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Integrated Implementation of Innovative Intersection Designs

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16. Abstract

This study evaluated the performance of pedestrian-bicycle crossing alternatives at Continuous Flow Intersections (CFI). Further, a comparison was also performed of CFI crossing types against a standard intersection designed to provide an equivalent volume-to-capacity ratio. Three CFI crossing alternatives were tested, namely Traditional, Offset, and Midblock crossings. In total, 24 alternative scenarios were generated by incorporating two bicycle path types, two right-turn control types, and two CFI types. These scenarios were analyzed through microsimulation on the basis of stopped delay, travel time, and number of stops.

Simulation results revealed the Offset crossing alternative incurred the least stopped delay for all user types. The Traditional crossing generated the least number of stops. The Midblock crossing can be considered as a supplement to either the Offset or Traditional crossing depending on the specific origin-destination patterns at the intersection. The exclusive bicycle path performed better than the shared-use path in most cases. However, these general trends may vary significantly at the route-level analysis. When compared with an equivalent standard intersection, aggregated results showed significant improvement for all CFI crossing types with respect to travel time and stopped delay, but the standard intersection had an equal or fewer number of stops. Future research includes incorporating pedestrian-bicycle safety, comfort, and the relative effects of these crossing alternatives on vehicular operations. Finally, a summary of the multimodal aspects of Reduced Crossings IU-Turn (RCUT) intersections, as studied by researchers at The Citadel is provided in Appendix B of this report. The reduction of the number of conflict points to as few as eight provided by RCUT intersection configurations was found to be beneficial to all roadway users including, motor vehicle traffic, pedestrians, bicyclists, and transit users.

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ABSTRACT

This study evaluated the performance of pedestrian-bicycle crossing alternatives at Continuous Flow Intersections (CFI). Further, a comparison was also performed of CFI crossing types against a standard intersection designed to provide an equivalent volume-to-capacity ratio. Three CFI crossing alternatives were tested, namely Traditional, Offset, and Midblock crossings. In total, 24 alternative scenarios were generated by incorporating two bicycle path types, two right-turn control types, and two CFI types. These scenarios were analyzed through microsimulation on the basis of stopped delay, travel time, and number of stops.

Simulation results revealed the Offset crossing alternative incurred the least stopped delay for all user types. The Traditional crossing generated the least number of stops. The Midblock crossing can be considered as a supplement to either the Offset or Traditional crossing depending on the specific origin-destination patterns at the intersection. The exclusive bicycle path performed better than the shared-use path in most cases. However, these general trends may vary significantly at the route-level analysis. When compared with an equivalent standard intersection, aggregated results showed significant improvement for all CFI crossing types with respect to travel time and stopped delay, but the standard intersection had an equal or fewer number of stops. Future research includes incorporating pedestrian-bicycle safety, comfort, and the relative effects of these crossing alternatives on vehicular operations.

Finally, a summary of the multimodal aspects of Reduced Crossings IU-Turn (RCUT) intersections, as studied by researchers at The Citadel is provided in Appendix B of this report. The reduction of the number of conflict points to as few as eight provided by RCUT intersection configurations was found to be beneficial to all roadway users including, motor vehicle traffic, pedestrians, bicyclists, and transit users.

Keywords: Continuous Flow intersection, Displaced left turn, Alternative intersection, Pedestrian, Bicycle, RCUT Multimodal effects

EXECUTIVE SUMMARY

Continuous Flow Intersections (CFIs), also known as Displaced Left-turn intersections (DLTs) have grown popularity in many countries primarily due to its reduced number of signal phases for vehicles as it removes the conflict between left-turn and opposing thru movements. However, due to its large footprint and unconventional displaced left-turn movement, pedestrians and bicycles experience unique challenges at this type of intersection. Therefore, it is important to evaluate different pedestrian-bicycle crossing alternatives at CFIs. The main objectives of this research are two-fold. The first objective is to evaluate the mobility performance of pedestrian and bicycle crossing facilities at CFIs. In addition to crossing alternatives, different alternative options for bicycle path type, vehicle right-turn control type, and CFI type are considered to generate various alternative scenarios. The second objective is to compare the CFI crossing alternatives with a standard intersection crossing of equivalent volume-to-capacity ratio. Three types of CFI crossing alternatives – Traditional, Offset, and Midblock crossing – are tested in this study. In total, 24 alternative scenarios were generated by varying the CFI type, right-turn control type, and the bicycle path type. All these alternative scenarios were analyzed through microsimulation based on average stopped delay, travel time, and number of stops.

