Investigation of Driving Behavior at Alternative Intersection Designs and Safety Improvement: A Driver Simulator Study

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Mohamed Abdel-Aty, Ph.D., P.E., PI
Ma'en Al-Omari, Ph.D.

Department of Civil, Environmental and Construction Engineering
University of Central Florida

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Mohamed Abdel-Aty, PhD, PE, Co-PI
Pegasus Professor, Chair
Department of Civil, Environmental and Construction Engineering
University of Central Florida
https://orcid.org/0000-0002-4838-1573

Ma’en Al-Omari, Ph.D.
Research Assistant
Department of Civil, Environmental and Construction Engineering
University of Central Florida
https://orcid.org/0000-0001-7277-3561

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16. Abstract

Alternative intersection designs have been proposed due to their theoretical expected ability to simultaneously enhance traffic safety and operation as a result of reducing the number of conflict points and signal phases. However, this was only achieved at very limited intersection designs which have a very low number of conflict points and under certain traffic conditions. For example, the restricted crossing U-turn (RCUT) intersection, which has the lowest number of conflict points among other proposed intersection designs, has operational advantages at extremely unbalanced traffic volumes. Our shifting movement (SM) intersection design, which has the same number of conflict points as the RCUT intersection, has been proposed to replace the RCUT implementation at intersections with medium to high minor traffic volumes. It was proven that it outperforms the RCUT intersection which has medium to high minor traffic volumes in terms of average delay and throughputs. This study aimed to investigate the safety aspects of this intersection design by utilizing the driving simulator. The effectiveness of using infrastructure to vehicle (I2V) communication for mitigating the confusion at alternative intersections was also investigated in the study. The results indicated that RCUT and SM intersections have similar safety performance and crossing them is safer than crossing the conventional intersection. However, there is a need to improve drivers' knowledge about the SM intersection, especially regarding the major left-turn movement. Most participants have found that using I2V communication is helpful in understanding the unconventional movement patterns.

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Abstract

Alternative intersection designs have been proposed due to their theoretical expected ability to simultaneously enhance traffic safety and operation as a result of reducing the number of conflict points and signal phases. However, this was only achieved at very limited intersection designs which have a very low number of conflict points and under certain traffic conditions. For example, the restricted crossing U-turn (RCUT) intersection, which has the lowest number of conflict points among other proposed intersection designs, has operational advantages at extremely unbalanced traffic volumes. Our shifting movement (SM) intersection design, which has the same number of conflict points as the RCUT intersection, has been proposed to replace the RCUT implementation at intersections with medium to high minor traffic volumes. It was proven that it outperforms the RCUT intersection which has medium to high minor traffic volumes in terms of average delay and throughputs. This study aimed to investigate the safety aspects of this intersection design by utilizing the driving simulator. The effectiveness of using infrastructure to vehicle (I2V) communication for mitigating the confusion at alternative intersections was also investigated in the study. The results indicated that RCUT and SM intersections have similar safety performance and crossing them is safer than crossing the conventional intersection. However, there is a need to improve drivers' knowledge about the SM intersection, especially regarding the major left-turn movement. Most participants have found that using I2V communication is helpful in understanding the unconventional movement patterns.

1 Introduction

Several intersection designs have been proposed as alternatives to the 4-leg conventional intersection design in order to improve traffic safety and operation at intersections. The effectiveness of alternative intersection designs comes from the reconfiguration of some movement patterns (mainly the left-turn movement) at alternative intersection designs. Prevention of conducting some movements directly at the main intersection by allowing to perform them upstream or downstream of the main intersection reduces the number of traffic conflicts between movements which results in two main advantages. Firstly, a low number of conflicts reduces the interaction between vehicles which is an indication of a safer traffic condition. The second benefit is reducing the average control delay at the intersection since alternative intersections provide two-phase signalization at the whole intersection.

However, the evaluation of alternative intersection designs indicated that enhancing traffic safety and operation simultaneously at the intersection has not been achieved at most alternative intersection designs. Some of them have more safety benefits than operation benefits. In contrast, other alternative intersection designs have more effectiveness in enhancing traffic operation than reducing the crash frequency. Few designs which have a very low number of conflict points have the efficiency to improve both (i.e. traffic safety and operation) but only under certain traffic conditions.

The restricted crossing U-turn (RCUT) intersection has 14 conflict points which is the lowest number of traffic conflict points at alternative intersection designs (*Hummer et al., 2014*). This number is less than half of the number of conflict points at the conventional signalized intersection (32 conflict points). As a result, many studies have found that the RCUT intersection has safety benefits represented by reducing the number and the severity of crashes (*Kim et al., 2007; Hummer and Jagannathan, 2008; Hochstein et al., 2009; Hughes et al., 2010; Inman and Haas, 2012; Inman et al., 2013; Edara et al., 2013; Edara et al., 2015; Hummer and Rao, 2017; Sun et al., 2019; Al-Omari et al., 2020*). Besides this, low values of average control delay and high throughput values were recorded at RCUT intersections due to reducing the number of signal phases from four (at the conventional signalized intersection) to two signal phases. However, its operation enhancement is manifested only under unbalanced traffic conditions (*Bared, 2009; Hughes et al., 2010; Kivlins and Naudzuns, 2011*)

The shifting movement (SM) interstation design which has been recently introduced by *Al-Omari and Abdel-Aty (2021)* has a similar number of traffic conflict points to the RCUT intersection. The authors found after conducting a microscopic simulation study that even though both alternative 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 minor 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 median U-Turn crossover-based 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.

2 Literature Review

2.1 Alternative Intersection Designs

Many alternative intersection designs have been proposed to replace the 4-leg conventional intersection implementation. Such as restricted crossing U-turn (RCUT) intersection, median U-turn intersection, Jughandle intersection, displaced left-turn intersection, and shifting movements (SM) intersection, etc. Only RCUT and SM intersections were considered for analysis in this study because they own the lowest number of conflict points among other alternative intersections. Figure 1 and 2 show RCUT and SM intersection designs.

The RCUT intersection consists of the main intersection and two median U-turn crossovers upstream and downstream of the main intersection. The SM intersection has three sub-intersections: the central area and upstream and downstream intersections. The side street of the SM intersection is provided as a service road for minor and major left-turn traffic.

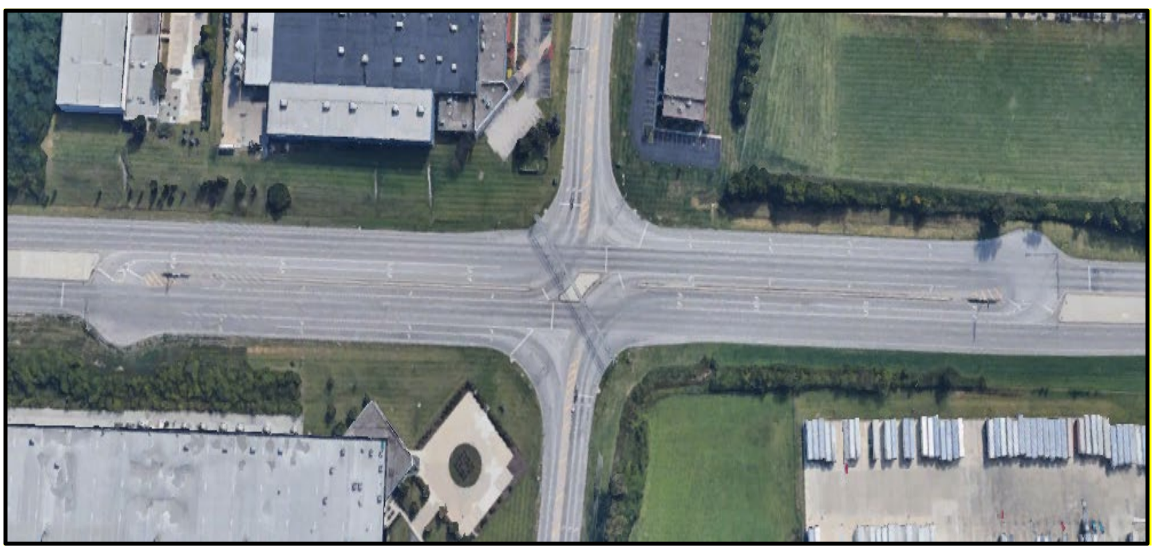

Figure 1: A RCUT Intersection at OH-4 Bypass and Symmes Rd, Hamilton, OH

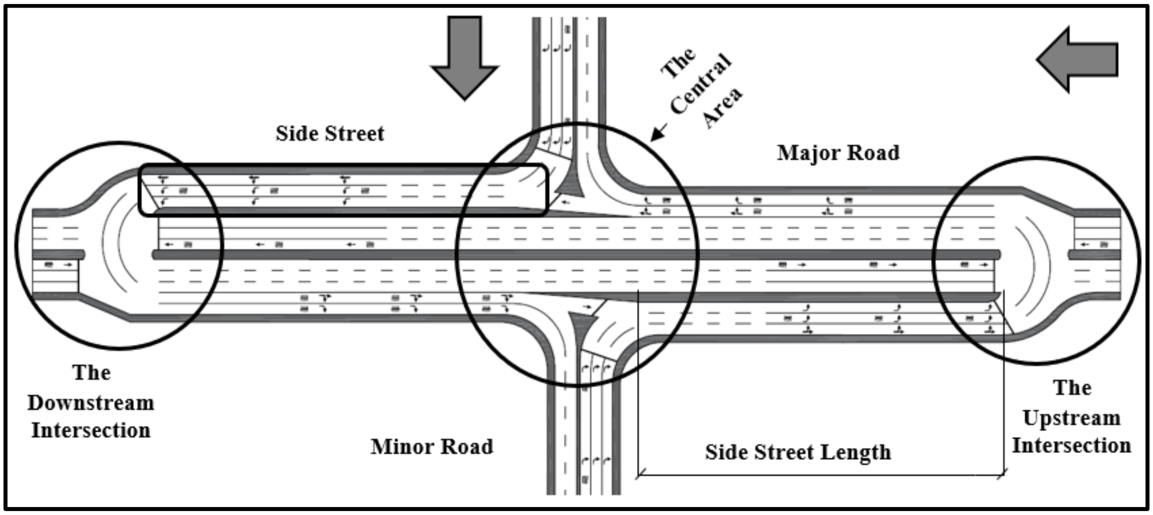

Figure 2: Shifting Movements (SM) intersection design (*Al-Omari and Abdel-Aty, 2021*)

Both RCUT and SM intersections provide a two-phase signalization at their intersections and therefore providing a two-phase signalization at the whole intersection level. Minor traffic and major left-turn traffic are simultaneously served at the main RCUT intersection into one signal phase while the second phase is reserved for the major through and right-turn traffic. At median U-turn crossovers, one signal phase is provided for major road traffic and the other phase is for the U-turn traffic. At the central area of the SM intersection, the minor traffic is stopped during the first signal phase to allow the major left-turn traffic to access the side street. While it has a green light in the second phase. Like at RCUT intersection crossovers', one signal phase is for serving the major road traffic while the other phase is for the traffic from the side street at upstream and downstream intersections.

Two movements are unconventionally done at the RCUT intersection (through and left-turn movements from the minor road), while the SM intersection is featured by four unconventional movement patterns (all movements from the minor road and the left-turn movement from the major road). These movements are prohibited to accomplished directly at the main intersection. Figure 3 shows schemes of traffic movements at RCUT and SM intersections.

