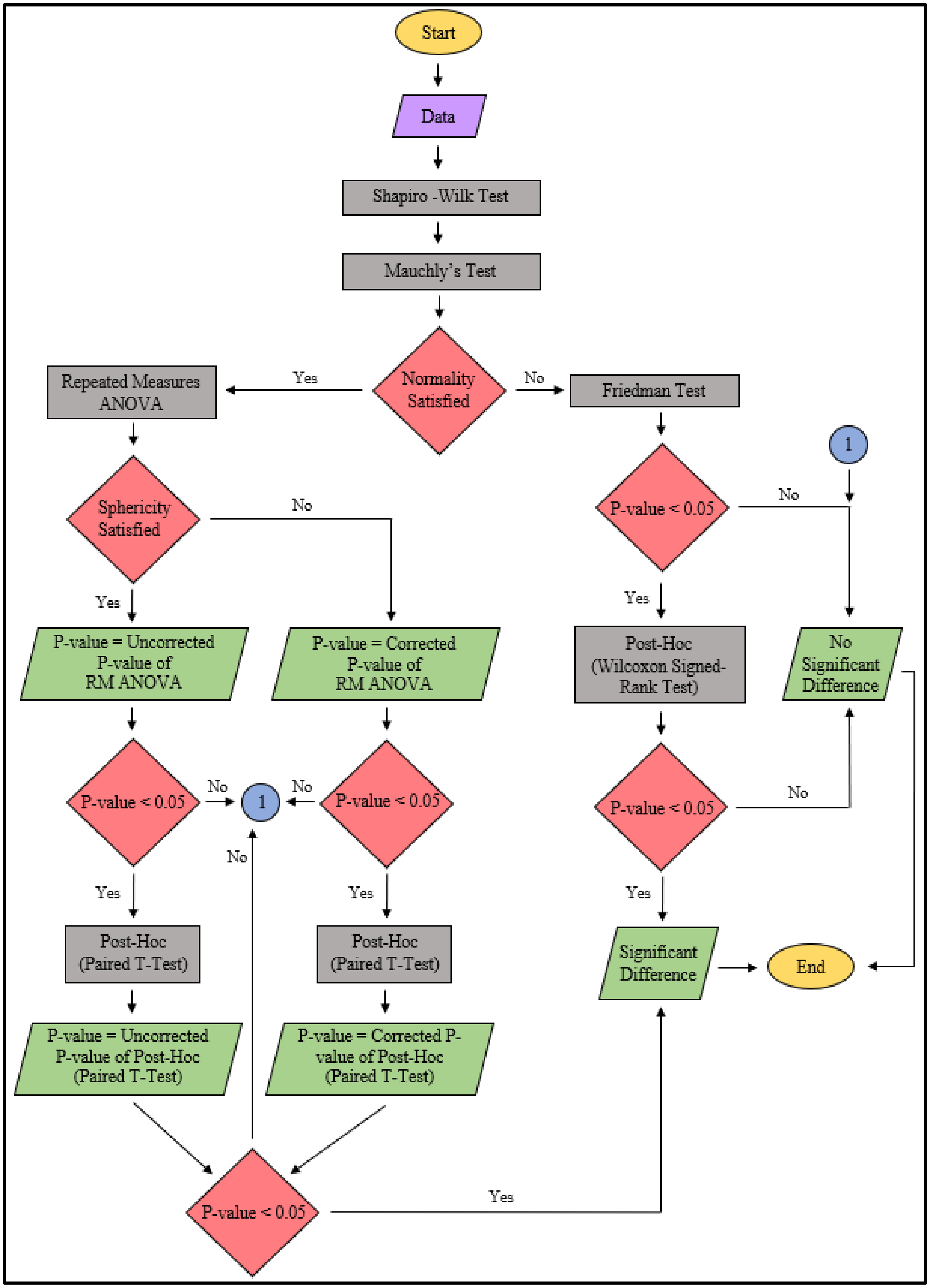


Figure 5.16: A flowchart for the analysis methodology of the first experiment

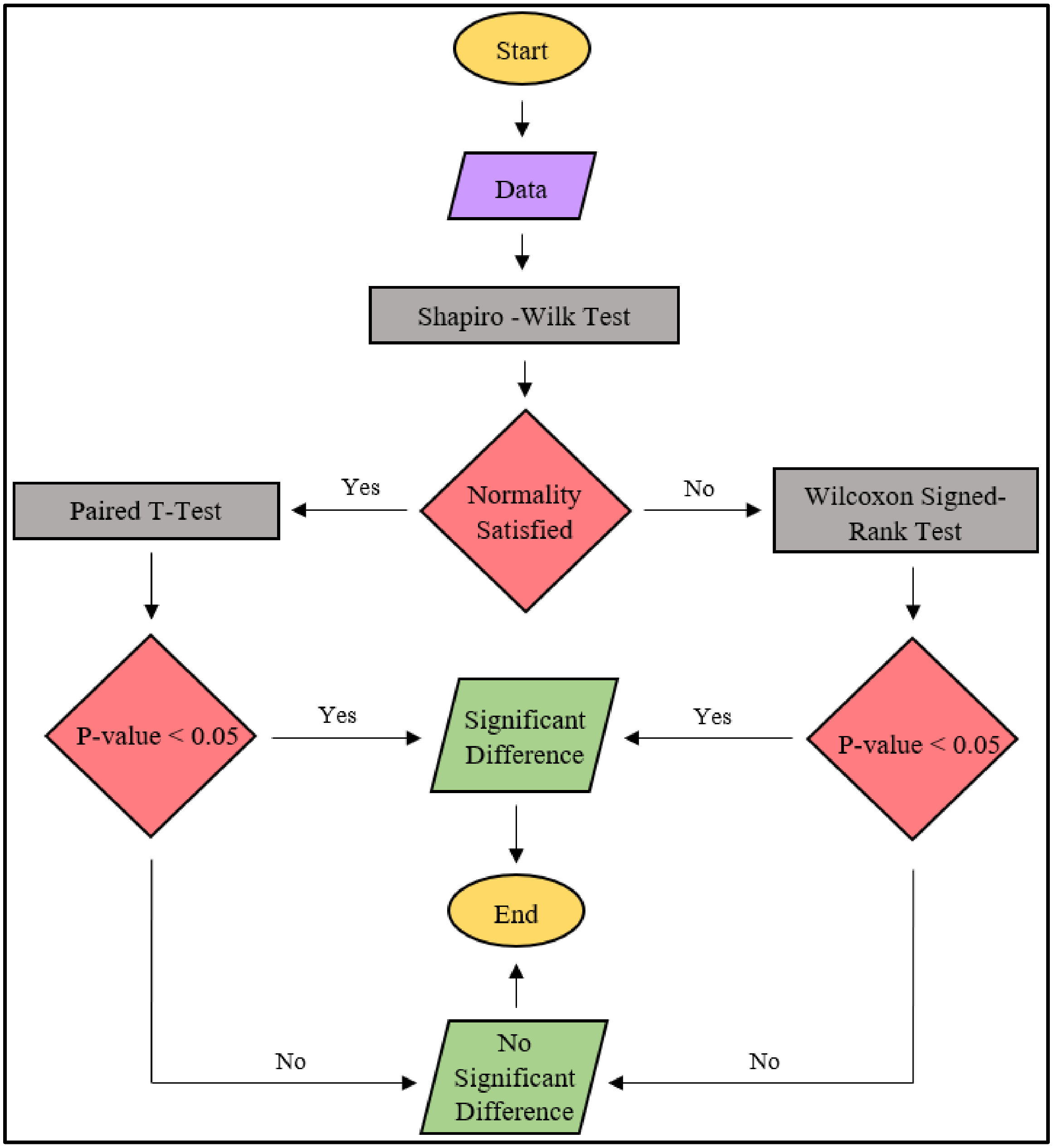


Figure 5.17: A flowchart for the analysis methodology of the second experiment

5.5 Analysis Results

5.5.1 Understanding of Unconventional Movements Patterns

After the experiment, the participant was asked to evaluate if he/she was confused at RCUT and SM intersections. Figure 5.18 shows that 19% of the participants were not confused while driving at RCUT and SM intersections. Seventy eight percent and 81% of participants found that RCUT and SM intersections are slightly confusing, respectively. While only 3% of participants got confused at the RCUT intersection.

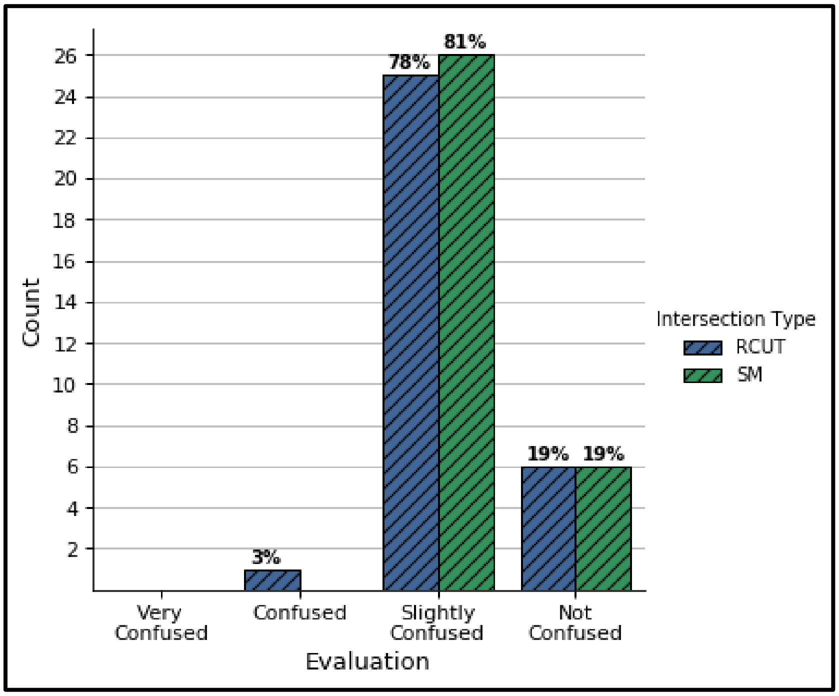


Figure 5.18: Evaluation of the confusion at RCUT and SM intersections
Note: RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection.

Figure 5.19 shows the number of accomplished and missed movements for every movement at conventional, RCUT, and SM intersections. Most participants have accomplished the minor right-turn, through, and left-turn movements at the three intersection types and the major left-turn movement at conventional and RCUT intersections. However, about half of participants only have accomplished the major left-turn at the SM intersection.