Results from the simulation runs revealed that for most route types, Midblock crossing generated the highest stopped delay, while the Offset crossing generated the lowest among the three crossing alternatives. Travel time showed the same trend as the stopped delay for most route types. Offset crossing generated the highest number of stops compared to the other two crossing types primarily due to the increased number of stages. Traditional crossing exhibited the least number of stops due to its straightforward configuration. Overall, exclusive bicycles generated significantly lower stopped delay, travel time, and number of stops than bicycles on the shared-use path. Route level analysis revealed several deviations from these common trends for some route types.

Post-Hoc Tukey test revealed the difference in stopped delay incurred by Midblock and Offset crossing is the most prominent. Except for exclusive bicycle stopped delay and number of stops, the difference in performance measures for other users between different pairs of crossing alternatives are statistically significant. When comparing an equivalent standard intersection crossing with a CFI crossing, a CFI with Traditional or Offset crossing incurred less stopped delay and travel time because of the reduced number of phases. However, a CFI with an Offset or a Midblock crosswalk generated a higher number of stops than a standard intersection because of the increased number of stages. For future research, we recommend testing other innovative crossing options, for instance, a combination of Midblock and Traditional crossing at a CFI. Further, it is suggested to investigate pedestrian-bicycle safety, comfort, and the relative effects of these crossing alternatives on vehicular operations.

A summary of the multimodal aspects of RCUT intersections was also investigated by The Citadel (see Appendix B). Results indicated that a reduction of the number of conflict points to as few as eight provided by RCUT configurations was found to be beneficial to all roadway users including, motor vehicle traffic, pedestrians, bicyclists, and transit users.

1. INTRODUCTION

1.1 Background

Addressing pedestrian and bicycle mobility in conjunction with traffic operation and motor vehicle efficiency is a critical concern in the design and configuration of transportation infrastructure. Pedestrians and bicycles often experience excessive delays, have higher risks, and safety concerns at signalized intersections due to the concentrated number of conflict points with motorized traffic flows and other factors related to cycle length and levels of congestion (Pulugurtha and Imran, 2015). Further, the overall quality of service for pedestrians and bicycles can be worse in the case of alternative intersections, which are designed primarily to improve the efficiency of vehicular movements.

Alternative intersections and interchanges like Continuous Flow Intersections (CFI), Restricted Crossing U-turns (RCUT), and Diverging Diamond Interchange (DDI) are gaining popularity all over the world (Jagannathan and Bared, 2005; Warchol et al., 2017; Holzem et al., 2015). An RCUT reroutes all minor street through and left movements to turn right at the main intersection, then utilize a U-turn crossover, and then return to the main intersection to finish the movement. CFI or Displaced Left-turn Intersection (DLT) is another alternative intersection which is mostly built in urban setup (Hughes et al., 2010) and at junctions where left-turn demand is expected to be high. In this system, additional signals upstream of the main intersection are introduced to move the left-turn lanes to the left of the exit lanes upstream of the main intersection. Thus, the conflict between the left-turn vehicles and the opposite through vehicles at the main intersection is transferred to the upstream intersections. Therefore, the main intersection can run as few as in two phases, which consequently improves the efficiency of vehicular movements. The signal timing of the upstream intersections can be designed in such a way that the upstream intersections do not incur additional delays to the opposing thru movements. A simplified line diagram of a CFI with displaced left-turn on two legs (Partial CFI) is shown in Figure 1-1.