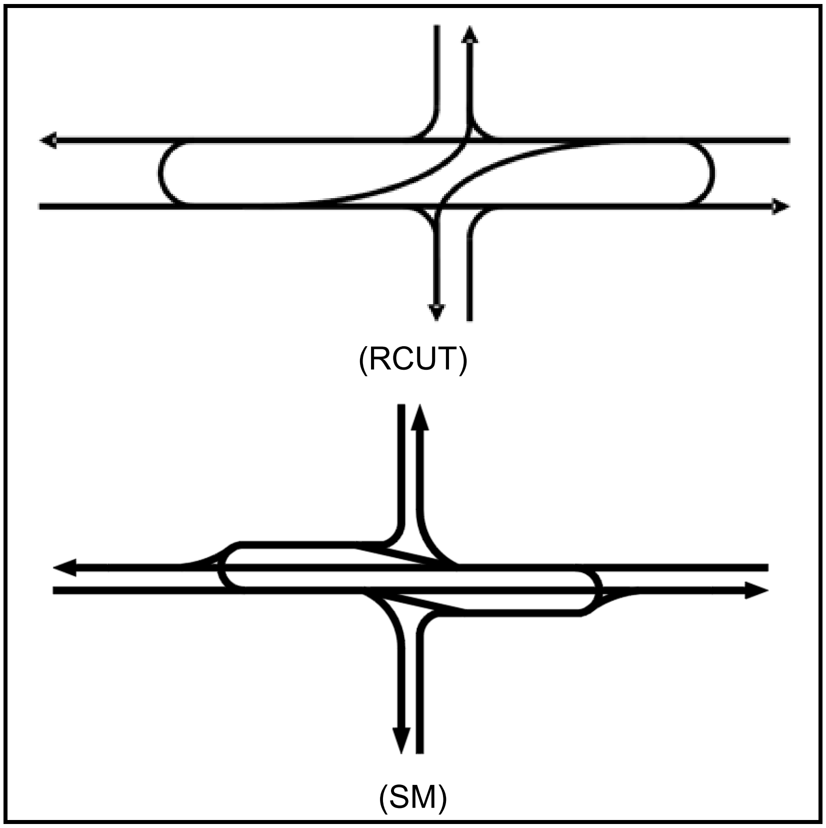

Figure 3: Schemes of traffic movements at RCUT (*AASHTO, 2004*) and SM intersections

Traffic movement patterns from the minor road at RCUT and SM intersections are somehow similar despite slight differences. In contrast, there is a major difference in performing the left-turn movement from the major road. At the RCUT intersection, all movements are done as usual (as at the conventional intersection) except minor through and left-turn movements. These two movements are performed by turning right at the main intersection then making a U-turn at the median U-turn crossover. By turning right at the main intersection, the minor through movement is done. At the SM intersection, all movements from the major road are done as they are at the conventional intersection except the left-turn movement. Major left-turn traffic accesses the side street in the central area and combines with the minor traffic. Minor road traffic must turn right to access the side street in the central area. The combined traffic (i.e. minor and major left-turn traffic) heads to the downstream intersection where it accesses the major road by turning left except the minor right-turn movement which is done by turning right at the downstream intersection. By turning right at the central area, minor through and major left-turn movements are accomplished.

2.2 Employment of Driving Simulation to Evaluate and Improve Safety at Unconventional Intersections

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.

3 Experiment Design

3.1 Geometric Design

Unconventional intersection designs which were considered in this study (i.e. RCUT and SM intersections) were 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 425ft 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 was provided. Figures 4, 5 and 6 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 sub-intersections at 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.

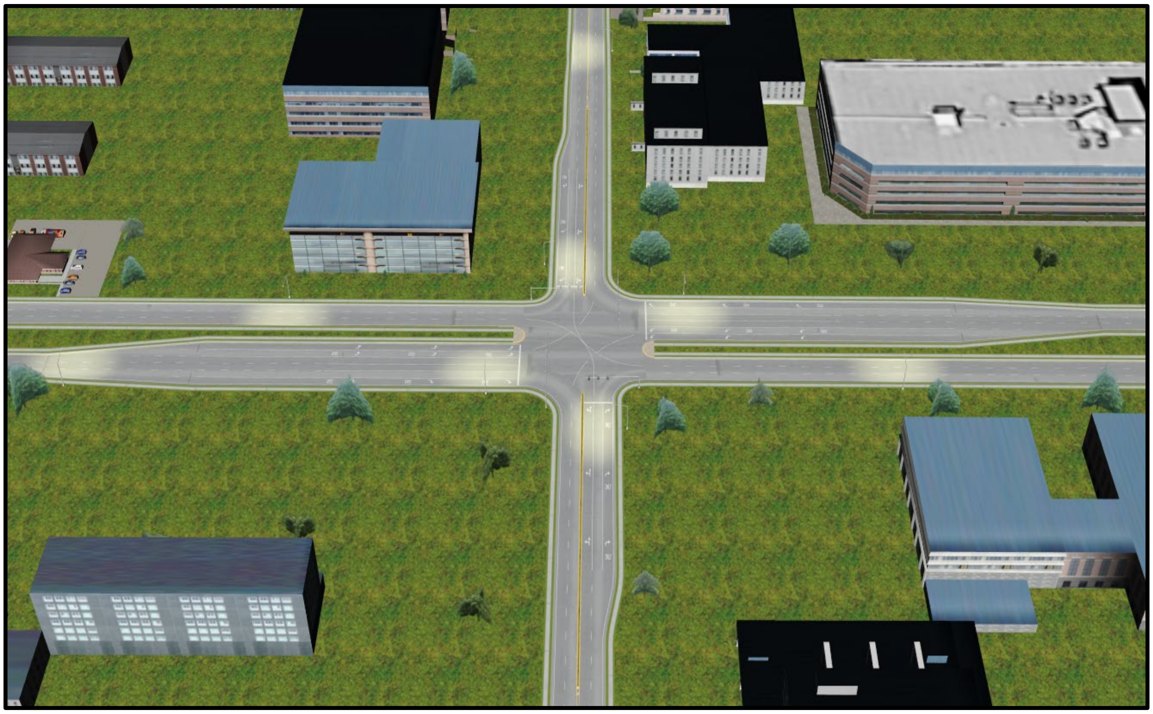

Figure 4: The conventional intersection design

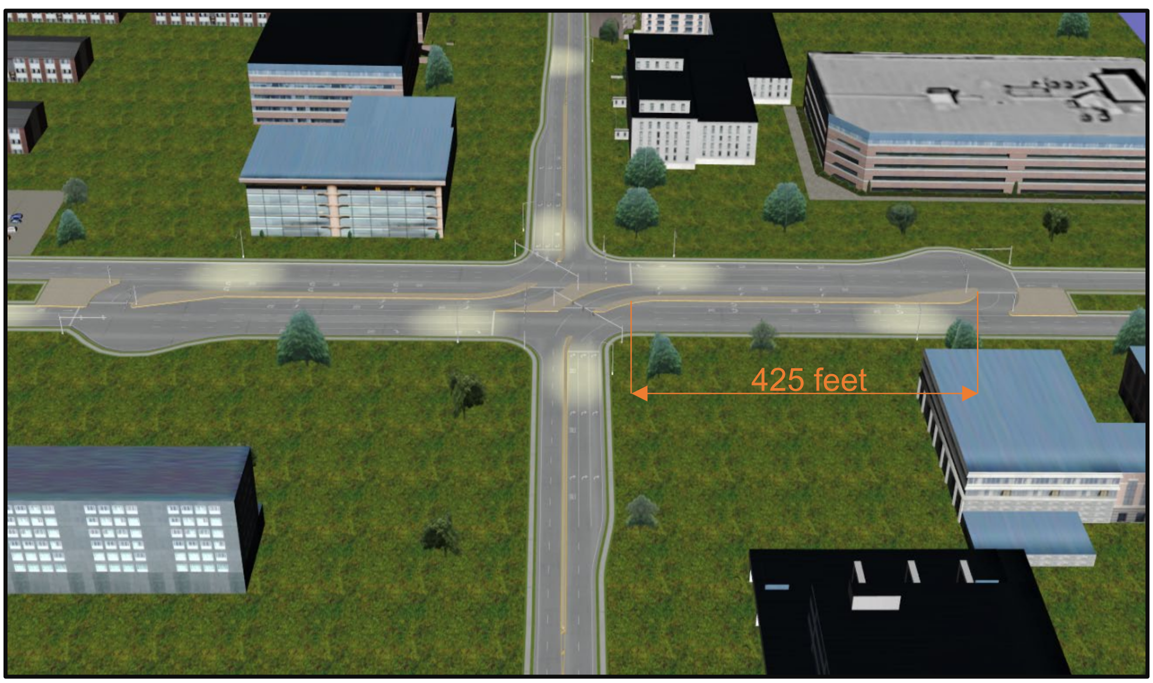

Figure 5: The RCUT intersection design

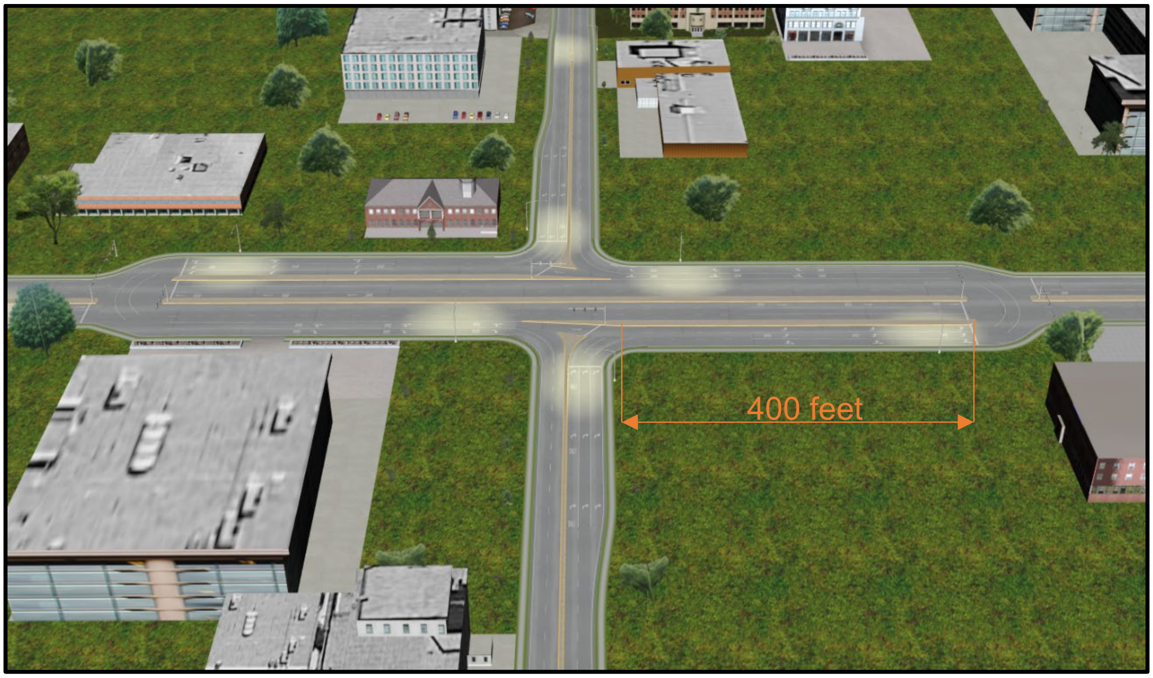

Figure 6: The SM intersection design

3.2 Signage

Different regulatory and guide signs were 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 were 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. Moreover, new signs were designed and installed at unconventional intersections to guide drivers on how to perform unconventional movements at RCUT and SM intersections. Figures 7, 8, and 9 show the used signs at conventional, RCUT, and SM intersections, respectively.