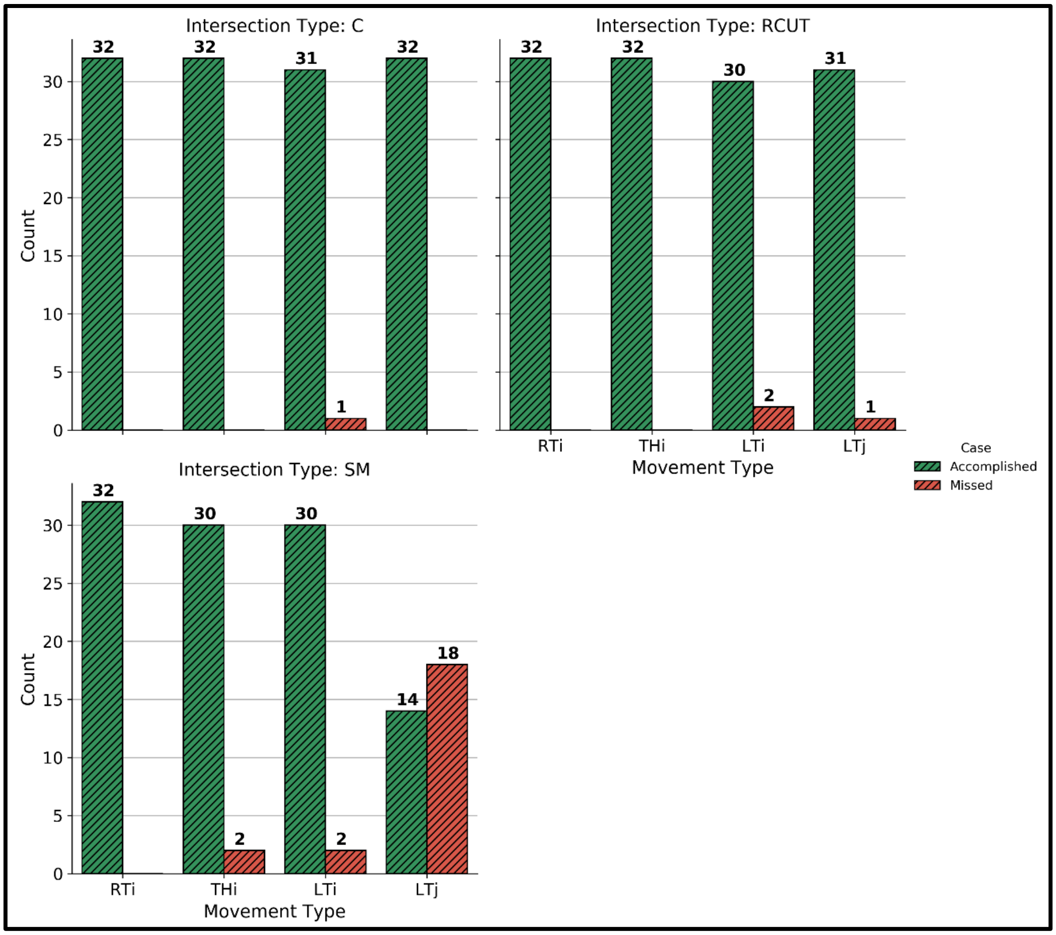


Figure 5.19: Number of accomplished and missed movements for every movement at conventional, RCUT, and SM intersections

Note: C: conventional intersection, RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, RTi: minor right-turn movement, THi: minor through movement, LTi: minor left-turn movement, LTj: major left-turn movement.

5.5.2 Driving Behavior at Unconventional Intersections

Several surrogate safety measures have been calculated while performing the different movements at the three intersection types. Table 5.1 shows descriptive statistics and the results of the adopted test to determine if the values of these measures at the three intersection types are significantly different or not.

The results indicated that significantly lower (P-value = 0.0001, 0.0004) speeding values (μ = 2.0 ± 1.9 mph) were recorded while performing the minor right-turn movement at the SM intersection in comparison with conventional and RCUT intersections (μ = 4.1 ± 3.3 mph, 3.2 ± 2.6 mph). While there was no significant difference in speeding behavior of this movement at conventioal and RCUT intersections. Minor through and left-turn movements at the conventional intersection are performed with significantly higher (C,RCUT: P-value = 0.0000, 0.0000; C,SM: P-value = 0.0000, 0.0004) speeding values (μ = 11.3 ± 7.9 mph, 4.7 ± 3.6 mph) than at RCUT and SM intersections (THi: μ = 1.1 ± 1.1 mph, 1.1 ± 1.3 mph; LTi: μ = 1.8 ± 1.6 mph, 2.5 ± 2.1 mph). There was no significant difference in speeding behavior of the minor through movement at RCUT and SM intersections, while drivers drive with significantly (P-value = 0.0272) more speeding (μ = 2.5 ± 2.1 mph) during performing the minor left-turn movement at the SM intersection in comaprison with the RCUT intersection (μ = 1.8 ± 1.6 mph). It was found that the speeding behavior while performing the major left-turn movement at the three intersection types is similar without significant difference.

The minor through movement at the conventional intersection is accomplished without sudden acceleration and sudden brake (μ = 0 ± 0 ft/s^2, 0 ± 0 ft/s^2) as significantly opposite (C,RCUT: P-value = 0.0006, 0.0001; C,SM: P-value = 0.0003, 0.0001) to acceleration and brakeing behaviors at RCUT and SM intersections where sudden acceleration and sudden brake behaviors have been recorded (RCUT: μ = 0.1 ± 0.1 ft/s^2, 0.6 ± 0.5 ft/s^2; SM: μ = 0.1 ± 0.1 ft/s^2, 0.6 ± 0.6 ft/s^2). Similar sudden acceleration and sudden brake behaviors have been noticed at RCUT and SM intersections. On the Other hand, there was no significant difference between sudden acceleration and sudden brake values of the other movements at the three intersection types except sudden acceleration values of the major left-turn movement. The results showed that this movement is performed at the conventional intersection with significantly (P-value = 0.0231) lower sudden acceleration values (μ = 0.0 ± 0.0 ft/s^2) in comparison to the value at the SM intersection (μ = 0.1 ± 0.1 ft/s^2).

The lane deviation of minor right-turn and major left-turn movements at the three intersection types were not significantly different. In contrast, the minor through movement at the conventional intersection is performed with significantly lower (P-value = 0.0000, 0.0000) lane deviation values (μ = 0.5 ± 0.2 ft) than at RCUT and SM intersections (μ = 1.5 ± 0.1 ft; 1.5 ± 0.2 ft). While there was no significant difference in the lane deviation of this movement at RCUT and SM intersections. On the other hand, the lane deviation of the minor left-turn movement at the SM intersection (μ = 1.3 ± 0.2 ft) is significantly lower (P-value = 0.0022, 0.0016) than at conventional and RCUT intersections (μ = 1.5 ± 0.2 ft; 1.5 ± 0.2 ft) without a significant difference in the lane deviation values of this movement at conventional and RCUT intersections. Figures 5.20 and 5.21 show the distribution of the different surrogate safety measures by movement and intersection types.

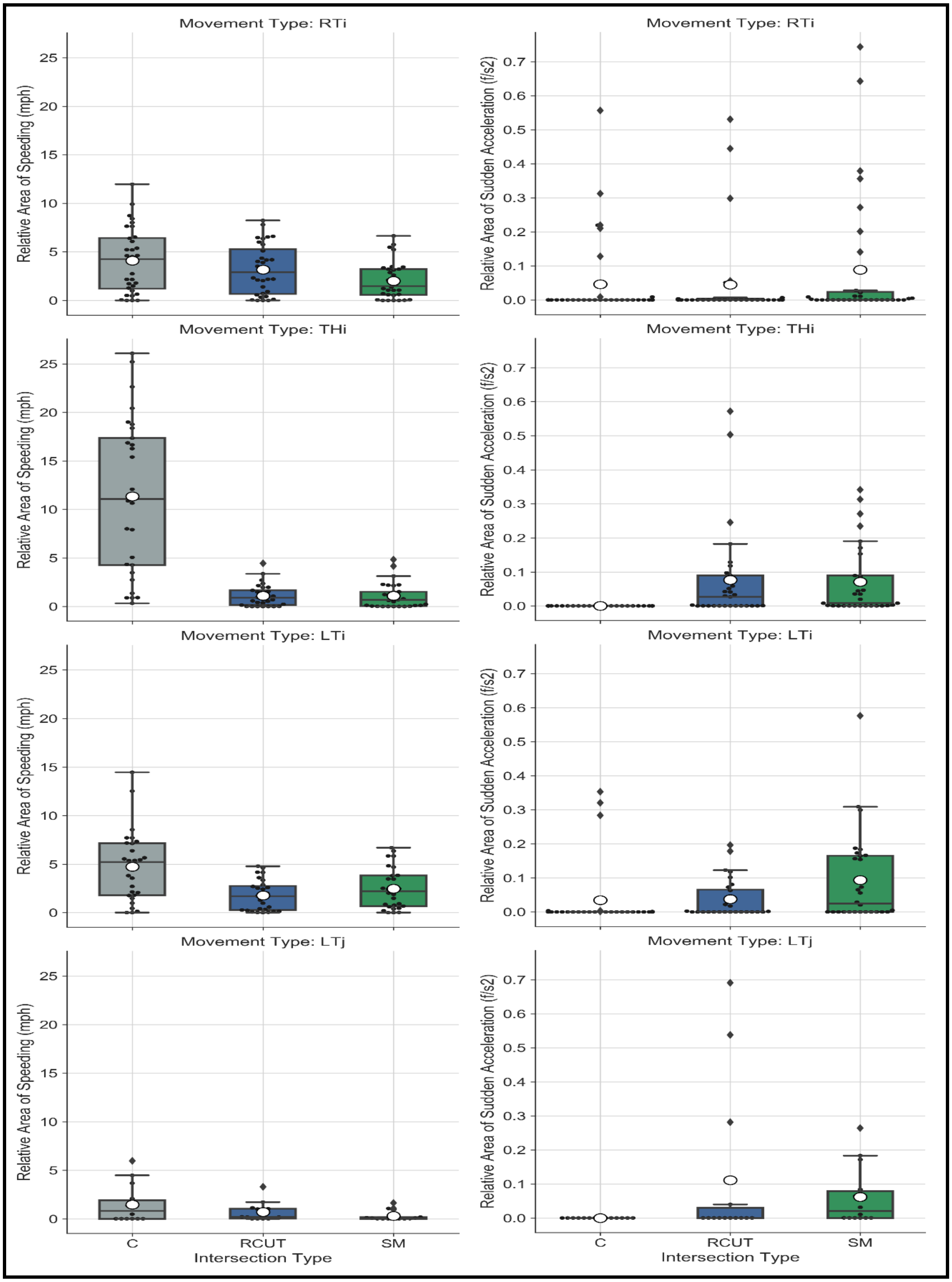


Figure 5.20: Distribution of relative area of speeding and sudden acceleration by movement and intersection types

Note: C: conventional intersection, RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, RTi: minor right-turn movement, THi: minor through movement, LTi: minor left-turn movement, LTj: major left-turn movement.