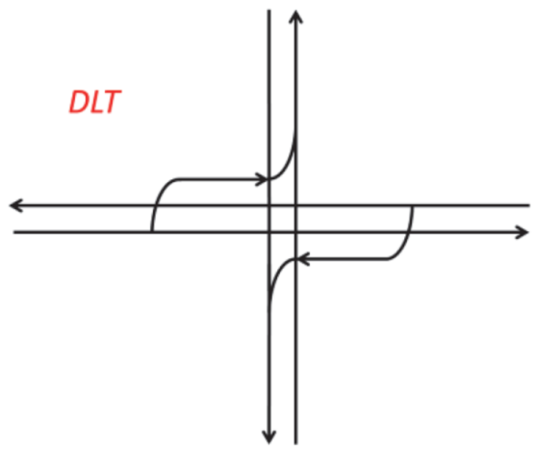


FIGURE 1-1: SCHEMATIC OF A CFI OR DLT INTERSECTION

Despite being favorable to vehicular movements, CFIs pose unique challenges to pedestrians and bicyclists. The footprint of a CFI is designed larger than an equivalent standard intersection in order to provide a sufficient radius of curvature for the displaced left-turn lanes. Further, the crosswalks need to be multi-staged when the signal timing plan of a CFI has two phases (Coates et al., 2014). On the other hand, while RCUT intersections reduce conflict points for pedestrians and bicycles, the currently used crosswalks are multi-staged, and the designs are foreign to most users. Since CFIs can be built in urban and suburban areas (Hughes et al., 2010) where pedestrian and bicycle activities are common, it is imperative to investigate different pedestrian and bicycle crossing options at these alternative intersections. The major focus of this study is on pedestrian-bicycle mobility at a CFI. It also focuses on pedestrian-bicycle considerations at RCUT intersections to a limited extent.

1.2 Research Objectives

The main objectives of this research are two-fold. The first objective is to evaluate the mobility performance of pedestrian and bicycle crossing facilities at CFIs. In addition to crossing alternatives, different alternative options for bicycle path type, vehicle right-turn control type, and CFI type are considered to generate various alternative scenarios. The second objective is to compare the CFI crossing alternatives with a standard intersection crossing designed to provide an equivalent volume-to-capacity ratio. VISSIM microsimulation tool was used to evaluate all crossing alternatives.

In addition to pedestrian-bicycle crossing alternative analysis at CFIs, a secondary objective of this study is to review the state-of-the-art practice of pedestrian-bicycle safety analysis and transit consideration at RCUT intersections. That discussion is provided in Appendix B of this report.

1.3 Scope

The scope of this research was limited to pedestrian and bicycle activities at CFIs. Specifically, the research sought to recommend crossing alternatives for pedestrians and bicycles at CFIs in terms of different performance measures and also to portray the contrast with the crossing at equivalent standard intersections. The effect of these crossing options on vehicular movements is not investigated in this study.

1.4 Organization of the Report

This report includes five chapters and two appendices, beginning with this introductory chapter. Chapters 2 covers the literature review. Chapter 3 presents the research methodology, including the analysis methods considered and details about the microsimulation models of alternative scenarios that were generated. Chapter 4 covers the results from the simulation runs and their interpretations. Conclusions and recommendations are provided in Chapter 5. There are four appendices that provide details on performance measures (Appendix A): Safety aspects of RCUT intersections (Appendix B), supplementary diagrams of pedestrian crossing facilities at innovative geometric designs (Appendix C), and a Summary of Accomplishments (Appendix D).

2. LITERATURE REVIEW

A review of the published literature on pedestrian and bicycle crossing facilities at alternative intersections (with the major focus on Continuous Flow Intersections or CFIs) is presented in this chapter. Studies that applied microsimulation techniques for evaluating pedestrian and bicycle crossing facilities are emphasized. The outcomes are expected to assist in simulating and evaluating pedestrian crossing facilities at CFIs.

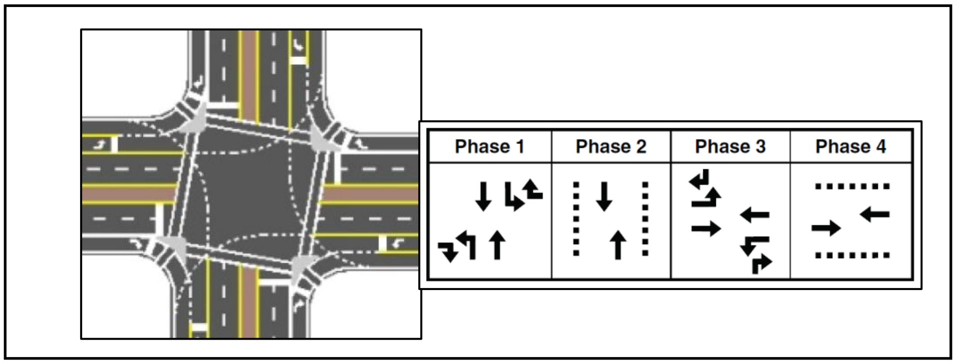
2.1 Application of Microsimulation in Pedestrian-Bicycle Studies