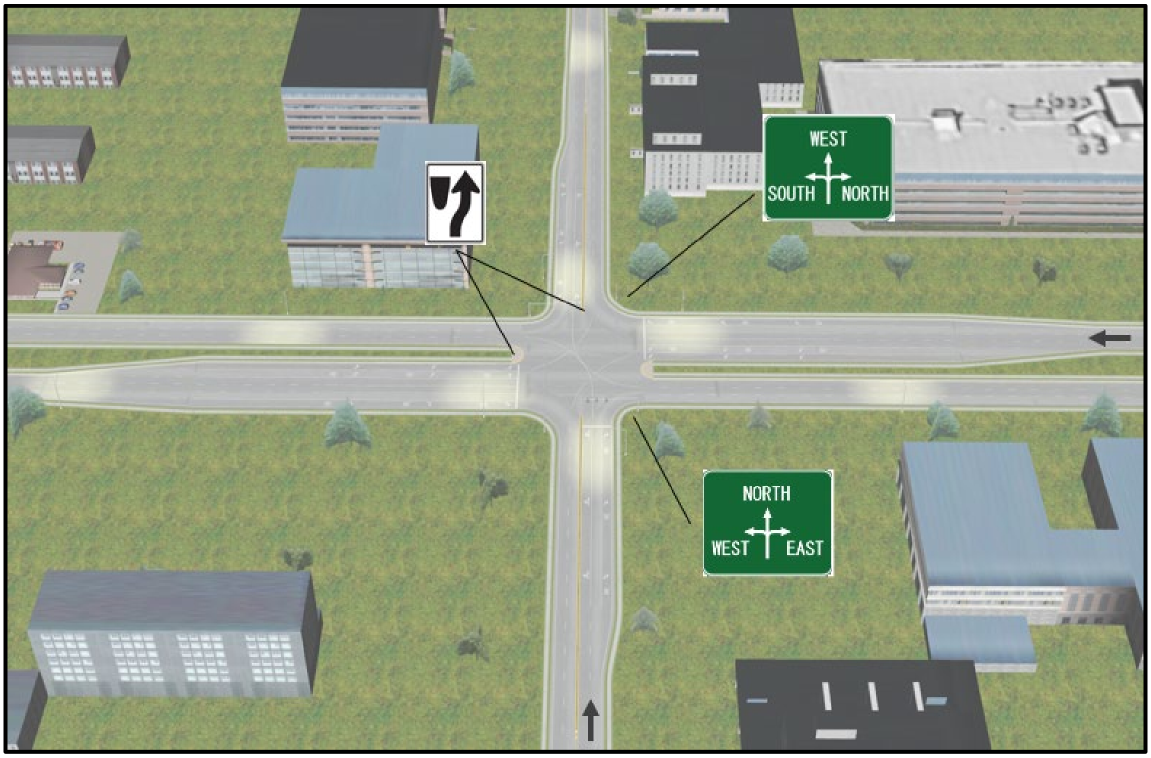

Figure 7: The used signs at the conventional intersection

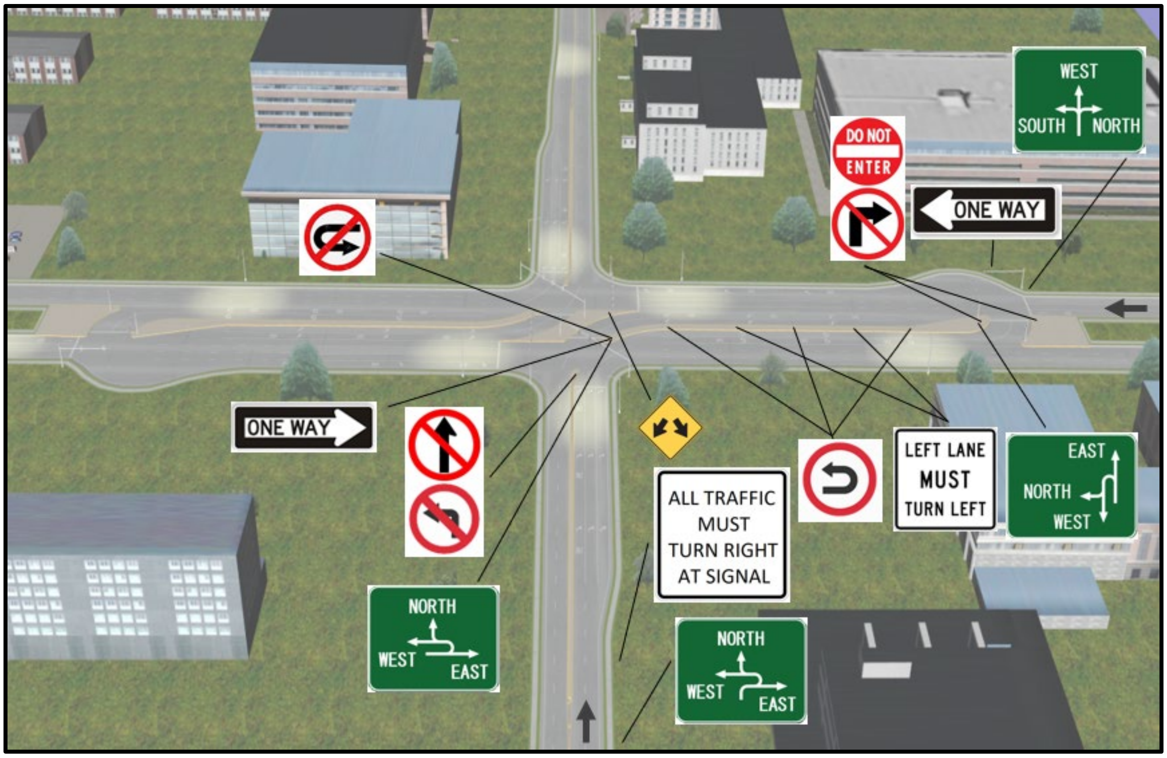

Figure 8: The used signs at the RCUT intersection

Figure 9: The used signs at the SM intersection

3.3 Design of Scenarios

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 infrastructure to vehicle (I2V) communication was also investigated in this study. However, this was analyzed separately because the implementation of I2V communication was 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 10 shows a schematic diagram for the two experiments in this study.

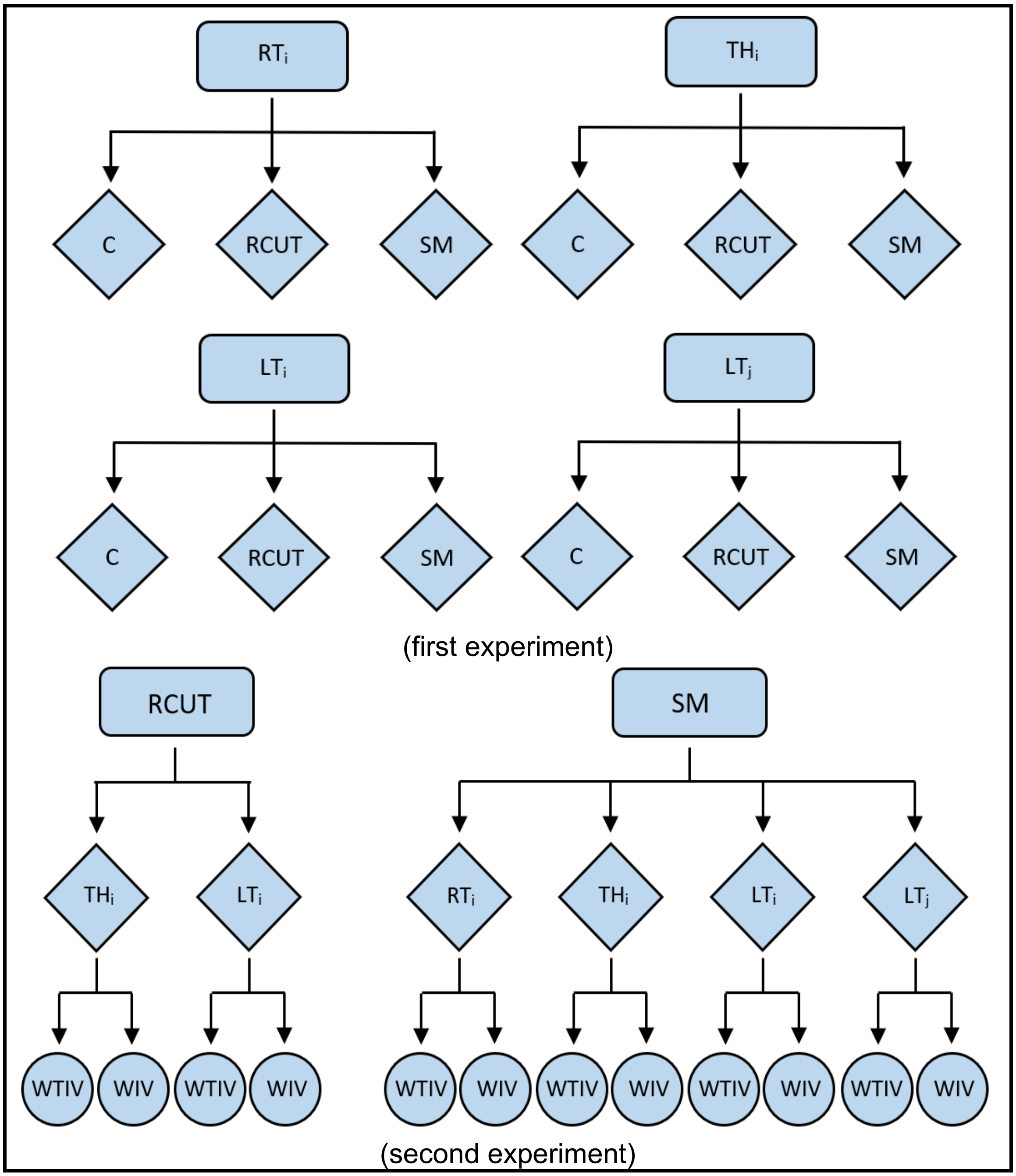

Figure 10: Schematic diagram of the first and second experiments' factor

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.

The I2V communication was simulated by sending navigation information for guiding drivers to accomplish the unconventional movements. Visual and voice messages were 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 were sent. The first message is sent to the driver 800 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 11). 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 12. The last message is related to this movement is sent once the driver did the U-turn 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 13 is also shown at the third stage of this movement.

Figure 11: An illustration diagram is shown 800 feet upstream the stop line at the main intersection

Figure 12: An illustration diagram is shown after leaving the stop line at the main intersection

Figure 13: An illustration diagram is shown at the RCUT intersection's crossover

Three (10-minutes) routes were 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 was 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 were 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 were sent 1100 feet upstream of the first stop line at the intersection. Figure 14 shows the designed routes in this study.

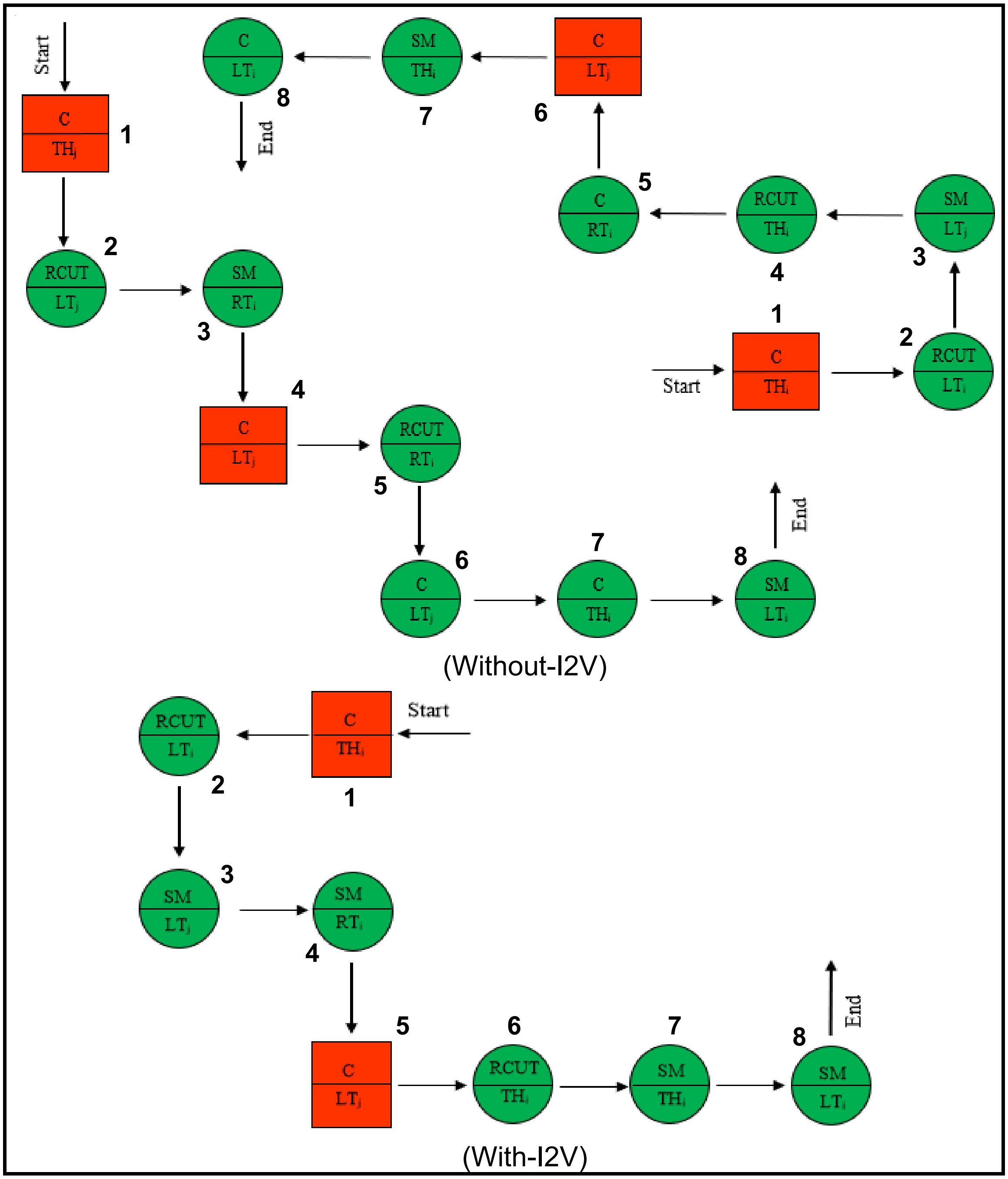

Figure 14: Without-I2V and with-I2V routes

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.