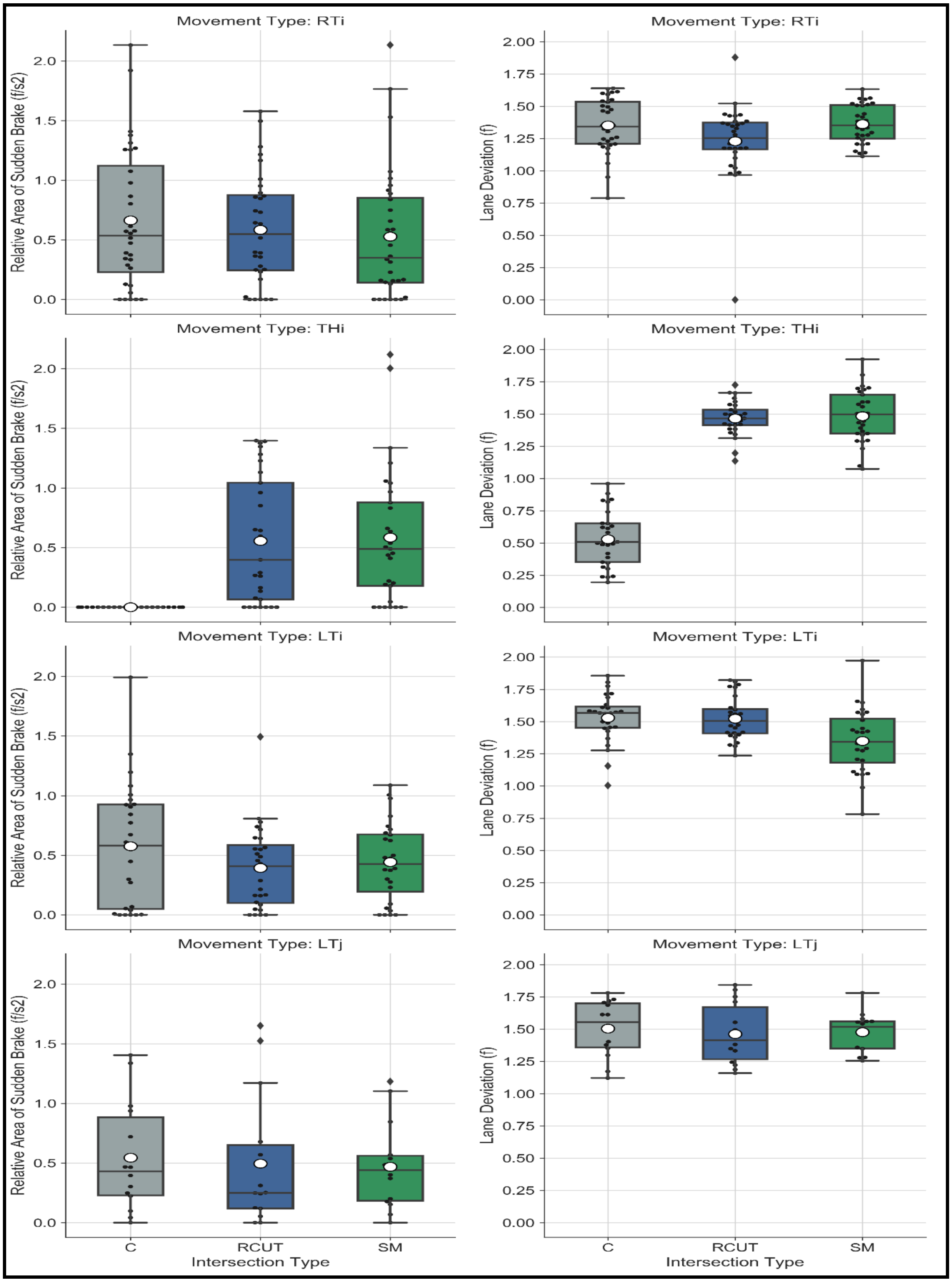


Figure 5.21: Distribution of relative area of sudden brake and lane deviation by movement and intersection types

Note: C: conventional intersection, RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, RTi: minor right-turn movement, THi: minor through movement, LTi: minor left-turn movement, LTj: major left-turn movement.

Table 5.1: Descriptive statistics of the surrogate safety measures and analysis results

Measure	**Intersection Type**	**Mean (Standard Deviation)**				**Comparison Level**	**Test Statistics, Degree of Fredom (P-value)**			
		RTi	**THi**	**LTi**	**LTj**		**RTi**	**THi**	**LTi**	**LTj**
Relative Area of Speeding (mph)						(C:RCUT:SM)	21.19^{F} (***0.0000***)	42.07^{F} (***0.0000***)	24.5^{F} (***0.0000***)	4.33^{F} (0.1146)
	C	4.1 (3.3)	11.3 (7.9)	4.7 (3.6)	1.5 (1.9)	(C:RCUT)	(0.0811)	(***0.0000***)	(***0.0000***)	-
	RCUT	3.2 (2.6)	1.1 (1.1)	1.8 (1.6)	0.7 (0.9)	(C:SM)	(***0.0001***)	(***0.0000***)	(***0.0004***)	-
	SM	2.0 (1.9)	1.1 (1.3)	2.5 (2.1)	0.3 (0.5)	(RCUT:SM)	(***0.0004***)	(0.9036)	(***0.0272***)	-
Relative Area of Sudden Acceleration (f/s^2)						(C:RCUT:SM)	2.95^{F} (0.2285)	25.41^{F} (***0.0000***)	7.25^{F} (***0.0266***)	10.24^{F} (***0.006***)
	C	0.0 (0.1)	0.0 (0.0)	0.0 (0.1)	0.0 (0.0)	(C:RCUT)	-	(***0.0006***)	(0.2161)	(0.1358)
	RCUT	0.0 (0.1)	0.1 (0.1)	0.0 (0.1)	0.1 (0.2)	(C:SM)	-	(***0.0003***)	(0.1602)	(***0.0231***)
	SM	0.1 (0.2)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	(RCUT:SM)	-	(0.8329)	(0.2161)	(0.9594)
Relative Area of Sudden Brake (f/s^2)						(C:RCUT:SM)	1.39^{F} (0.5001)	32.71^{F} (***0.0000***)	3.23^{F} (0.1992)	1.86^{F} (0.3951)
	C	0.7 (0.6)	0.0 (0.0)	0.6 (0.5)	0.5 (0.5)	(C:RCUT)	-	(***0.0001***)	-	-
	RCUT	0.6 (0.5)	0.6 (0.5)	0.4 (0.3)	0.5 (0.6)	(C:SM)	-	(***0.0001***)	-	-
	SM	0.5 (0.5)	0.6 (0.6)	0.4 (0.3)	0.5 (0.4)	(RCUT:SM)	-	(0.6892)	-	-
Lane Deviation (f)						(C:RCUT:SM)	3.0^{F} (0.2231)	280.66, 2/56RA (***0.0000***)	7.7, 2/54RA (***0.0011***)	0.14, 2/26RA (0.8732)
	C	1.4 (0.2)	0.5 (0.2)	1.5 (0.2)	1.5 (0.2)	(C:RCUT)	-	-20.02, 28^{T} (***0.0000***)	0.14, 27^{T} (0.8932)	-
	RCUT	1.2 (0.3)	1.5 (0.1)	1.5 (0.2)	1.5 (0.2)	(C:SM)	-	-19.76, 28^{T} (***0.0000***)	3.38, 27^{T} (***0.0022***)	-
	SM	1.4 (0.1)	1.5 (0.2)	1.3 (0.2)	1.5 (0.2)	(RCUT:SM)	-	-0.42, 28^{T} (0.6778)	3.52, 27^{T} (***0.0016***)	-

Note: C: conventional intersection, RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, RTi: minor right-turn movement, THi: minor through movement, LTi: minor left-turn movement, LTj: major left-turn movement, RA: RM-ANOVA, F: Friedman test, T: Paired T-test.

5.5.3 Evaluation of the Effectiveness of Using Infrastructure-To-Vehicle Communication

The first approach for evaluating the effectiveness of using I2V communication is its role in helping drivers to understand and accomplish the desired movement. The Chi-Square test (RCUT: $X^2(1) = 0.0076$, P-value = 0.9304; SM: $X^2(3) = 3.9288$, P-value = 0.2693) indicated that there is no association between using I2V communication and performing the unconventional movements at RCUT and SM intersections despite that there was a notable increase in the number of participants who performed the major left-turn movement at the SM intersection by using I2V communication. Figure 5.22 shows that by using I2V communication most drivers have done the major left-turn movement at the SM intersection. The number of drivers that accomplished this movement was doubled in the I2V communication environment. Moreover, the number of drivers that accomplished minor through and left-turn movements at RCUT and SM intersections slightly increased by implementing I2V communication.

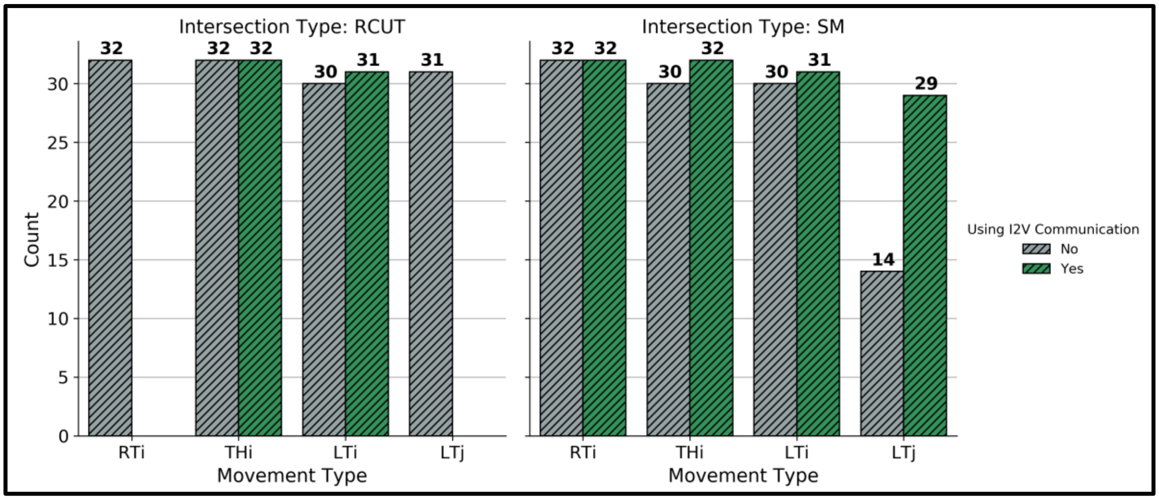


Figure 5.22: Number of accomplished unconventional movements at RCUT and SM intersections with and without using I2V communication

Note: RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, RTi: minor right-turn movement, THi: minor through movement, LTi: minor left-turn movement, LTj: major left-turn movement.