The application of microsimulation tools to assess non-motorized users' safety and mobility at various types of intersections has been found in several studies. The concept of simulating pedestrians as vehicles in VISSIM was introduced by Ishaque and Nolan (Ishaque and Nolan, 2009). It demonstrated the details of pedestrian and vehicular traffic simulation in a VISSIM environment for a series of standard intersections. Field data on various parameters such as pedestrian speed, flow rate, compliance, vehicle travel time, and vehicle flow rate were collected for a route in London, UK. The route consisted of six intersections in series and a total of nine pedestrian crosswalks. There was no interaction among the pedestrians so that their performance measures were not affected unaffected by their density. Calibration and validation of vehicular flow data were promising and evidenced a successful simulation. However, the simulated speed of pedestrians had a poor correlation with the observed speed data. Therefore, the model was recalibrated using a different model, which exhibited significant improvement of the correlation. Overall, this study described the important elements regarding pedestrian crossing at a signalized intersection. Holzem et al. (Holzem et al., 2015) also modeled pedestrians and bicycles in VISSIM as vehicles without any interaction to test different crossing alternatives at superstreets. Four types of pedestrian crossings are recognized in superstreets: diagonal, median, midblock, and 2-stage Barnes Dance. Three types of bicycle crossing facilities, namely direct crossing, vehicle U-turn, bicycle U-turn – are evaluated as well. Edara et al. (Edara et al., 2015) simulated both Double Crossover Intersection (DXI) and Diverging Diamond Interchange (DDI) in a VISSIM environment and the performance measures of pedestrian-bicycles were contrasted against those for a traditional intersection. Several scenarios for each intersection geometry were generated by varying traffic volume.

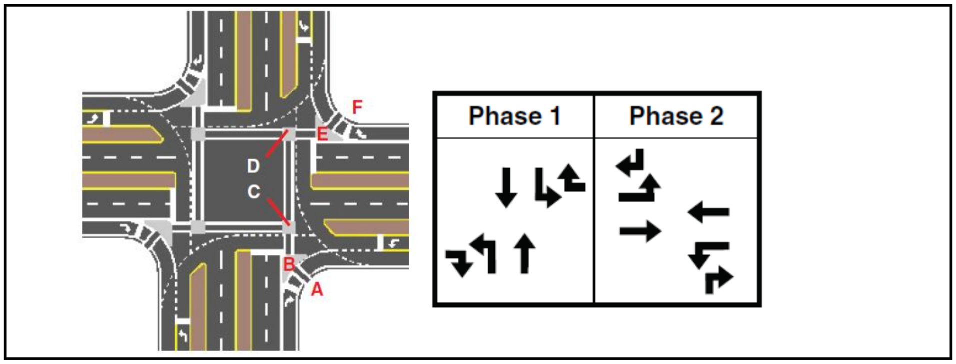
2.2 Simulation of Pedestrian-Bicycle Crossing Alternatives at CFIs

The application of microsimulation in assessing CFI performance was found as early as 2005 (Jagannathan et al., 2005). That study demonstrated the assessment of one pedestrian crossing type – a multi-staged crossing with refuge islands – at three different geometric designs of the CFI using VISSIM. The geometries modeled were: a four-legged CFI with two displaced left-turn legs (Partial CFI), a four-legged CFI with four displaced left-turn legs (Full CFI), and a three-legged CFI (T-intersection) with displaced left turns only at the major street approach. Note that the most common CFI geometry built in the U.S. is the four-legged Partial CFI.

Linear programming along with microsimulation was utilized in a few studies as well. Coates et al. (Coates et al., 2014) compared pedestrian safety and mobility for two types of crossing facilities in a four-legged CFI, namely Traditional and Offset, using VISSIM. Figure 2-1 (a) and (b) show the geometry of these two crossing facilities along with their phase sequences. The traditional crossing generated less crossing time than the offset crossing due to the straightforward structure but incurred additional delays to the vehicular movements. To tackle this issue, this study proposed an adaptive control strategy for reducing vehicular delay in a CFI with Traditional crossing. A multi-objective mixed-integer programming model was proposed by (Zhao et al., 2015) to achieve the best operational performance of a CFI by changing the CFI type, configuration of the right-turn lane, distance to the displaced left-turn junction, and signal timing plan. However, it did not focus on the crosswalk geometries of the CFI. Zhao et al. (2019) proposed to improve the operation of a CFI by shifting the crossing location of left-turning bicycles to the midblock location, so there is no conflict with thru traffic. A linear programming tool was used to optimize the geometry and signal timing, and it was tested by simulating a real intersection in VISSIM. Constraints added to the linear programming were based on the phase plan, cycle length, minimum green time, queue storage capacity for left-turn bicycles and vehicles, saturation flow rate, and degree of saturation.