4 Experiment Development

4.1 Scenario Development

The MiniSim 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 was 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. Figure 15 shows the NADS device.

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 were designed for sending different types of messages to guide the driver to be on the desired track. Figures 16, 17 and 18 show the graphical user interface (GUI) of TMT, ISAT, and NADS software, respectively.

Figure 15: The National Advanced Driving Simulator (NADS) MiniSim^{TM} at UCF

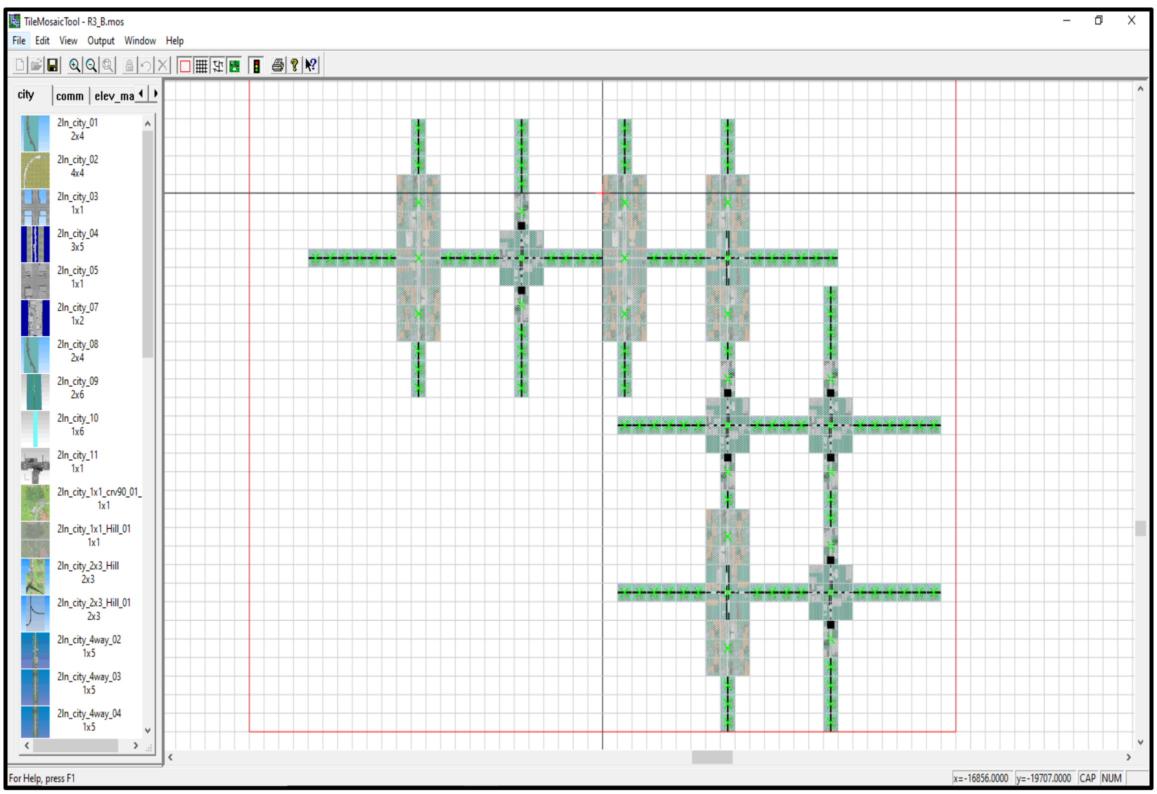

Figure 16: GUI of Tile Mosaic Tool (TMT) software

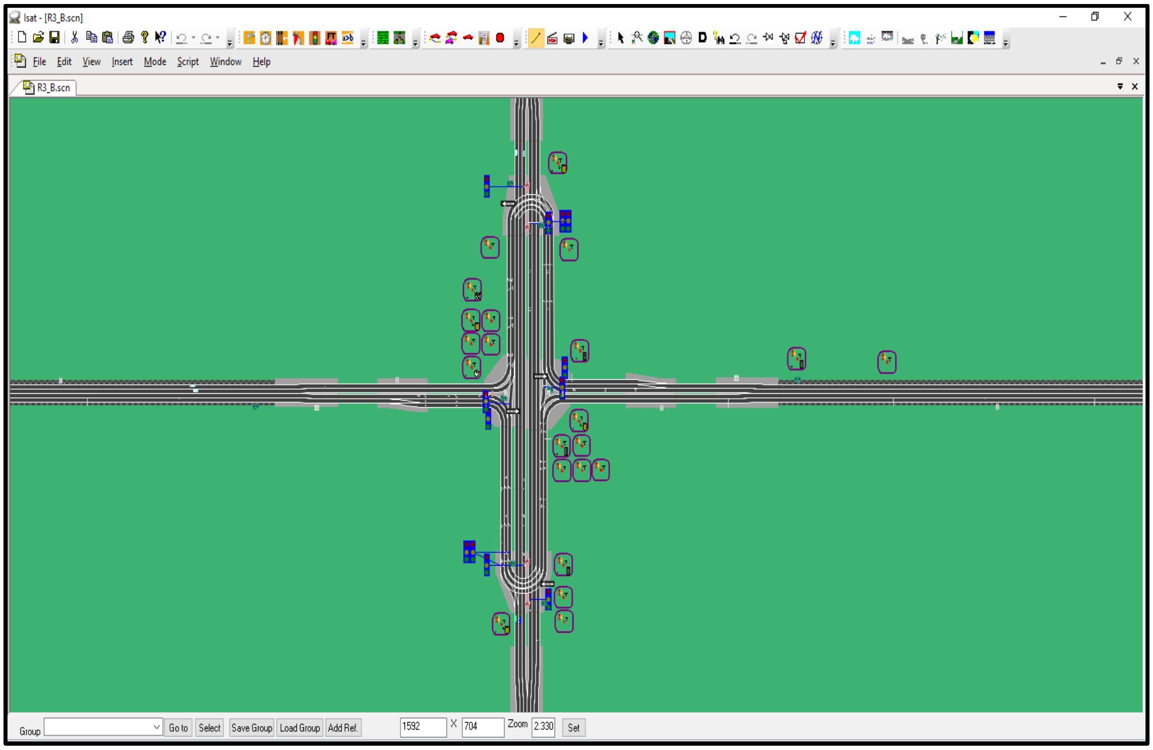

Figure 17: GUI of Interactive Scenario Authoring Tools (ISAT) software

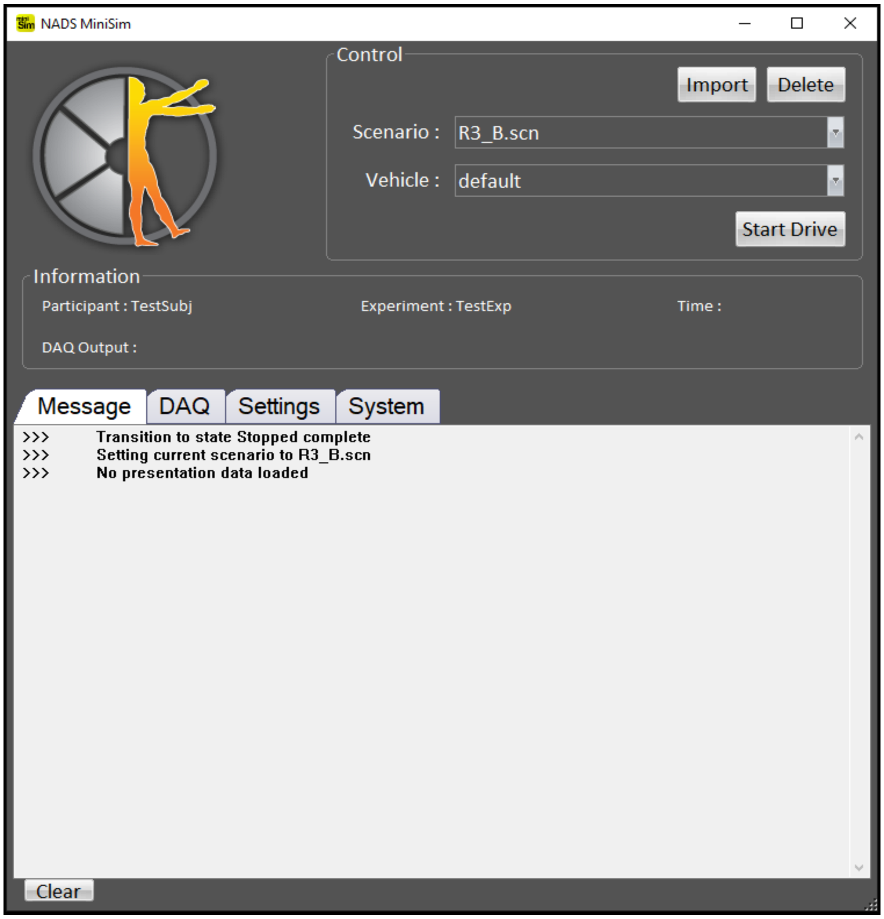

Figure 18: GUI of NADS MiniSim^{TM} software

Triggers were 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.

4.2 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 COVID 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 19 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 0.5 values for the effect size parameter (*Faul et al. 2009*), it was found that the minimum required sample size is 20 and 27 for the analysis of variance (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.