Figure 5.23 shows the participants' evaluation of the usefulness of using I2V communication in guidance at unconventional intersections. Most of the participants have found that providing I2V communication during performing the unconventional movements either is helpful (12% and 25% at RCUT and SM intersections, respectively) or very helpful (75% and 66% at RCUT and SM intersections, respectively).

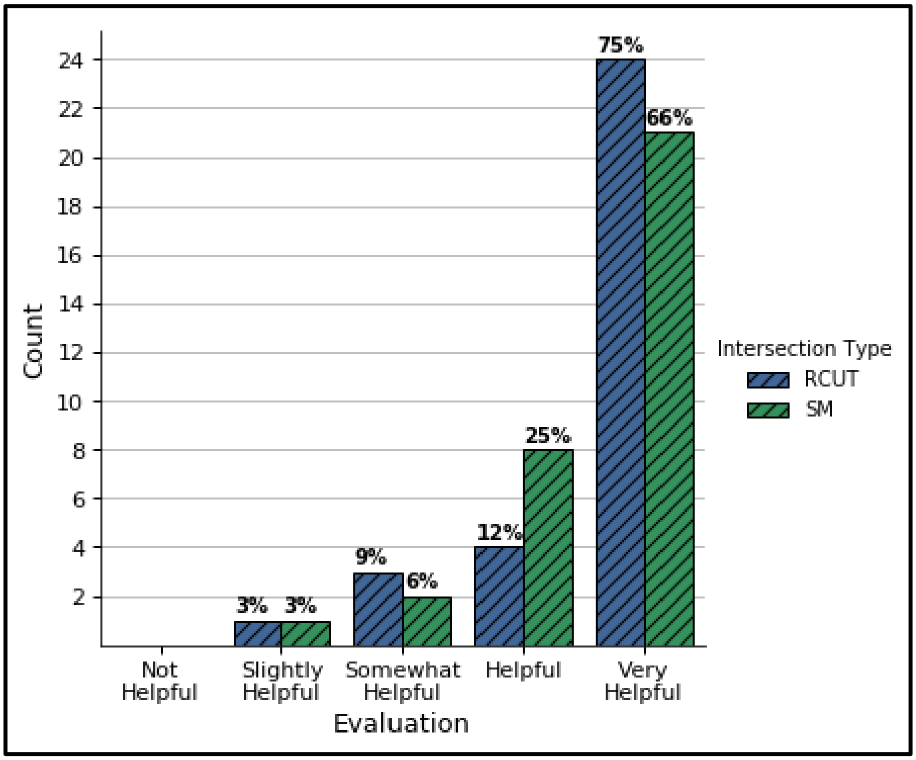


Figure 5.23: Evaluation of using I2V communication at RCUT and SM intersections
Note: RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection.

The second approach for the evaluation is the investigation of the influence of I2V communication implementation on improving traffic safety at RCUT and SM intersections. It was found that speeding, sudden acceleration, sudden brake, and lane deviation behaviors with and without using I2V communication are very similar and there were no significant differences except few cases. Significantly higher (P-value = 0.0415, 0.0362) speeding values (μ = 1.7 ± 1.7 mph, 1.7 ± 1.7 mph) have been recorded at RCUT and SM intersections while performing the minor through movement with using I2V communication in comparison without using it (μ = 1.1 ± 1.1 mph, 1.1 ± 1.3 mph). The lane deviation (μ = 1.4 ± 0.1 ft) during doing the minor through movement at the RCUT intersection with using I2V communication is significantly less (P-value = 0.0013) than without using it (μ = 1.5 ± 0.1 ft). It was also found that using I2V communication at the SM intersection significantly (P-value = 0.0479) increases the lane deviation (μ = 1.6 ± 0.1 ft) during performing the major left-turn movement in comparison with the absence of this technology (μ = 1.5 ± 0.2 ft). Figures 5.24 and 5.25 show the distribution of the different surrogate safety measures with and without implementing I2V communication. Table 5.2 shows descriptive statistics of these measures and the results of the adopted test to determine whether the difference between values is significant.

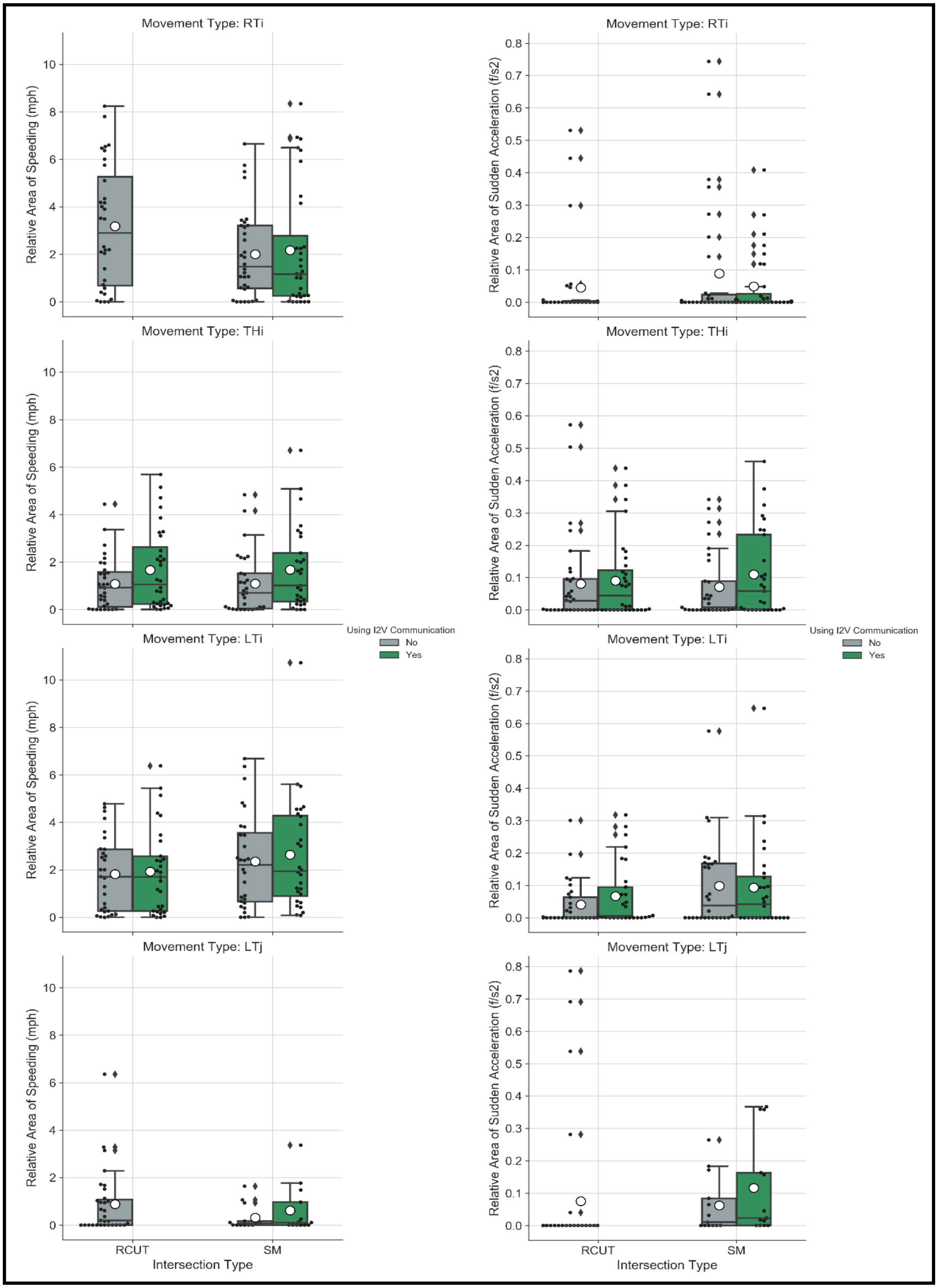


Figure 5.24: Distribution of relative area of speeding and sudden acceleration by movement and intersection types with and without using I2V communication

Note: RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, RTi: minor right-turn movement, THi: minor through movement, LTi: minor left-turn movement, LTj: major left-turn movement.