(a)



(b)

FIGURE 2-1: CFI GEOMETRY AND PHASE SEQUENCE FOR (a) TRADITIONAL CROSSING (b) OFFSET CROSSING (COURTESY, COATES ET AL., 2014)

2.3 Frameworks for Analyzing Pedestrian-Bicycle Crossings at CFIs

Several studies proposed analytical frameworks to evaluate the operation of CFIs in terms of pedestrian-bicycle crossings and vehicle movements. Wang et al. (2019) developed an analytical model to calculate pedestrian delay at a CFI for three types of crossings and tested its accuracy with VISSIM. In addition to a traditional and an offset crossing, it demonstrated the application of an exclusive pedestrian phase. Only pedestrian movements on all directions (e.g., thru and diagonals) run in this exclusive pedestrian phase. However, this study did not consider the delay to vehicles accrued by pedestrians to cross such a large intersection diagonally. FHWA published an analytical tool called “Cap-X” (Lochrane, 2011) that compares the performance of eight types of intersections, including CFIs for different vehicle demands and lane configurations. Virginia Department of Transportation (VDOT) developed a tool (VJuST, 2017) to analyze the performance of 26 Alternative Intersections and Interchanges in terms of vehicular congestion, safety, and pedestrian accommodation for screening purposes. Although these studies provide a quick sketch-level assessment of alternative intersections, the methods are deterministic in nature and cannot capture the stochasticity involved with the demand and capacity of the intersections

2.4 Qualitative Assessment of Pedestrian-Bicycle Crossings at CFIs

A few studies discussed the pedestrian-bicycle accommodations of the CFI using only qualitative assessment. Chlewicki (2017) demonstrated the current practice of pedestrian-bicycle crossing facilities at innovative intersections qualitatively and proposed several improvement options. In this paper, the term "Innovative Geometric Designs" (IGDs) was used instead of an alternative intersection. This study introduced several general principles of a pedestrian crossing at various IGDs, including pedestrian sight distance, crossing distance, and pedestrian phasing. Exclusive pedestrian phasing was recommended during the pedestrian-bicycle peak hour if that does not conflict with vehicular peak hours.

The study discussed pedestrian crossing facilities at seven types of IGDs. Additional diagrams explaining this study by Chlewicki (2017) is provided in Appendix C. The summary of the discussion for CFI crossing facilities is provided below:

1. Crossing option at the main intersection: Pedestrian-bicycle crossing at the min intersection of a CFI can be either multi-staged (Offset) or single staged (Traditional). This study preferred a multi-staged crossing over a long, single-staged one since it eliminates the conflicts between turning vehicles and pedestrians.
2. Midblock Crossing with Median Sidewalk: It proposed a new crossing design where one stage of crossing occurs upstream from the main intersection and the other stages occur midblock near the displaced left-turn intersection. According to this design, the signal at the displaced left turn and the main intersection can be easily synchronized so that pedestrian-bicycles experience progression through the two intersections.

This study also proposed modified versions of the crossing alternatives mentioned above. For instance, it proposed a crossing alternative similar to the Offset crossing, where one stage to cross a street takes place at the main intersection and another one at the midblock intersection (Figure 2-2). It also proposed a "Median sidewalk" and "Reduce median" crossing options. However, pedestrian-bicycles need to cover a long distance over a narrow median with vehicle movements on both sides according to these modified designs. Thus, their level of comfort is likely to be degraded.