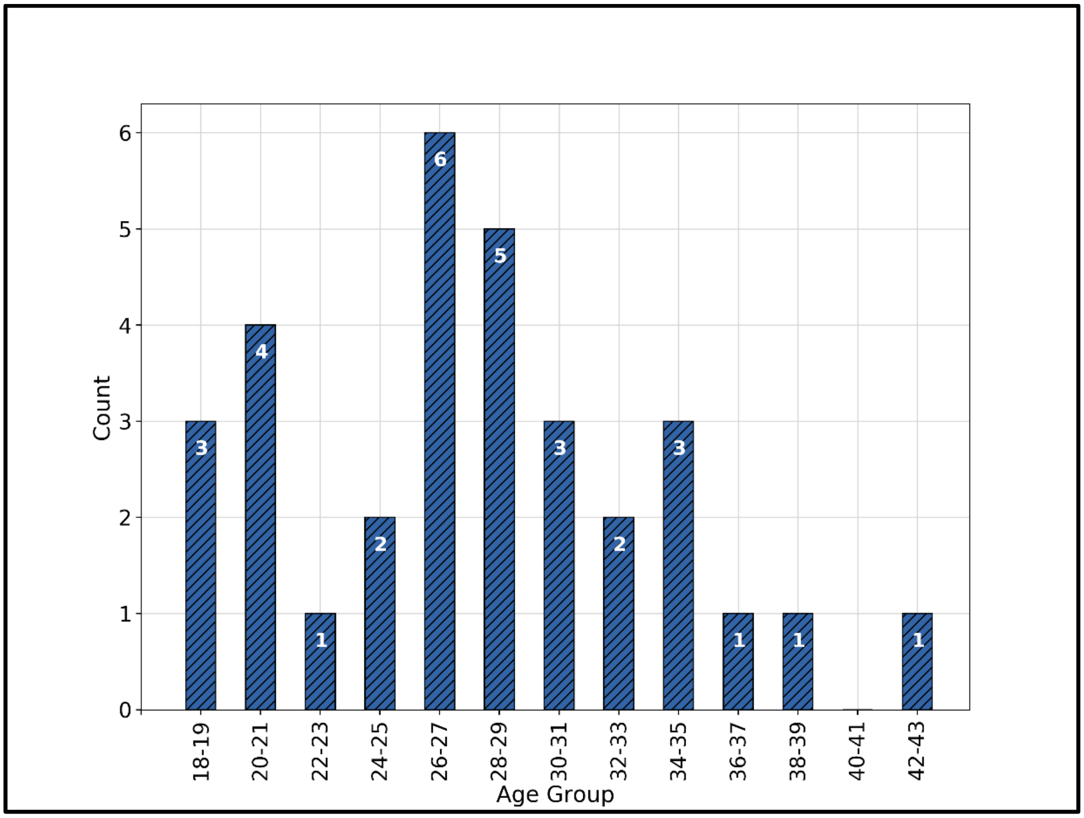

Figure 19: Histogram of Participants' Ages

4.3 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 COVID-19 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 some personal and driving experience information. 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 the with-I2V and without-I2V routes and the order of without-I2V routes themselves was changed to mitigate the order effect. Having two route configurations, two arrangements for the with-I2V route (in the beginning or in the last) and two arrangements for without-I2V routes produced 8 (2 x 2 x 2) different 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 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 were 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 (or the 85th percentile of the speed) 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 (*Silva and Eugenio Naranjo, 2020*) (or the 85th percentile value of the acceleration) line where acceleration is above the 6.6 ft/s^2. The value of 6.6 ft/s2 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 (or the 85th percentile value of the deceleration) line where deceleration is above

the 6.6 ft/s^2 (or the 85th percentile of the deceleration). 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 repeated measures analysis of variance (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 were used to check the normality and sphericity assumptions, respectively. The Post-Hoc test (Paired T-test) was employed if the one-way repeated measures 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 20 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 21 shows a flowchart for the analysis methodology of the second experiment.

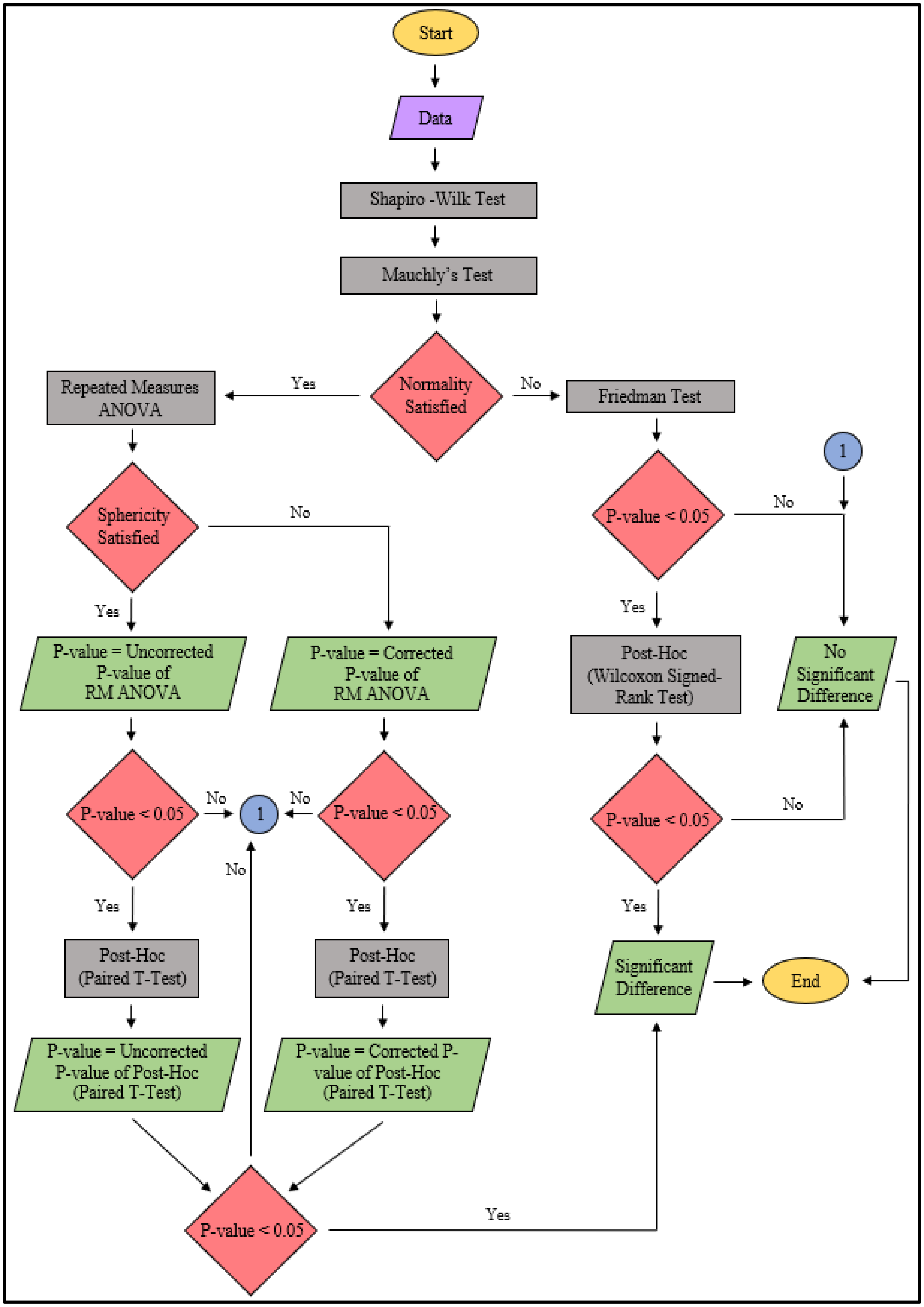

Figure 20: A flowchart for the analysis methodology of the first experiment

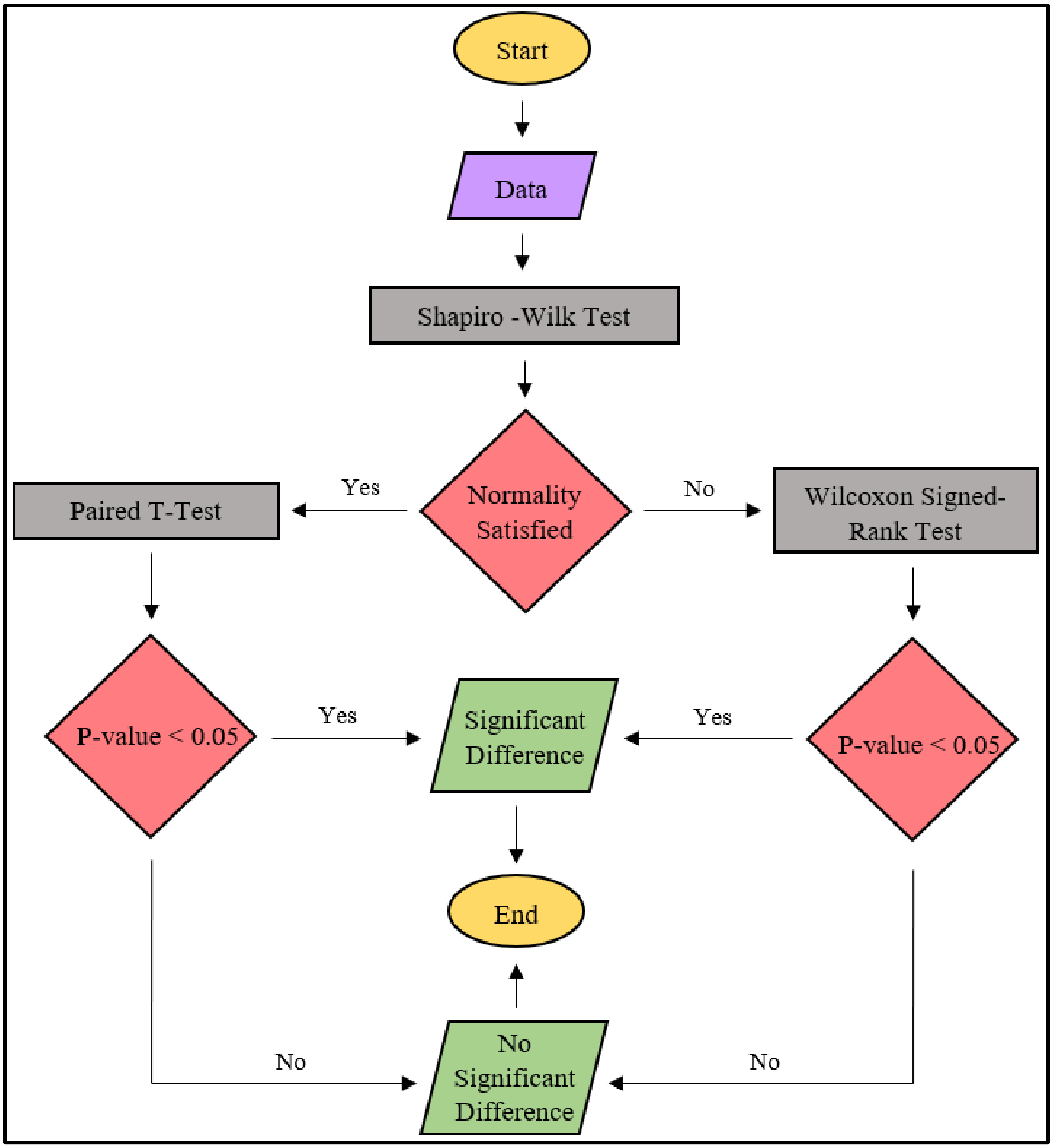

Figure 21: A flowchart for the analysis methodology of the second experiment

6 Results

6.1 Understanding of the Unconventional Movements Patterns

After the experiment, the participant was asked to evaluate if he/she was confused at RCUT and SM intersections. Figure 22 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.

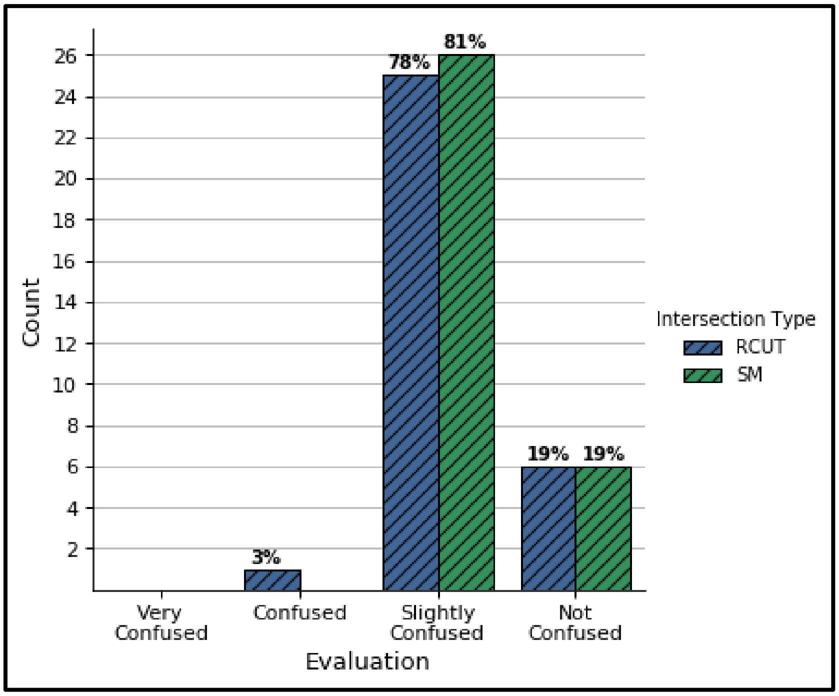

Figure 22: Evaluation of the confusion at RCUT and SM intersections

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

Figure 23 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.