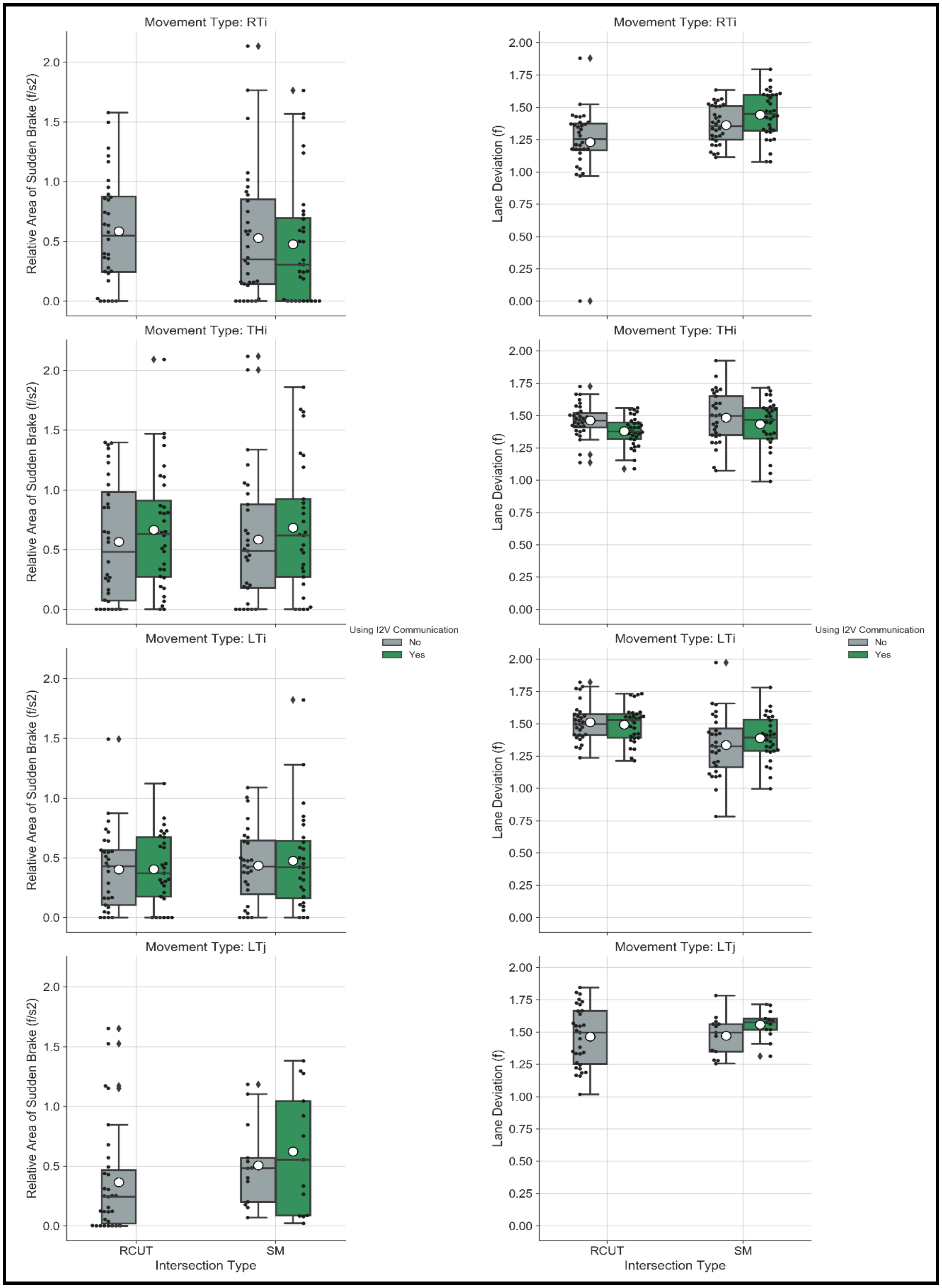


Figure 5.25: Distribution of relative area of sudden brake and lane deviation by movement and intersection types with and without using I2V communication

Note: RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, RTi: minor right-turn movement, THi: minor through movement, LTi: minor left-turn movement, LTj: major left-turn movement.

Table 5.2: Descriptive statistics of the surrogate safety measures and analysis results with and without using I2V communication

Measure	Intersection Type	Using I2V Commun-ication	Mean (Standard Deviation)				Test Statistics (P-value)			
			RTi	THi	LTi	LTj	RTi	THi	LTi	LTj
Relative Area of Speeding (mph)	RCUT	No	3.2 (2.6)	1.1 (1.1)	1.8 (1.6)	0.9 (1.4)	-	155.0^{W} (***0.0415***)	189.0^{W} (0.7499)	-
		Yes	-	1.7 (1.7)	1.9 (1.8)	-				
	SM	No	2.0 (1.9)	1.1 (1.3)	2.4 (2.0)	0.3 (0.5)	239.0^{W} (0.8600)	111.0^{W} (***0.0362***)	192.0^{W} (0.8022)	11.0^{W} (0.1731)
		Yes	2.2 (2.5)	1.7 (1.7)	2.6 (2.4)	0.6 (1.0)				
Relative Area of Sudden Acceleration (f/s^{2})	RCUT	No	0.0 (0.1)	0.1 (0.1)	0.0 (0.1)	0.1 (0.2)	-	142.0^{W} (0.5812)	123.0^{W} (0.2879)	-
		Yes	-	0.1 (0.1)	0.1 (0.1)	-				
	SM	No	0.1 (0.2)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	105.0^{W} (0.4852)	107.0^{W} (0.1353)	135.0^{W} (0.6682)	24.0^{W} (0.4236)
		Yes	0.0 (0.1)	0.1 (0.1)	0.1 (0.1)	0.1 (0.2)				
Relative Area of Sudden Brake (f/s^{2})	RCUT	No	0.6 (0.5)	0.6 (0.5)	0.4 (0.3)	0.4 (0.5)	-	181.0^{W} (0.1207)	175.0^{W} (0.9899)	-
		Yes	-	0.7 (0.5)	0.4 (0.3)	-				
	SM	No	0.5 (0.5)	0.6 (0.6)	0.4 (0.3)	0.5 (0.4)	165.0^{W} (0.3869)	139.0^{W} (0.2297)	186.0^{W} (0.6987)	-1.42^{T} (0.1810)
		Yes	0.5 (0.5)	0.7 (0.6)	0.5 (0.4)	0.6 (0.5)				
Lane Deviation (f)	RCUT	No	1.2 (0.3)	1.5 (0.1)	1.5 (0.2)	1.5 (0.2)	-	3.53^{T} (***0.0013***)	0.51^{T} (0.6138)	-
		Yes	-	1.4 (0.1)	1.5 (0.1)	-				
	SM	No	1.4 (0.1)	1.5 (0.2)	1.3 (0.2)	1.5 (0.2)	-2.26^{T} (***0.0312***)	1.19^{T} (0.2444)	-1.27^{T} (0.2136)	-2.2^{T} (***0.0479***)
		Yes	1.4 (0.2)	1.4 (0.2)	1.4 (0.2)	1.6 (0.1)				

Note: RCUT: restricted crossing U-turn intersection, SM: shifting movements intersection, RTi: minor right-turn movement, THi: minor through movement, LTi: minor left-turn movement, LTj: major left-turn movement, T: Paired T-test, W: Wilcoxon Signed-Rank test.

5.6 Discussion of Results

Missing the major left-turn movement at the SM intersection could be interpreted by two reasons: 1) the driver did not understand how to perform this movement at the SM intersection, or 2) the driver forgot the desired direction or where is the desired direction. Half of the drivers who missed this movement by either continuing straight or turning right at the central area stated that they did not get enough information from signs on how to perform the movement. While others who also missed the movement succeeded to access the side street, but they said that they forgot the desired direction or where is the desired direction after leaving the side street.

Several measures can be adopted to improve drivers' awareness and behavior about performing the major left-turn movement at the SM intersection. Firstly, improvement of the driver knowledge about traffic movement patterns at the SM intersection through the different media sources and transportation agencies' publications. Adopting different sign configurations and locations could help for getting drivers' attention to provide clearer information on how to perform this movement as installing the signs at the median (on the left-hand side of the driver) where could have a better influence because of they will be at the driver's line of sight. Overhead signs could also have a better influence on getting drivers' attention at sufficient distance upstream of the intersection. Using I2V communication will be an effective solution as found that most participants have accomplished this movement in the I2V communication environment.

Speeding behavior is a major cause of crashes especially at intersections (*Pirdavani et al., 2010*). It is mainly related to fatal crashes where it contributed to 26% of fatal crashes in 2019 (*NHTSA, 2021*), therefore low speeding values while doing the movement is an indicator for a safer traffic operation. Accordingly and although that the minor right-turn movement pattern at conventional, RCUT, and SM intersections is similar, turning right at the SM intersection is safer than at conventional and RCUT intersections as a result of the significantly lowest speeding values. Traffic operation while performing minor through and left-turn movements at RCUT and SM intersection is safer than at the conventional intersection due to the significantly higher speeding values while doing these movements in a conventional way. Turning left from the minor road at the RCUT intersection is safer than doing this at the SM intersection. The compulsion of drivers to deviate from the straight track by making turning movements at the main intersection and the median crossover (at the RCUT intersection) and the upstream/downstream intersection (at the SM intersection) mitigates the speeding behavior of the driver. Figures 5.26, 5.27, and 5.28 show speed profiles for the different movements at the three intersection designs. It is shown that the driver reduces the speed while turning right and making a U-turn. On the other hand, this interprets the high values of sudden acceleration and sudden brake at RCUT and SM intersections while performing the minor through movement in comparison with the conventional intersection which increases the potential for crash occurrence because sudden acceleration and sudden brake are indicators of aggressive driving behavior (Aljaafreh *et al., 2012*) and they associated with crash occurrence especially rear-end crashes.