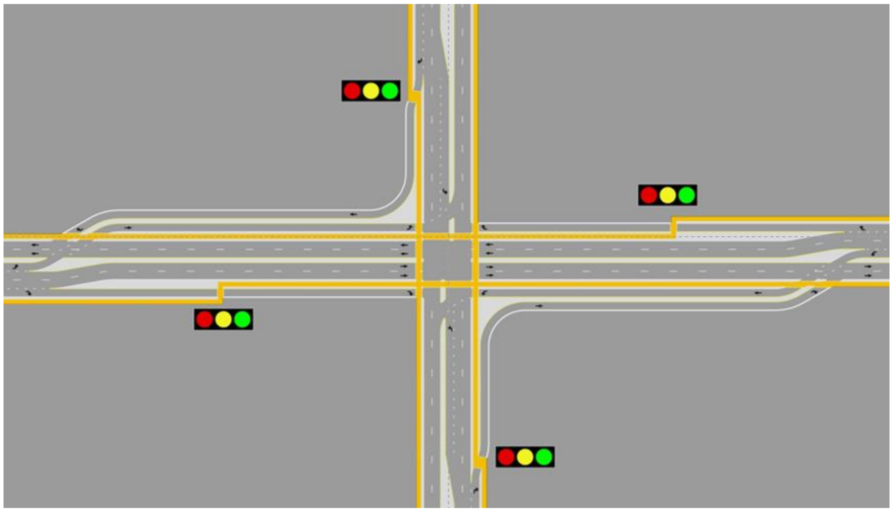


FIGURE 2-2: MODIFIED OFFSET CROSSING (CHLEWICKI, 2017)

Several guidance reports have been published regarding the mobility and safety of pedestrian-bicycles in a CFI. Among these, the Utah Department of Transportation (UDOT) and FHWA (UDOT, 2018; FHWA, 2014) discussed the configuration of pedestrian-bicycle crossing facilities at a CFI along with its signal timing plan. The objective of the UDOT guidance report was to accelerate the acceptance of CFI use in Utah. It discussed the configuration of pedestrian-bicycle crossing facilities and associated signal timing plans. The critical points of the guideline are described below:

- The report recommended shortening the length of signalized pedestrian crossings whenever possible to allow maximum signal timing flexibility.
- In the case where pedestrians need to cross the right turn bypass lane without any dedicated phasing, proper warnings should be given to yielding right turners to ensure pedestrian safety.
- If a CFI is designed without a right turn bypass lane, right turn on red (RTOR) must be prohibited.
- One challenge of designing bicycle crossing facilities at a CFI is to provide appropriate guidance to the bicyclists so that they can embrace the novel geometric design.
- It also pointed out the fact that bicyclists' choice of selecting a crossing option depends on their experience and confidence. Inexperienced bicyclists try to avoid vehicular lanes and are likely to use the crosswalk. Referring to Figure 2-3 below, inexperienced cyclists are likely to use the crosswalk in contrast to experienced cyclists who are inclined to use direct vehicular paths.

Despite the qualitative guidance, no numerical example or analysis was presented in this study to assess different options of pedestrian-bicycle crossing facilities at a CFI.

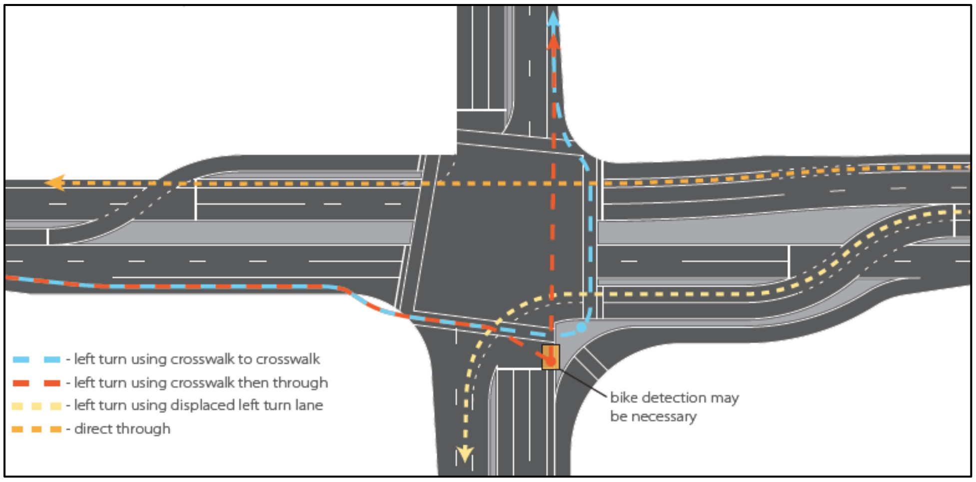


FIGURE 2-3: BICYCLE CROSSING OPTIONS AT A CFI (COURTESY: UDOT, 2013)

The FHWA (2014) also published a report to provide general ideas regarding the current practices of various CFI installations both in terms of vehicular and pedestrian crossings. Two different types of pedestrian crossing configurations with and without conflicting left turners (Traditional and Offset, respectively) were recognized in this report. Regarding the vehicle right-turn movements, design consideration for both signal and yield control was provided as well.