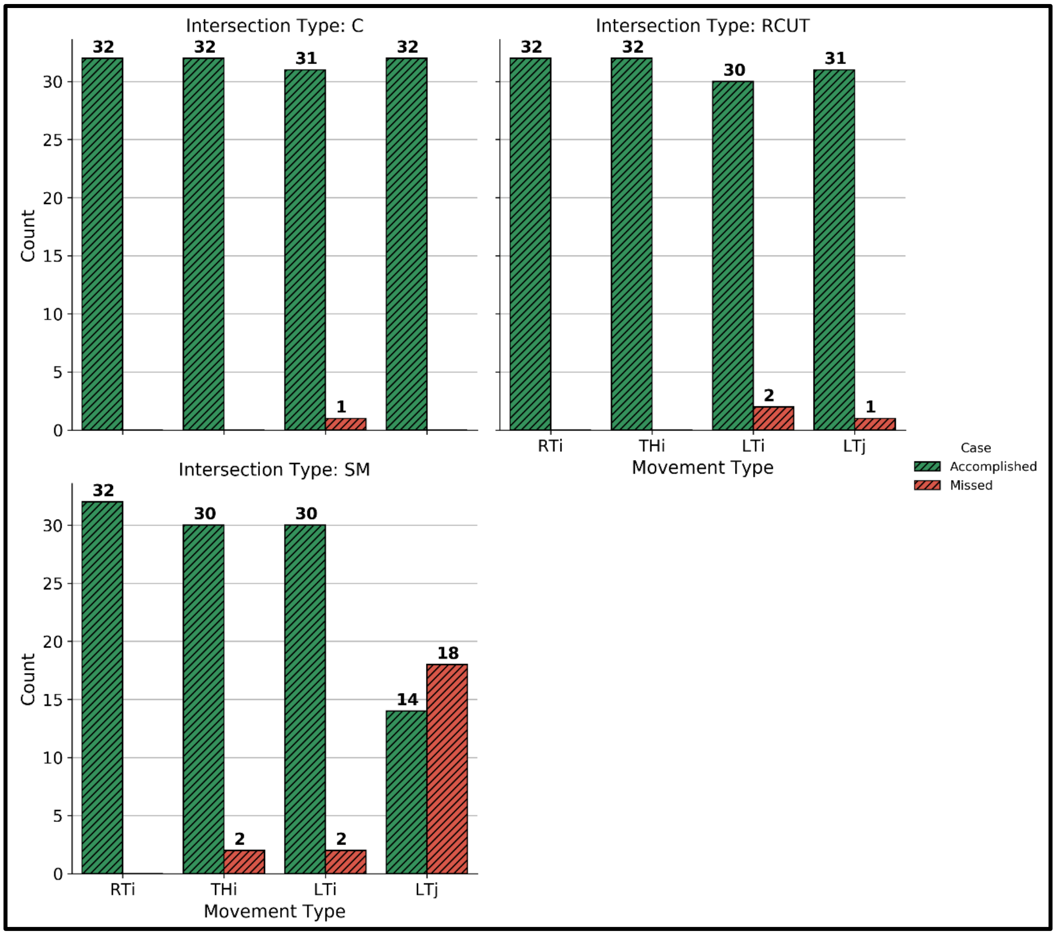

Figure 23: Number of accomplished and missed movements for every movement at conventional, RCUT, and SM intersections

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.

6.2 Driving Behavior at Unconventional Intersections

Several surrogate safety measures were calculated while performing the different movements at the three intersection types. Table 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 (P-value = 0.0811) 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 (P-value = 0.9036), while drivers drive with significantly (P-value = 0.0272) more speeding (μ = 2.5 ± 2.1 mph) 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 (P-value = 0.1146).

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 brake behaviors at RCUT and SM intersections where sudden acceleration and sudden brake behaviors were 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 were noticed at RCUT and SM intersections (P-value = 0.8329, 0.6892). 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 lower (P-value = 0.0231) sudden acceleration values ($\mu = 0.0 \pm 0.0$ ft/s^2) in comparison to the SM intersection ($\mu = 0.1 \pm 0.1$ ft/s^2).

The lane deviation of minor right-turn and major left-turn movements at the three intersection types were not significantly different (P-value = 0.2231, 0.8732). In contrast, the minor through movement at the conventional intersection is performed with significantly lower (P-value = $\leqslant$ 0.0000, $\leqslant$ 0.0000) lane deviation values ($\mu = 0.5 \pm 0.2$ ft) than at RCUT and SM intersections ($\mu = 1.5 \pm 0.1$ ft; 1.5 ± 0.2 ft). While there was no significant difference in the lane deviation of this movement at RCUT and SM intersections (P-value = 0.6778). On the other hand, the lane deviation of the minor left-turn movement at the SM intersection ($\mu = 1.3 \pm 0.2$ ft) is significantly lower (P-value = 0.0022, 0.0016) than at conventional and RCUT intersections ($\mu = 1.5 \pm 0.2$ ft; 1.5 ± 0.2 ft) without a significant difference in the lane deviation values of this movement at conventional and RCUT intersections (P-value = 0.8932). Figures 24 and 25 show the distribution of the different surrogate safety measures by movement and intersection types. Similar results were gotten by adopting the 85th percentile value as the threshold value.

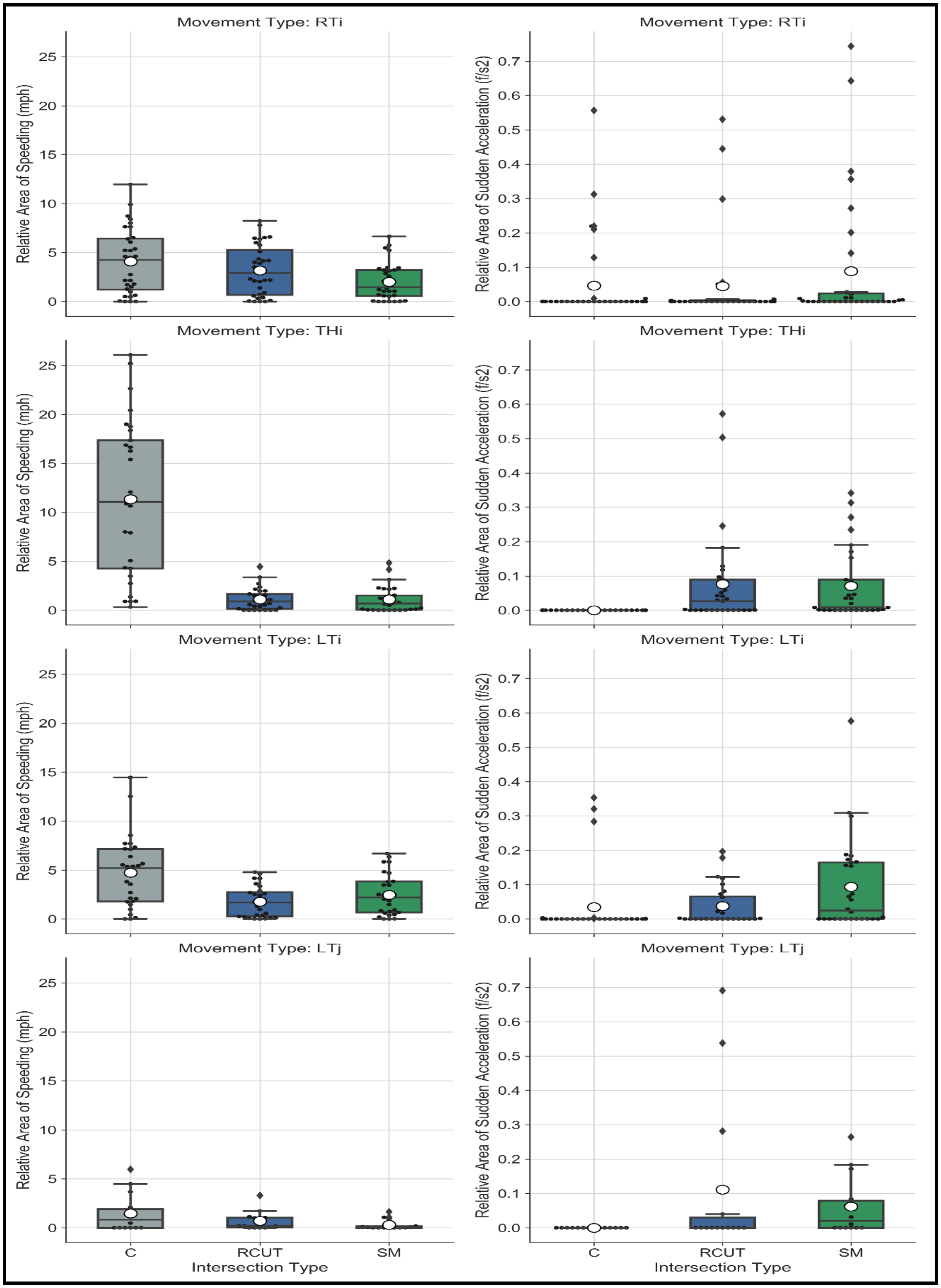

Figure 24: Distribution of relative area of speeding and sudden acceleration by movement and intersection types

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.

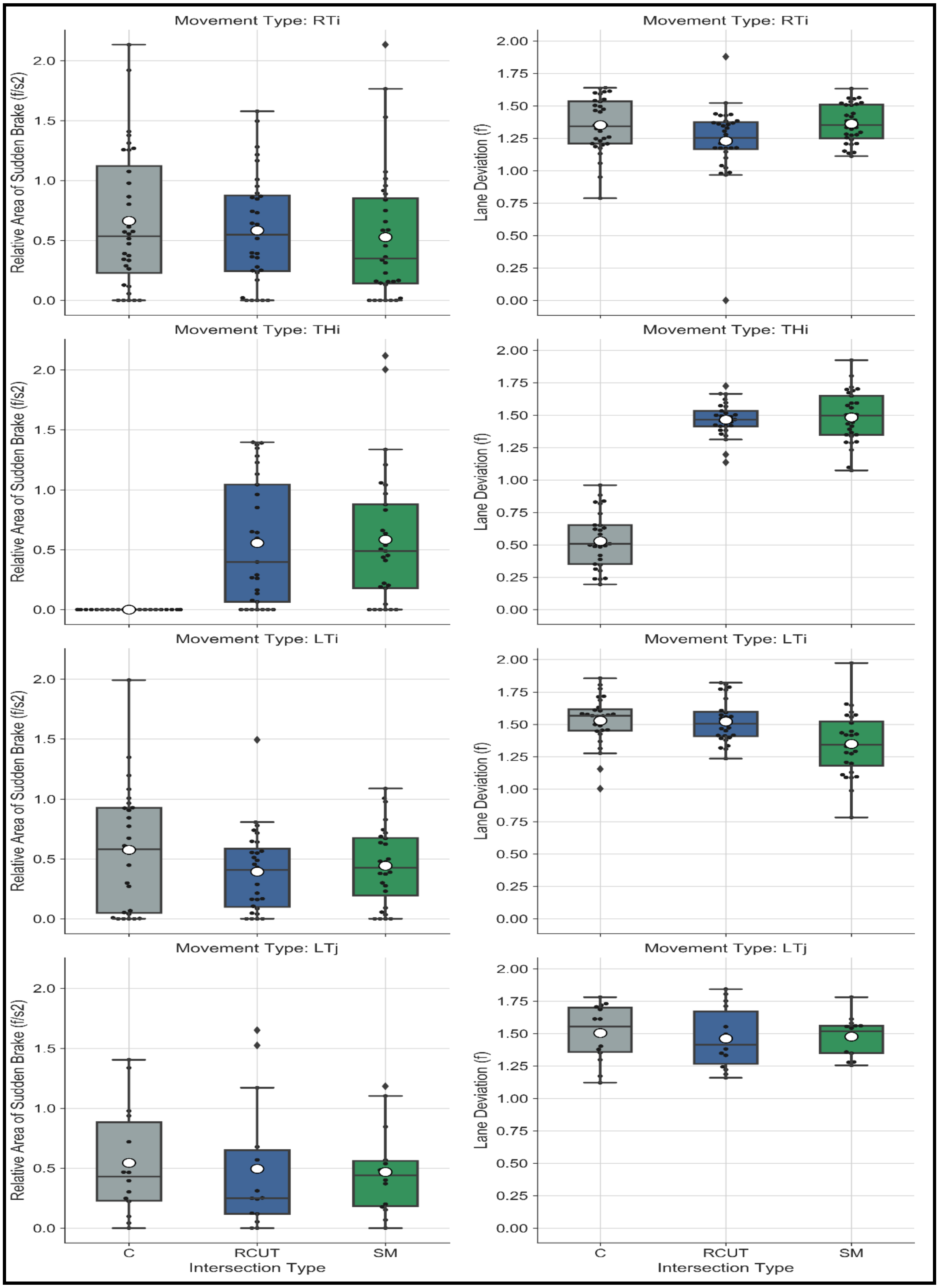

Figure 25: Distribution of relative area of sudden brake and lane deviation by movement and intersection types

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 1: Descriptive statistics of the surrogate safety measures and analysis results

Measure	Intersection Type	Mean (S.D.) RTi	Mean (S.D.) THi	Mean (S.D.) LTi	Mean (S.D.) LTj	Comparison Level	Test Statistics, Degree of Fredom (P-value) RTi	Test Statistics, Degree of Fredom (P-value) THi	Test Statistics, Degree of Fredom (P-value) LTi	Test Statistics, Degree of Fredom (P-value) 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***)	10.241^{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, 2/56^{A} (≤ ***0.0000***)	7.7, 2/54^{A} (***0.0011***)	0.14, 2/26^{A} (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, A = RM ANOVA, F = Friedman test, T = Paired T-test.