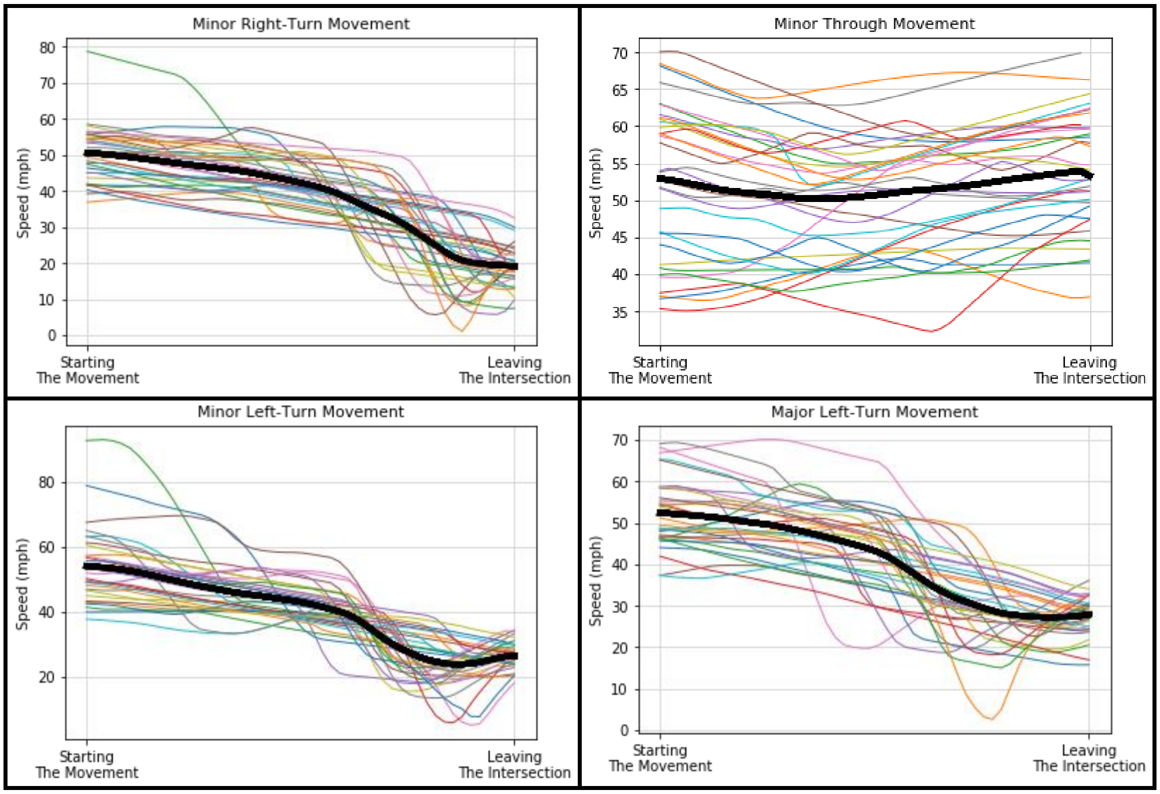


Figure 5.26: Speed profiles at the conventional intersection

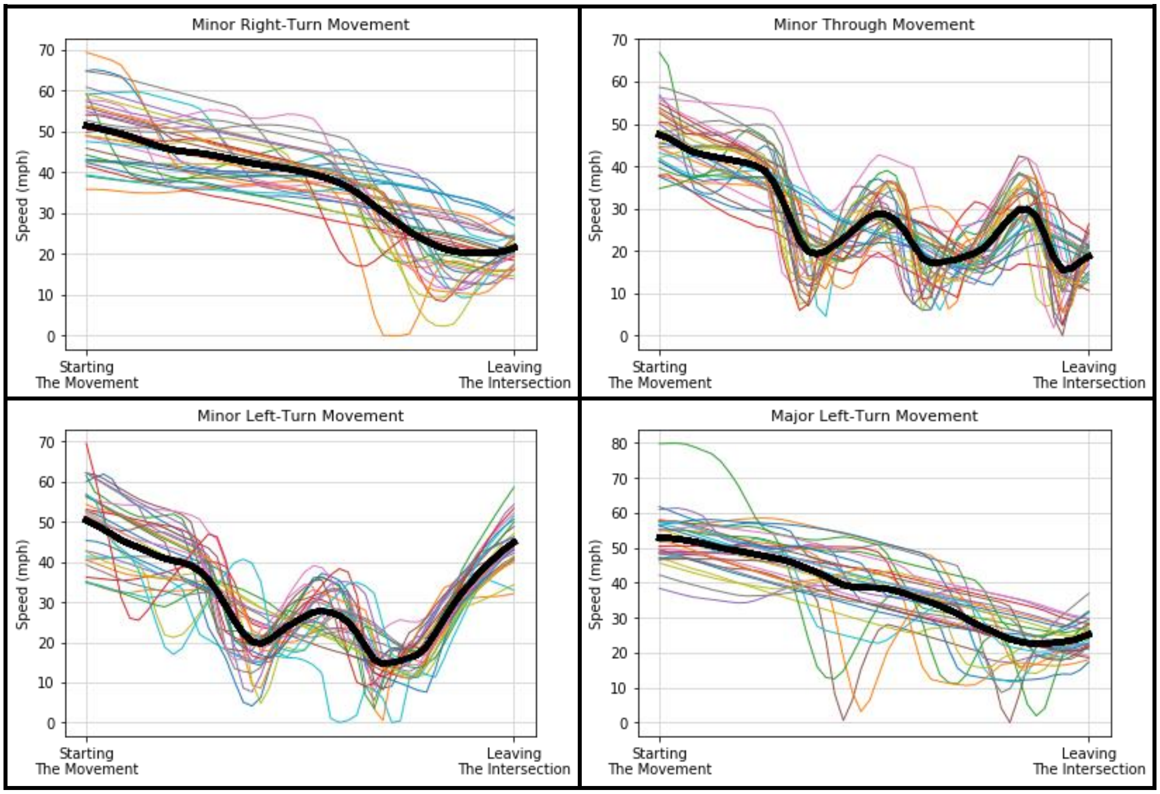


Figure 5.27: Speed profiles at the RCUT intersection

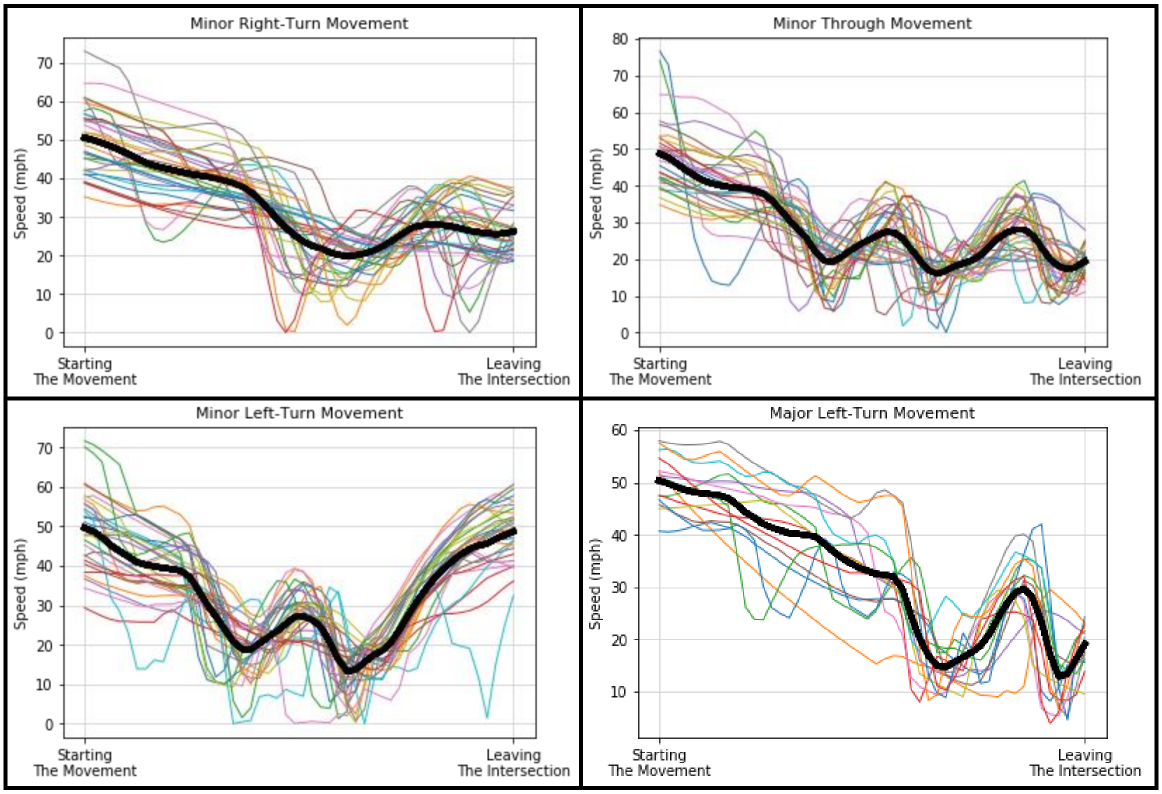


Figure 5.28: Speed profiles at the SM intersection

Moreover, plenty of turning movements while performing the minor through movement at RCUT and SM intersections (3 turning movements) could be the reason for the high lane deviation values while doing this movement at RCUT and SM intersections in comparison with the conventional intersection. Since the lane deviation is a measure of driving stability, performing the minor through movement at the conventional intersection is done with more stable driving behavior in comparison with at RCUT and SM intersections. On the other hand, turning left from the minor road at the SM intersection is done with the most stabilization among other intersections.

Even though that all these surrogate safety measures are indicators for traffic safety, the most relevant behavior with severe crash occurrence is speeding. Therefore, performing the minor through movement at RCUT and SM intersections is safer than at the conventional intersection although the high sudden acceleration, sudden brake, and lane deviation values. Turning left from the minor road at RCUT and SM intersections is safer than at the conventional intersection. In addition, performing this movement at the RCUT intersection is safer than at the SM intersection although the low lane deviation values while turning left at the SM intersection. In contrast, turning right from the minor road at the SM intersection is safer than at conventional and RCUT intersections. While there was no significant difference in driving behavior while turning left from the major road among the three intersection designs.

The lack of significant differences in driving behavior while performing most of the movements at RCUT and SM intersections with and without using I2V communication gives an indication that participants who successfully performed the unconventional movements at RCUT and SM intersections without using I2V communication were totally understanding the patterns of these movements and they accomplished the movements without confusion.

5.7 Conclusions and Recommendations

Investigation of the traffic safety effectiveness of the SM intersection and the driving behavior while performing the unconventional movements of the SM intersection was the main objective of this driving simulation experiment. Furthermore, evaluation of the extent of the helpfulness of using I2V communication on mitigating drivers' confusion while maneuvers at RCUT and SM intersections was also accomplished in this study. The SM intersection along with conventional and RCUT intersections was simulated in the NADS MiniSim^{TM} driving simulator at UCF. Several signs were designed and installed at these intersections to guide and help drivers to perform the unconventional movements at RCUT and SM intersections. The driving data was obtained from thirty-two participants who have totally completed the experiment. Normalized relative area of speeding, sudden acceleration, and sudden brake and lane deviation were the performance measures that have been adopted for the evaluation in this study.

Most participants have accomplished the unconventional movements at RCUT and SM intersections. However, about half of participants have missed the major left-turn movement at the SM intersection. The results indicated that RCUT and SM intersections have similar safety effectiveness and performing the minor road movements at them is safer than at the conventional intersection. The evaluation of using I2V communication indicated that it is effective in guiding drivers to perform the major left-turn movement at the SM intersection and most participants have found it helpful.

Improving drivers' awareness regarding the major left-turn movement at the SM intersection must be achieved by educating drivers through the different media sources. Testing the effectiveness of different sign configurations to guide drivers for performing the major left-turn movement at the SM intersection must be covered in future research.

CHAPTER 6: CONCLUSIONS

6.1 Summary

This dissertation aims to investigate the safety and operational effectiveness of the median crossover-based signalized intersections on arterials by attaining five main tasks: (1) evaluation of the safety benefits of implementing median U-turn crossover-based intersections (i.e. median U-turn (MUT) and restricted crossing U-turn (RCUT) intersections) by developing safety performance functions (SPF) and estimating crash modification factors (CMF) for the different crash severities and types, (2) proposition of a new intersection design (i.e. the shifting movements (SM) intersection) as an alternative to the 4-leg conventional intersection and to replace the implementation of the RCUT intersection under moderate and heavy minor road traffic conditions, (3) evaluation of the operational performance of the SM intersection design in the microscopic simulation environment, (4) evaluation of the safety performance of the SM intersection design in the driving simulation environment, and (5) evaluation of the effectiveness of implementing infrastructure-to-vehicle (I2V) communication on the driving behavior and mitigation of confusion at unconventional intersection designs.

In Chapter 3, SPFs for the crash frequency at MUT intersections were developed and CMFs for the implementation of MUT and RCUT intersections were estimated for the different crash severities and types to quantify their effectiveness in crash reduction. The results concluded that MUT and RCUT intersections have similar effects on crash reduction, and they are safer than conventional intersections due to their effectiveness in reducing most crash types. The RCUT intersection is more recommended for implementation than the MUT intersection due to its higher ability to reduce crash severity (i.e., equivalent property damage only value) at the intersection.