2.5 Performance Measures

To evaluate pedestrian-bicycle crossing facilities, the most common measures used in past studies are average or maximum delay per route per pedestrian (Holzem et al., 2015; Edara et al., 2005; Jagannathan et al., 2005), average or total stops per pedestrian crossing (Holzem et al., 2015; Edara et al., 2005), total stopped delay per pedestrian crossing geometry (Holzem et al., 2015; Edara et al., 2005) and travel time per pedestrian crossing geometry (Holzem et al., 2015;, Coates et al., 2014). Coates et al. used exposure rate and time to cross to evaluate the safety and mobility of pedestrians at a CFI, respectively. The Highway Capacity Manual (HCM, 2016) described a Level of Service criteria based on average delay to evaluate pedestrian and bicycle crossing. Holzem et al., analyzed pedestrian-bicycle crossing facilities at superstreets using the method described in the Highway Capacity Manual and other delay-based performance measures. Pedestrian accommodation is analyzed in VJust (Vjust, 2017) using three performance measures– namely – pedestrian safety, wayfinding or crosswalk alignment, and delay. Safety is estimated based on the direction of traffic flow, number of pedestrian-vehicle conflict points, and crosswalk length (relative to a traditional intersection). Delay is estimated using traffic signal cycle length and number of crossings for each movement. Combining these measures, pedestrian accommodation is evaluated as static ratings (better, similar, or worse) compared to a traditional intersection.

The summary of these different performance measures used by different studies are presented in Table 2-1.

Table 2-1: PERFORMANCE MEASURES USED IN PAST STUDIES

MOEs	Study
Average delay per stop per route per pedestrian	Jagannathan & Bared (2005), Holzem (2015), Edara et al. (2003), HCM (2016)
Maximum average delay per route per pedestrian	Jagannathan & Bared (2005), Edara et al. (2005)
Maximum average stops per pedestrian crossing geometry	Holzem (2015)
Total stopped delay per pedestrian crossing geometry	Holzem (2015), Edara et al. (2005)
Total number of stops per pedestrian crossing geometry	Holzem (2015), Edara et al. (2005)
Travel time per pedestrian crossing geometry	Holzem (2015), Coates et al. (2014)
Pedestrian exposure rate	Coates et al. (2014)
Combined static ranking	VJust (2017)

2.6 Summary

From the survey of available literature, it is apparent that several studies used microsimulation tools to evaluate pedestrian-bicycle crossing facilities at signalized intersections. The most common performance measures for pedestrian-bicycle mobility used by these studies are the descriptive statistics of stopped delay, number of stops, and travel time. Among these studies, only a few focused on CFIs and reported the performance on an aggregated level. Consequently, research on testing different crossing alternatives and the variation in performance on a route-level is scarce. Further, the performance of the CFI crossing types relative to an equivalent standard intersection has not been studied to the authors' knowledge.

3. RESEARCH METHODOLOGY

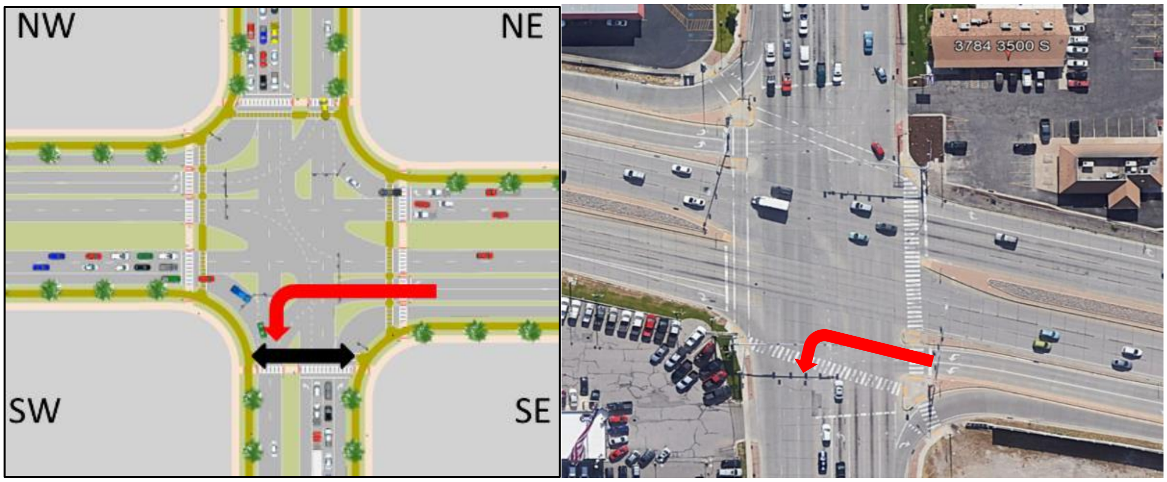
This chapter describes the methodology adopted to evaluate pedestrian-bicycle crossing alternatives at CFIs. First, three types of pedestrian-bicycle crossing geometries considered in this study are described. Next, the details of the analysis using simulation are presented. Then, the development of alternative scenarios by introducing two types of right turn control, bicycle path, and CFI type are presented. Finally, the model development process for an equivalent standard intersection is discussed.