6.3 Evaluation of the Effectiveness of Using I2V 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 26 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.

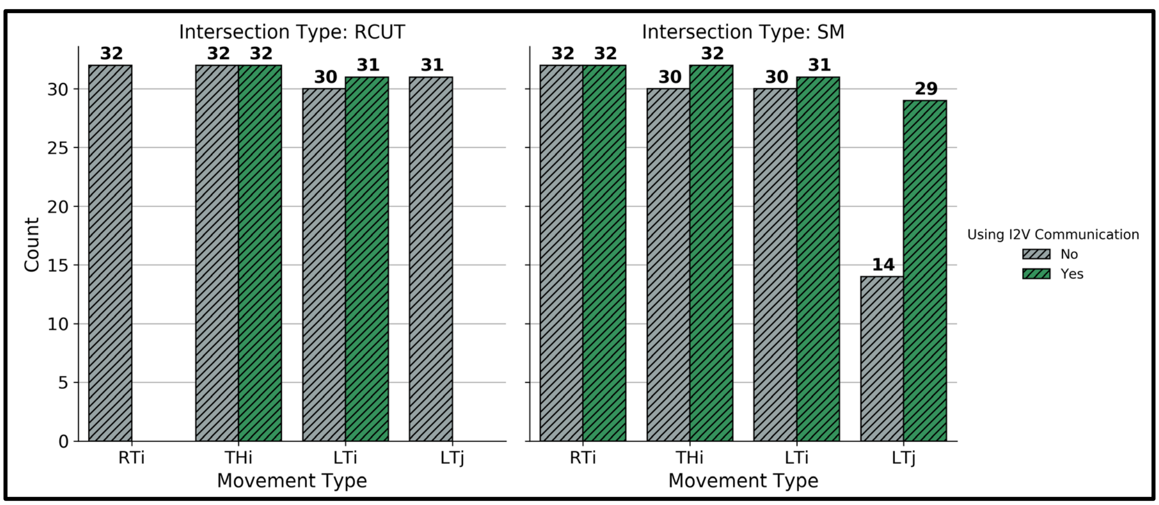

Figure 26: Number of accomplished unconventional movements at RCUT and SM intersections with and without using I2V communication

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 27 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).

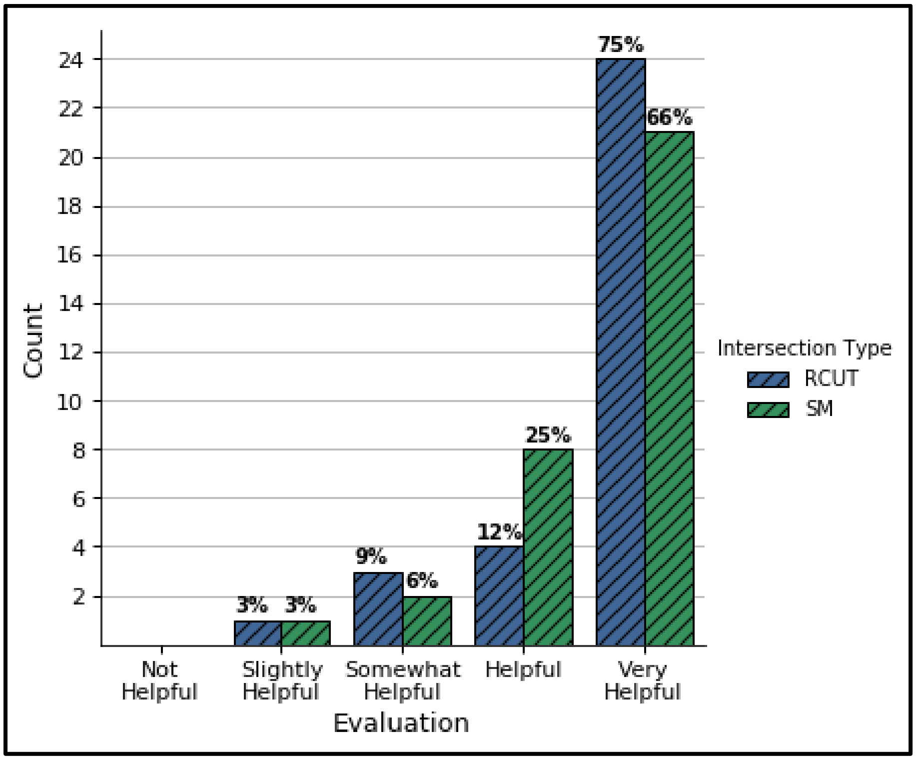

Figure 27: Evaluation of Using I2V Communication at RCUT and SM Intersections

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 ($\mu = 1.7 \pm 1.7$ mph, 1.7 ± 1.7 mph) were recorded at RCUT and SM intersections while performing the minor through movement with using I2V communication in comparison without using it ($\mu = 1.1 \pm 1.1$ mph, 1.1 ± 1.3 mph). The lane deviation ($\mu = 1.4 \pm 0.1$ 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 ($\mu = 1.5 \pm 0.1$ ft). It was also found that using I2V communication at the SM intersection significantly (P-value = 0.0479) increases the lane deviation ($\mu = 1.6 \pm 0.1$ ft) during performing the major left-turn movement in comparison with the absence of this technology ($\mu = 1.5 \pm 0.2$ ft). Figures 28 and 29 show the distribution of the different surrogate safety measures with and without implementing I2V communication. Table 2 shows descriptive statistics of these measures and the results of the adopted test to determine whether the difference between values is significant.

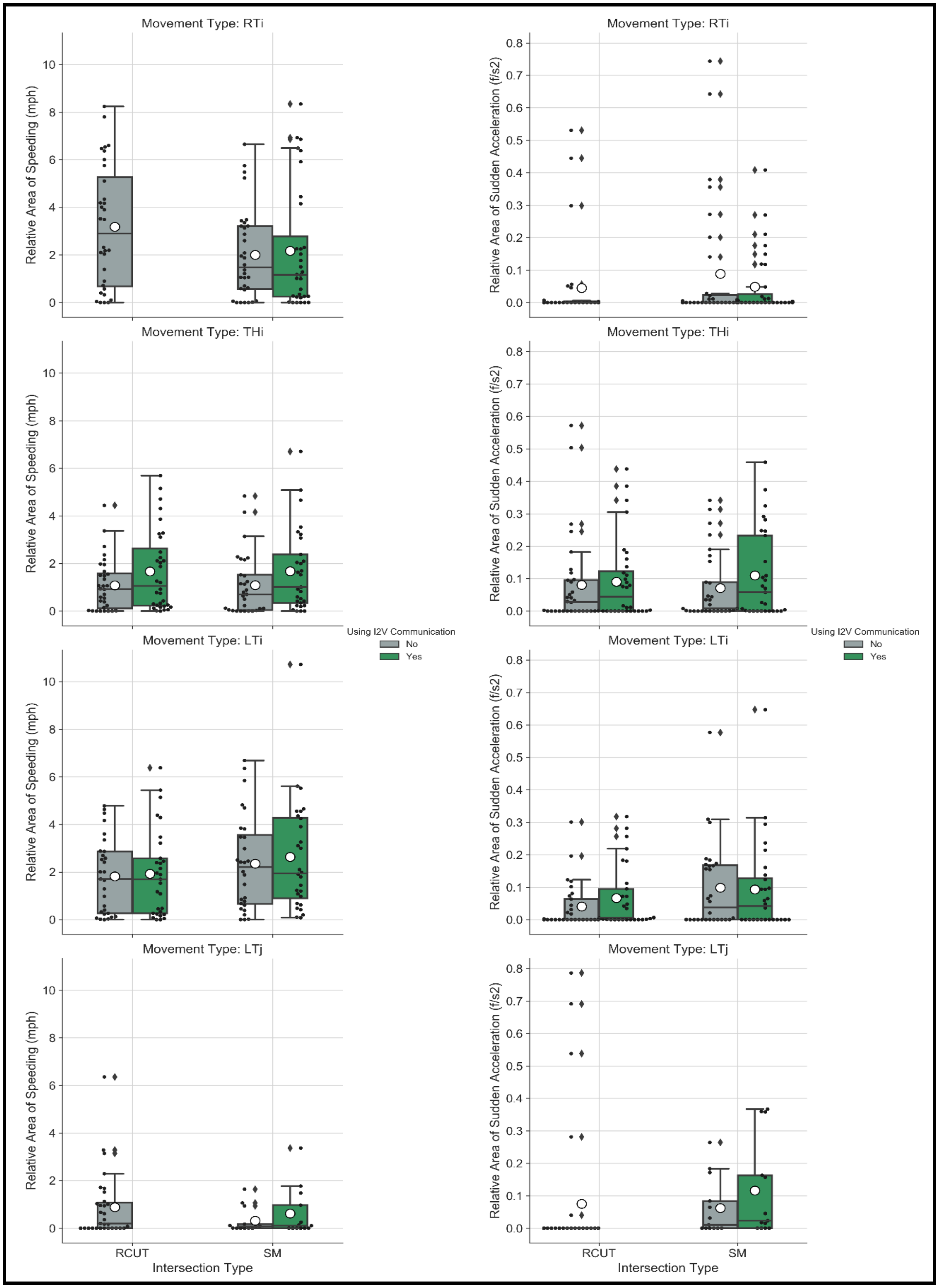

Figure 28: Distribution of relative area of speeding and sudden acceleration by movement and intersection types with/without using I2V communication

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.