In Chapter 4, a new 4-leg intersection design (i.e., the SM intersection design) has been proposed and introduced. Evaluation of the operational performance of the SM intersection design compared to conventional and RCUT intersections has been conducted in the microscopic simulation environment. Different traffic volume levels and left-turn proportions have been assumed to represent the peak hour with moderate to high left-turn traffic volumes. The results demonstrated that unconventional intersection designs have a better performance at heavy traffic volumes and left-turn proportions. The SM intersection design outperforms the RCUT design at moderate to heavy traffic volumes. Therefore, the SM intersection is recommended for implementation at locations with moderate and high minor road traffic volumes.

In Chapter 5, evaluation of the safety effectiveness of the SM intersection and the driving behavior while performing the unconventional movements of the SM intersection was accomplished by using the driving simulator. Furthermore, evaluation of the effectiveness of using I2V communication on mitigation of confusion while maneuvers at RCUT and SM intersections was also accomplished. The normalized relative area of speeding, sudden acceleration, and sudden brake and lane deviation measures were the performance measures that have been adopted for the evaluation. The results indicated that a considerable number of participants have missed the major left-turn movement at the SM intersection. RCUT and SM intersections have similar safety effectiveness and performing minor-road movements at them is safer than at the conventional intersection. The evaluation of using I2V communication indicated that it is effective in guiding drivers to perform the major left-turn movement at the SM intersection.

6.2 Implications

The dissertation developed SPFs for predicting crash frequency at MUT intersections and estimated CMFs for the different crash severities and types at MUT and RCUT intersections to quantify their effectiveness in crash reduction. This provides a solid reference for decision-makers concerning the conversion from conventional intersections to MUT and RCUT intersections. The dissertation proposed a new intersection design (the SM intersection) that has the ability to improve traffic safety and operation at intersections, particularly under high entering traffic volumes.

APPENDIX: APPROVAL OF HUMAN RESEARCH

UNIVERSITY OF CENTRAL FLORIDA

Institutional Review Board
FWA00000351
IRB00001138Office of Research
12201 Research Parkway
Orlando, FL 32826-3246

APPROVAL

September 20, 2019

Dear Mohamed Abdel-Aty:

On 9/20/2019, the IRB reviewed the following submission:

Type of Review:	Initial Study
Title:	Investigation of Driving Behavior at Alternative Intersection Designs and Safety Improvement: A Driver Simulator Study
Investigator:	Mohamed Abdel-Aty
IRB ID:	STUDY00000782
Funding:	Name: University of Iowa, Grant Office ID: 1066995, Funding Source ID: 69A3551747131
Grant ID:	1066995;
IND, IDE, or HDE:	None
Documents Reviewed:	• consent_form_2019_simulator_V4.pdf, Category: Consent Form; • Data collection sheet, Category: Other; • IRB protocal, Category: IRB Protocol; • Simulation questionnaire_After (1).docx, Category: Survey / Questionnaire; • Simulation questionnaire_Before (1).docx, Category: Survey / Questionnaire;

The IRB approved the protocol from 9/20/2019.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system.

If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Adrienne Showman
Designated Reviewer

REFERENCES

AASHTO. *A Policy on Geometric Design of Highways and Streets*. American Association of State Highway Transportation Officials, Washington D.C., USA, 2004.

AASHTO. *Highway Safety Manual*. American Association of State Highway Transportation Officials, Washington D.C., USA, 2010.

Abdel-Aty, M. A., and A. E. Radwan. Modeling Traffic Accident Occurrence and Involvement. *Accident Analysis and Prevention*, 2000. 32(5): 633-642.

Aljaafreh, A., N. Alshabatat, and M. S. N. Al-Din. Driving Style Recognition Using Fuzzy Logic. *In Proceedings of the 2012 IEEE International Conference on Vehicular Electronics and Safety (ICVES)*. Istanbul, Turkey, 2012. 460-463.

Al-Omari, M. M. A., M. Abdel-Aty, J. Lee, L. Yue, and A. Abdelrahman. Safety Evaluation of Median U-Turn Crossover-Based Intersections. *Transportation Research Record,* 2020. 2674(7): 206-218.

Al-Omari, M. M. A., and M. Abdel-Aty. Evaluation of a New Intersection Design, "Shifting Movements". *Transportation Research Record*, 2021. 2675(10): 1352-1363.

AustRoads. *Road Safety Engineering Risk Assessment Part 7: Crash Rates Database*. Sydney, NSW, Australia, 2010.

Azizi, L., A. Sheikholeslami, and F. B. Khalili. Safety Analysis of Unconventional U-Turn Using Neural Network and Crash Prediction Model. *In 10th International Congress on Advances in Civil Engineering*. Middle East Technical University, Ankara, Turkey, 2012. 17-19.

Azizi, L., and A. Sheikholeslami. Safety Effect of U-Turn Conversions in Tehran: Empirical Bayes Observational Before-and-After Study and Crash Prediction Models. *Journal of Transportation Engineering*, 2013. 139(1): 101-108.

Bared, J. G., and E. I. Kaisar. Median U-Turn Design as An Alternative Treatment for Left Turns at Signalized Intersections. *ITE Journal*, 2002. 72(2): 50-54.

Bared, J. *Restricted Crossing U-Turn Intersection*. Publication No. FHWA-HRT-09-059. Federal Highway Administration (FHWA), U.S. Department of Transportation, Washington, D.C., USA, 2009.

Bujang, M. A., and T. H. Adnan. Requirements for Minimum Sample Size for Sensitivity and Specificity Analysis. *Journal of Clinical and Diagnostic Research: JCDR*, 2016. 10(10): 1-6.

Campbell, J. L., C. M. Richard, and J. Graham. *Human Factors Guidelines for Roadway Systems*. NCHRP Report 600B. Transportation Research Board, National Research Council, Washington, D.C, 2008.

Carter, D., R. Srinivasan, F. Gross, and F. Council. *Recommended Protocols for Developing Crash Modification Factors*. Final Report NCHRP, 2012. 2027(314).

Castronovo, S., P. W. Dorothy, M. C. Scheuer, and T. L. Maleck. *The Operational and Safety Aspects of the Michigan Design for Divided Highways*. Volume I, Michigan State University, College of Engineering. 1995.

Claros, B., Z. Zhu, P. Edara, and C. Sun, Design Guidance for J-Turns on Rural High-Speed Expressways. *Transportation Research Record*, 2017. 2618(1), 69-77.

Edara, P., C. Sun, and S. Breslow. *Evaluation of J-turn Intersection Design Performance in Missouri*. No. cmr 14-005. Missouri Department of Transportation, Missouri, USA, 2013.

Edara, P., S. Breslow, C. Sun, and B. R. Claros. Empirical Evaluation of J-turn Intersection Performance: Analysis of Conflict Measures and Crashes. *Transportation Research Record*, 2015. 2486(1): 11-18.

El Esawey, M., and T. Sayed. Operational Performance Analysis of the Unconventional Median U-turn Intersection Design. *Canadian Journal of Civil Engineering*, 2011. 38(11): 1249-1261.

Faul, F., E. Erdfelder, A. Buchner, and A. G. Lang. Statistical Power Analyses Using G* Power 3.1: Tests for Correlation and Regression Analyses. *Behavior Research Methods*, 2009. 41(4): 1149-1160.

Fitzpatrick, K., D. Lord, and B. J. Park. Accident Modification Factors for Medians on Freeways and Multilane Rural Highways in Texas. *Transportation Research Record*, 2008. 2083(1), 62-71.

Gluck, J. S., H. S. Levinson, and V. G. Stover. Impacts of Access Management Techniques. *Transportation Research Board*, 1999. 420.

Griffith, M. S. Safety Evaluation of Rolled-in Continuous Shoulder Rumble Strips Installed on Freeways. *Transportation Research Record*, 1999. 1665(1), 28-34.

Gross, F., B. N. Persaud, and C Lyon. *A Guide to Developing Quality Crash Modification Factors*. Publication No. FHWA-SA-10-032. Federal Highway Administration. U.S. Department of Transportation, Washington, D.C., USA, 2010.

Haley, R. L., S. E. Ott, J. E. Hummer, R. S. Foyle, C. M. Cunningham, and B. J. Schroeder. Operational Effects of Signalized Superstreets in North Carolina. *Transportation Research Record*, 2011. 2223(1): 72-79.

Hashim, I. H., M. Ragab, and G. M. Asar. Evaluation of Operational and Environmental Performance of Median U-Turn Design Using Microscopic Simulation. *International Journal for Traffic and Transport Engineering*, 2017. 7(1): 37-51.

Hauer, E. *Observational Before-After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*. Pergamon Press, Elsevier Science Ltd, Oxford, United Kingdom, 1997.

Henderson, S., and N. Stamatiadis. Use of Median U-Turns to Improve Traffic Flow Along Urban Arterials. *Journal of the Transportation Research Forum*, 2001. 40(2), 137-145.

Highway Capacity Manual, *Transportation Research Board*, National Research Council, Washington, DC, U.S.A, 2010.

Hochstein, J. L., T. H. Maze, T. M. Welch, H. Preston, and R. Storm. The J-Turn Intersection: Design Guidance and Safety Experience. *Presented at 88th Annual Meeting of Transportation Research Board*, Washington, D.C., U.S.A, 2009.

Holzem, A. M., J. E. Hummer, C. M. Cunningham, S. W. O'Brien, B. J.Schroeder, and K. Salamati. Pedestrian and Bicyclist Accommodations and Crossings on Superstreets. *Transportation Research Record*, 2015. 2486(1): 37-44.

Hughes W., R. Jagannathan, D. Sengupta, and J. Hummer. *Alternative Intersections/Interchanges: Informational Report (AIIR)*. Publication No. FHWAHRT-09-060. Office of Research, Development, and Technology. Federal Highway Administration, U.S. Department of Transportation, McLean, VA, U.S.A, 2010.

Hummer, J. E., and R. Jagannathan. An Update on Superstreet Implementation and Research. *Presented at 8th National Conference on Access Management, Transportation Research Board*, Baltimore, MD, U.S.A, 2008.

Hummer, J. E., R. L. Haley, S. E. Ott, R. S. Foyle, and C. M. Cunningham. *Superstreet Benefits and Capacities*. Publication No. FHWA/NC/2009-06. Department of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, North Carolina, USA, 2010.

Hummer, J., B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Restricted Crossing U-turn Informational Guide*. Publication No. FHWA-SA-14-070. Office of Safety. Federal Highway Administration (FHWA), U.S. Department of Transportation, Washington, D.C., USA, 2014.

Hummer, J. E., and S. Rao. *Safety Evaluation of a Signalized Restricted Crossing U-Turn*. Publication No. FHWA-HRT-17-082. Office of Safety Research and Development. Federal Highway Administration, U.S. Department of Transportation, McLean, VA, U.S.A, 2017.

Inman, V. W. Evaluation of Signs and Markings for Partial Continuous Flow Intersection. *Transportation Research Record*, 2009. 2138(1): 66-74.

Inman, V. W., and R. P. Haas. *Field Evaluation of a Restricted Crossing U-Turn Intersection*. Publication No. FHWA-HRT-11-067. Office of Safety Research and Development. Federal Highway Administration, U.S. Department of Transportation, McLean, VA, U.S.A, 2012.

Inman, V. W., R. P. Haas, and C. D. Yang. Evaluation of Restricted Crossing U-Turn Intersection as a Safety Treatment on Four-Lane Divided Highways, *ITE Journal*, 2013. 83 (9): 29-35.

Jagannathan, R. *Synthesis of the Median U-Turn Intersection Treatment, Safety, and Operational Benefits*. Publication No. FHWA-HRT-07-033. Office of Research, Development, and Technology. Federal Highway Administration. U.S. Department of Transportation, McLean, VA, U.S.A. 2007.

Kach, B. *The Comparative Accident Experience of Directional and Bi-Directional Signalized Intersections*. Michigan Department of Transportation, Modeling and Analysis Subunit. 1992.

Kennedy, J. V., R. Gorell, L. Crinson, A. Wheeler, and M. A. Elliott. *Psychological Traffic Calming*. 2005.

Kim, T., P. K. Edara, and J. G. Bared. Operational and Safety Performance of a Nontraditional Intersection Design: The Superstreet. *Proceeding of the 86th Annual Meeting of the Transportation Research Board*. Washington, DC, USA, 2007.

Kivlins, A., and J. R. Naudzuns. Analysis of Unconventional Signalized At-Grade Intersections. *Scientific Journal of Riga Technical University*, 2011. 12: 17-26.

La Torre, F., L. Domenichini, and A. Nocentini. Effects of Stationary Work Zones on Motorway Crashes. *Safety Science*, 2017. 92: 148-159.

Levinson, H. S., F. J. Koepke, D. Geiger, D. Allyn, and C. Palumbo. Indirect Left-Turns: The Michigan Experience. *Proceeding of the 4th Annual National Access Management Conference*. Portland, OR, USA, 2000.

Lord, D., and J. A. Bonneson. Development of Accident Modification Factors for Rural Frontage Road Segments in Texas. *Transportation Research Record*, 2007. 2023(1): 20-27.

Lu, J. J., and S. Dissanayake. Safety Evaluation of Direct Left Turns Vs Right Turns Followed by U-Turns Using Traffic Conflict Technique. *Traffic and Transportation Studies*, 2002. 1039-1046.

Maki, R. E. Directional Crossovers: Michigan's Preferred Left Turn Strategy. *Proceeding of the 75th Annual Meeting of the Transportation Research Board*. Washington, DC, USA, 1996.

Manual on Uniform Traffic Control Devices for Streets and Highways. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2009.

Manuel, A., K. El-Basyouny, and M. T. Islam. Investigating the Safety Effects of Road Width on Urban Collector Roadways. *Safety Science*, 2014. 62: 305-311.

Moreno, A. T., and A.García. Use of Speed Profile as Surrogate Measure: Effect of Traffic Calming Devices on Crosstown Road Safety Performance. *Accident Analysis and Prevention*, 2013. 61: 23-32.

MUID, GitBook, https://attap.gitbooks.io/muid.

Naghawi, H. H., and W. I. A. Idewu. Analysing Delay and Queue Length Using Microscopic Simulation for the Unconventional Intersection Design Superstreet. *Journal of the South African Institution of Civil Engineering*, 2014. 56(1): 100-107.

Naghawi, H., K. Jadaan, R. Al-Louzi, and T. Hadidi. Analysis of the Operational Performance of Three Unconventional Arterial Intersection Designs: Median U-Turn, Superstreet and Single Quadrant. *International Journal of Architectural, Civil and Construction Sciences*, 2018A. 12(3): 387-395.

Naghawi, H., A. AlSoud, and T. AlHadidi. The Possibility for Implementing the Superstreet Unconventional Intersection Design in Jordan. *Periodica Polytechnica Transportation Engineering*, 2018B. 46(3): 122-128.

National Highway Traffic Safety Administration. *Quick Facts 2019*. DOT HS 813 124. U.S. Department of Transportation, Washington, D.C., 2021.

Olarte, R., J. G. Bared, L. F. Sutherland, and A. Asokan. Density Models and Safety Analysis for Rural Unsignalised Restricted Crossing U-Turn Intersections. *Procedia-Social and Behavioral Sciences*, 2011. 16: 718-728.

Ott, S. E., R. L. Haley, J. E. Hummer, R. S. Foyle, and C. M. Cunningham, Safety Effects of Unsignalized Superstreets in North Carolina. *Accident Analysis and Prevention*, 2012. 45: 572-579.

Park, J., and M. Abdel-Aty. Assessing the Safety Effects of Multiple Roadside Treatments Using Parametric and Nonparametric Approaches. *Accident Analysis and Prevention*, 2015. 83: 203-213.

Park, J., M. Abdel-Aty, and J. Lee. Use of Empirical and Full Bayes Before–After Approaches to Estimate the Safety Effects of Roadside Barriers with Different Crash Conditions. *Journal of Safety Research*, 2016. 58: 31-40.

Park, J., M. Abdel-Aty, and J. Lee. School Zone Safety Modeling in Countermeasure Evaluation and Decision. *Transportmetrica A: Transport Science*, 2019. 15(2): 586-601.

PBS and J. U.S. ROUTE 17 Corridor Study, Brunswick County, Phase III (Functional Designs), Final Report. Prepared for the North Carolina Department of Transportation, 2005.

Pirdavani, A., T. Brijs, T. Bellemans, and G. Wets. Evaluation of Traffic Safety at Un-Signalized Intersections Using Microsimulation: A Utilization of Proximal Safety Indicators. *Advances in Transportation Studies*, 2010. 22: 43-50.

Rahman, M., Y. Zhou, and J. Rogers. Performance Evaluation of Median U-Turn Intersection for Alleviating Traffic Congestion: An Agent-Based Simulation Study. *Proceeding of the IISE Annual Conference*. Orlando, Florida, USA, 2019.

Reid, J. D., and J. E. Hummer. Analyzing System Travel Time in Arterial Corridors with Unconventional Designs Using Microscopic Simulation. *Transportation Research Record*, 1999. 1678(1): 208-215.

Reid, J. D., and J. E. Hummer. Travel Time Comparisons between Seven Unconventional Arterial Intersection Designs. *Transportation Research Record*, 2001. 1751(1): 56-66.

Savino, M. R. *Standardized Names and Definitions for Driving Performance Measures*. Tufts University, Medford, MA, USA, 2009.

Silva, I., and J. Eugenio Naranjo. A Systematic Methodology to Evaluate Prediction Models for Driving Style Classification. *Sensors*, 2020. 20(6): 1692.

Stephens, A. N., V. Beanland, N. Candappa, E. Mitsopoulos-Rubens, B. Corben, and M. G. Lenné. A Driving Simulator Evaluation of Potential Speed Reductions Using Two Innovative Designs for Signalised Urban Intersections. *Accident Analysis and Prevention*, 2017. 98: 25-36.

Sun, C., Z. Qing, P. Edara, B. Balakrishnan, and J. Hopfenblatt. Driving Simulator Study of J-Turn Acceleration–Deceleration Lane and U-Turn Spacing Configurations. *Transportation Research Record*, 2017. 2638(1): 26-34.

Sun, X., M. A. Rahman, and M. Sun. Safety Analysis of RCUT Intersection. *Proceeding of the 6th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS)*, IEEE, Poland, 2019. 1-6.

Taha, M. A., and A. S. Abdelfatah. Impact of U-Turns as Alternatives to Direct Left-Turns on the Operation of Signalized Intersections. *Journal of Traffic and Logistics Engineering*, 2015. 3(1): 12-17.

VanVoorhis, C. W., and B. L. Morgan. Understanding Power and Rules of Thumb for Determining Sample Sizes. *Tutorials in Quantitative Methods for Psychology*, 2007. 3(2): 43-50.

Vlakveld, W. P., D. Twisk, M. Christoph, M. Boele, R. Sikkema, R. Remy, and A. L. Schwab. Speed Choice and Mental Workload of Elderly Cyclists on Ebikes In Simple and Complex Traffic Situations: A Field Experiment. *Accident Analysis and Prevention*, 2015. 74: 97-106.

Wu, L., D. Lord, and Y. Zou. Validation of Crash Modification Factors Derived from Cross-Sectional Studies with Regression Models. *Transportation Research Record*, 2015. 2514(1), 88-96.

Wu, X., L. N. Boyle, D. Marshall, and W. O’Brien. The Effectiveness of Auditory Forward Collision Warning Alerts. *Transportation Research Part F: Traffic Psychology and Behaviour*, 2018. 59: 164-178.

Xu, L., X. Yang, and G. L. Chang. Computing the Minimal U-Turn Offset for an Unsignalized Superstreet. *Transportation Research Record*, 2017. 2618(1): 48-57.

Yang, X. K., and H. G. Zhou. CORSIM-Based Simulation Approach to Evaluation of Direct Left Turn versus Right Turn plus U-Turn from Driveways. *Journal of Transportation Engineering*, 2004. 130(1): 68-75.

Yue, L., M. Abdel-Aty, J. Lee, and A. Farid. Effects of Signalization at Rural Intersections Considering the Elderly Driving Population. *Transportation Research Record*, 2019. 2673(2): 743-757.

Yue, L. M. Abdel-Aty, Y. Wu, J. Yuan, and M. Morris. Influence of Pedestrian-To-Vehicle Technology on Drivers’ Response and Safety Benefits Considering Pre-Crash Conditions. *Transportation Research Part F: Traffic Psychology and Behaviour*, 2020. 73: 50-65.

Zhang, W., N. Kronprasert, and J. Bared. *Restricted Crossing U-Turn Intersection Design for Improving Safety and Mobility at High-Speed*, 2013.

Zhong, Z., M. M. Nejad, I. I. Lee, and E. Earl. *Unconventional Arterial Intersection Designs under Connected and Automated Vehicle Environment: A Survey*. 2018.

Zhou, H., P. Hsu, J. J. Lu, and J. E. Wright. Optimal Location of U-Turn Median Openings on Roadways. *Transportation Research Record*, 2003. 1847(1): 36-41.

Zicat, E., J. M. Bennett, E. Chekaluk, and J. Batchelor. Cognitive Function and Young Drivers: The Relationship Between Driving, Attitudes, Personality, And Cognition. *Transportation Research Part F: Traffic Psychology and Behaviour*, 2018. 55: 341-352.