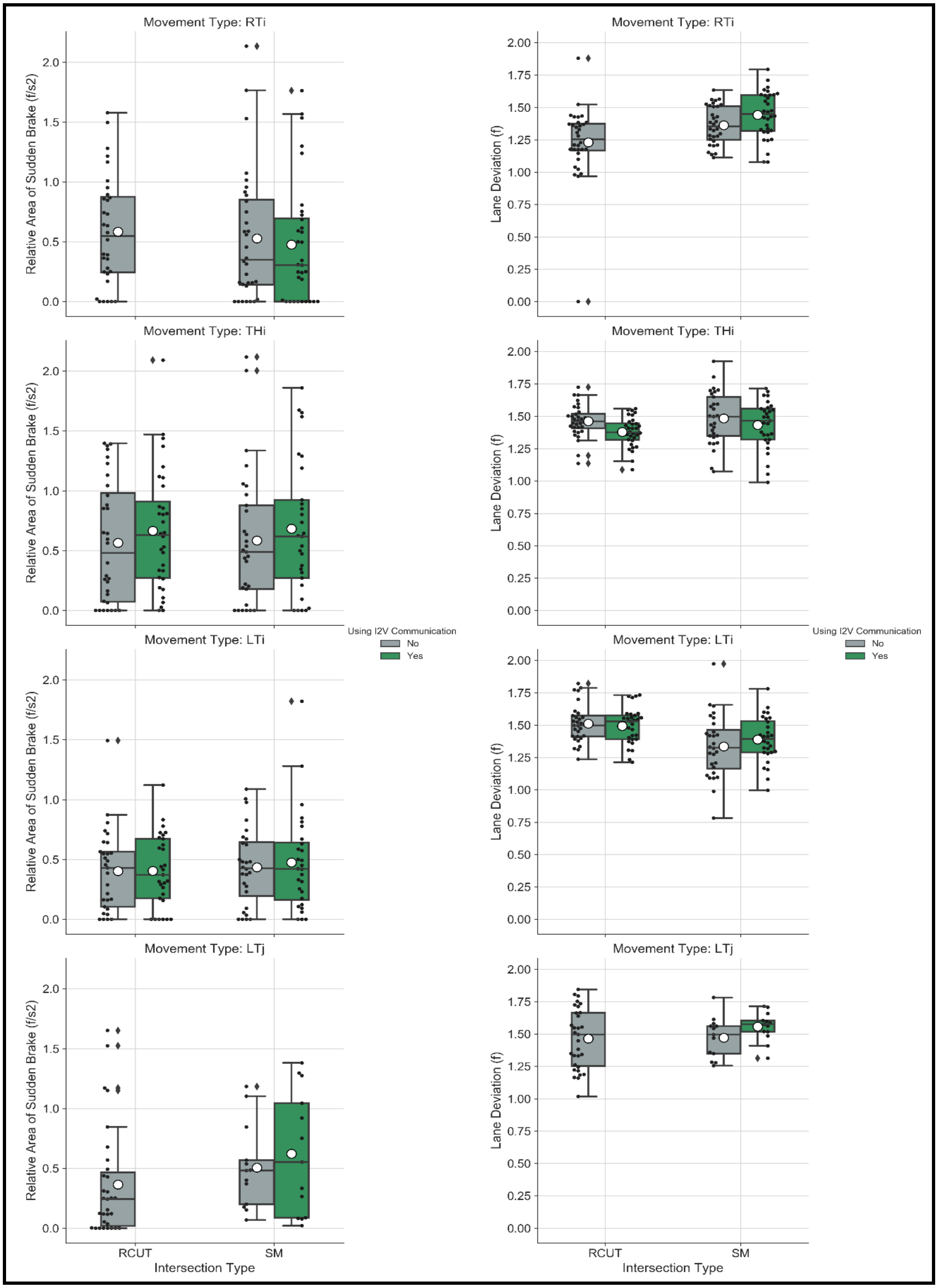

Figure 29: Distribution of relative area of sudden brake and lane deviation by movement and intersection types with/without using I2V communication

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

Measure	Intersection Type	Using I2V Communication	Mean (S.D.)				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/s²)	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/s²)	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.

7 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 30, 31, and 32 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 (*Houston et al., 2003*) and they associated with crash occurrence especially rear-end crashes.

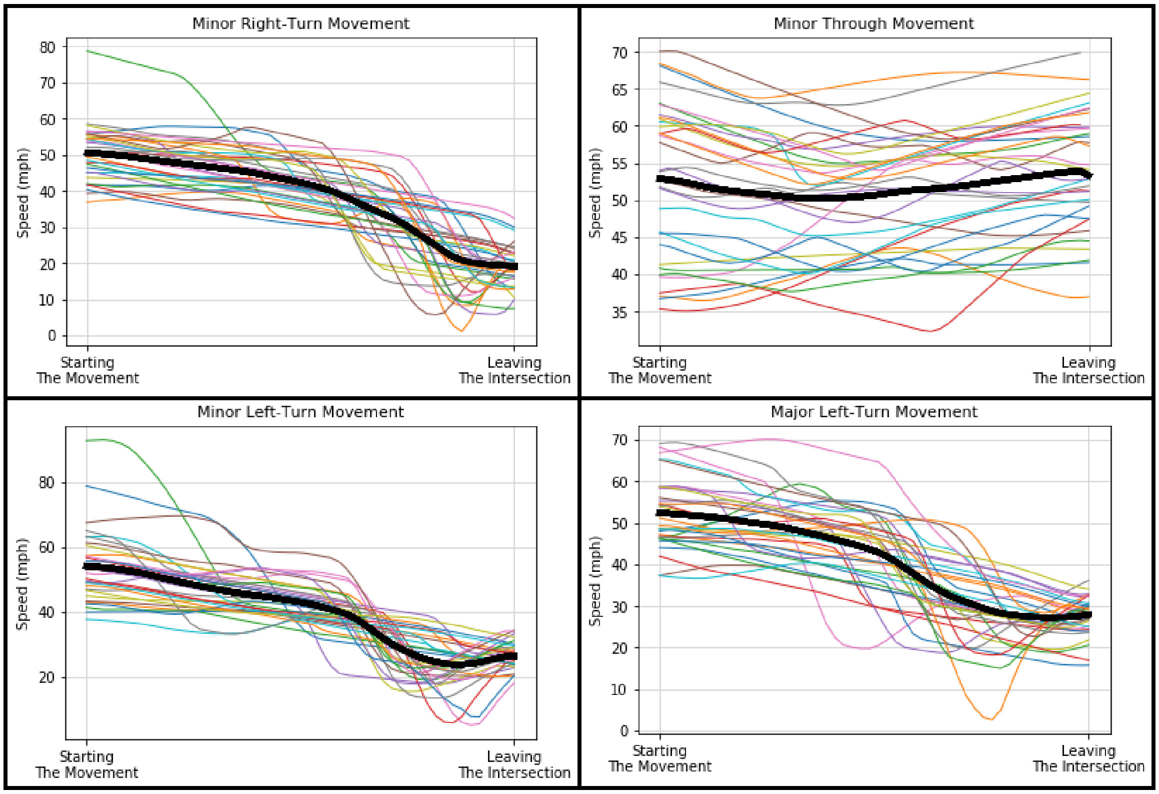

Figure 30: Speed profiles at the conventional intersection

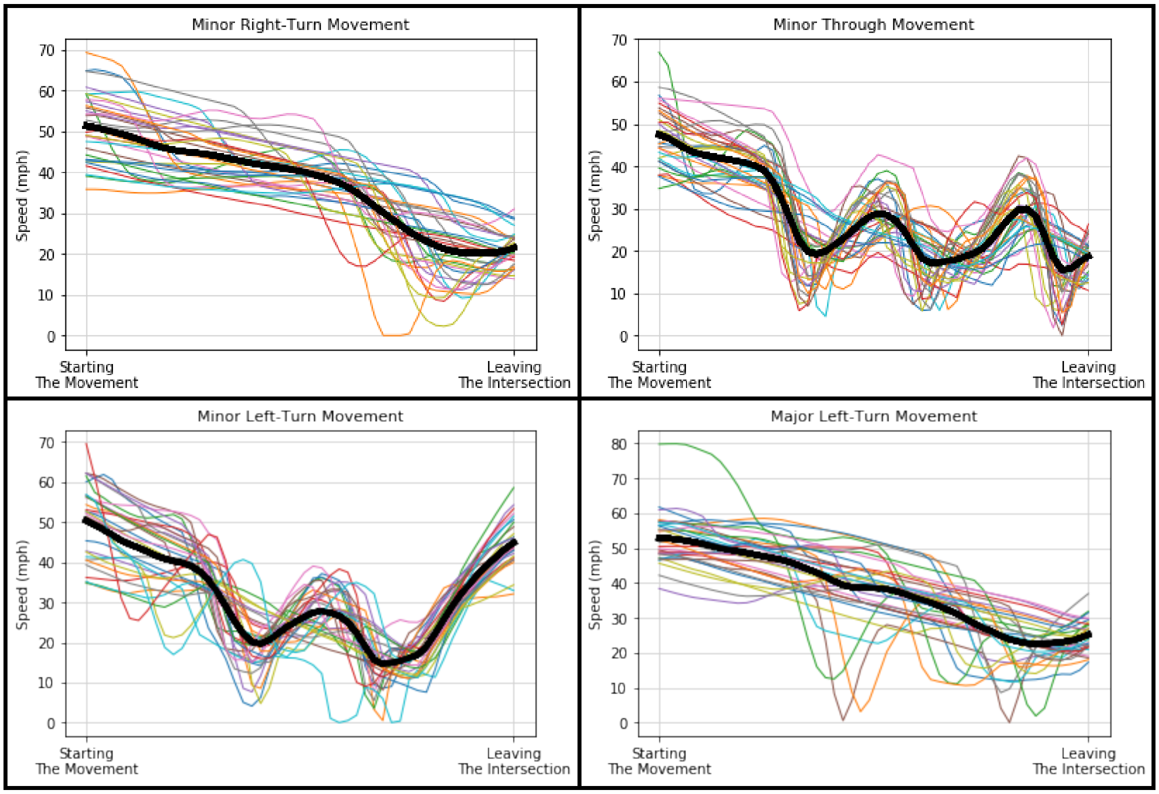

Figure 31: Speed profiles at the RCUT intersection

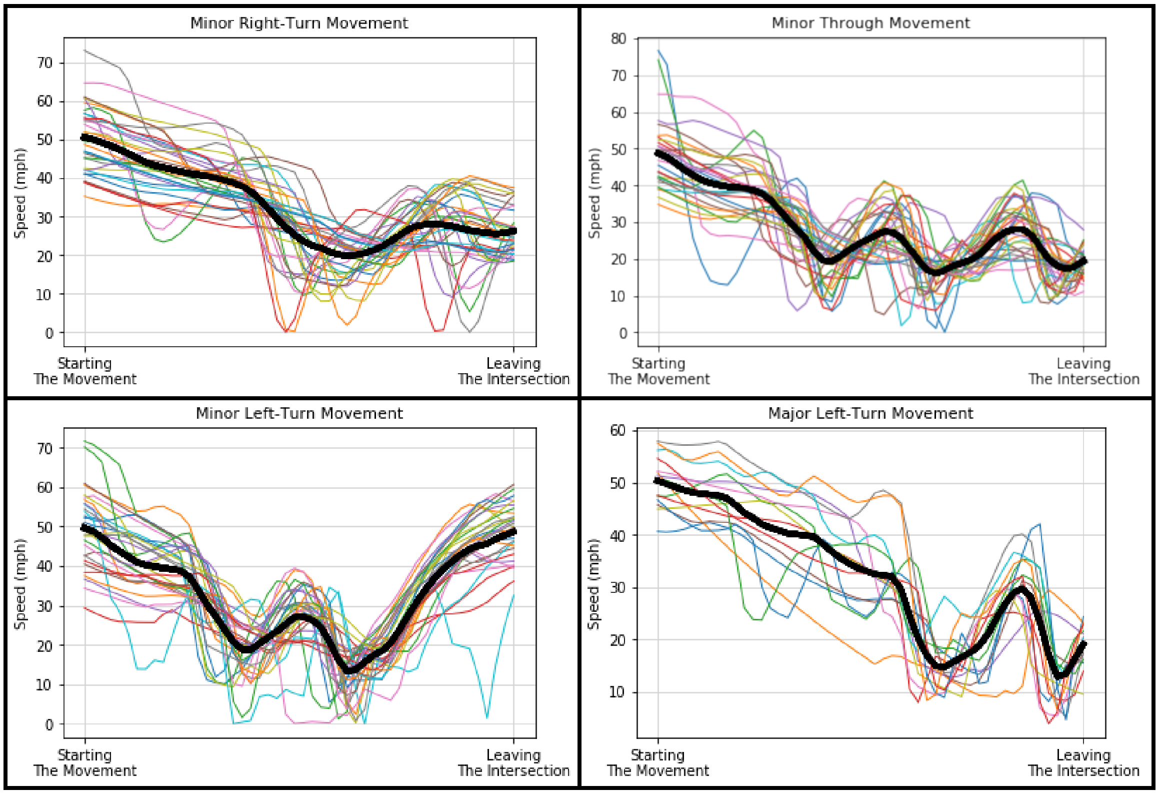

Figure 32: Speed profiles at the SM intersection

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.

8 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™ driving simulator at the University of Central Florida. 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.

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