3.1 Crossing Alternatives

In this study, three types of crossing alternatives are proposed to be tested for both pedestrians and bicycles. Two of these crossing alternatives – namely the Traditional and Offset crossing – are currently used in practice at existing CFIs. The third type, called the Midblock crossing, was proposed by (Chlewicki 20*17*); however, to the authors' best knowledge, it is not currently in use at any CFI. In addition, two types of bicycle paths – namely shared-use paths and exclusive paths – are modeled in this study.

3.1.1 Traditional Crossing

Illustration of a Traditional crossing for pedestrians and bicycles at a CFI is shown in Figure 3-1. This crossing configuration is widely used in the US. Similar to a standard four-legged intersection, the vehicular left-turn movement from one approach conflicts with the parallel pedestrian-bicycle crossing. Due to the heavy left turn presence at CFIs, the left turn is frequently protected. Consequently, the signal controller's ring-barrier system requires four phases as the left turn and pedestrian-bicycle crossing cannot run simultaneously. The primary advantage of this crossing type is that all the users need only one stage to cross any leg. This crossing type was also termed a "Split 2-phase Crossing" in a past study (Coates et al., 2014).

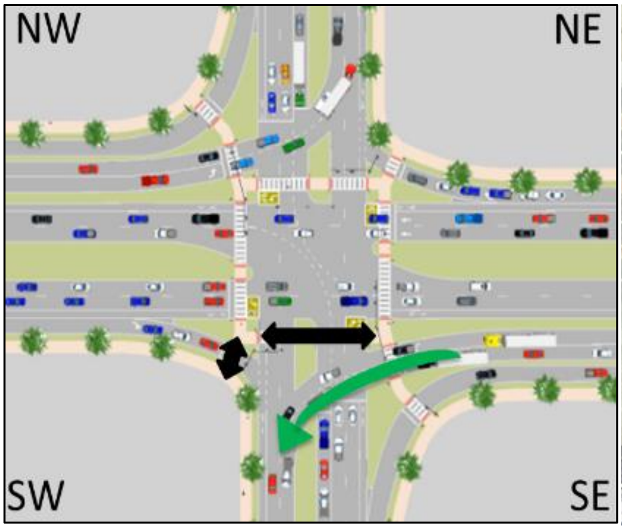


(a) (b)

FIGURE 3-1: (a) SCHEMATIC OF TRADITIONAL CROSSING (b) AN EXAMPLE OF THIS CROSSING TYPE IN WEST VALLEY CITY, UT

3.1.2 Offset Crossing

Several CFIs in Mexico and a few in the US (e.g., East Eisenhower Blvd. & Madison Ave. in Loveland, CO and Beechmont Ave. & Five Mile Rd in Cincinnati, OH) have crosswalks aligned such that they do not conflict with the parallel left turns from the displaced left-turn legs. As shown in Figure 3-2, this design "offsets" the crosswalk toward the inside of the intersection, hence the term Offset crossing. As the left turn movement can simultaneously run with the parallel pedestrian-bicycle movement, this crossing geometry requires only two phases in the ring-barrier system. However, the major disadvantage of this crossing type is that pedestrians and bicycles need at least two phases to cross each leg of the intersection. More phases may be needed if the right turns are signalized.



(a)

(b)

FIGURE 3-2: (a) SCHEMATIC OF OFFSET CROSSING (b) AN EXAMPLE OF THIS CROSSING TYPE IN LOVELAND, CO

3.1.3 Midblock Crossing

This crossing type is similar to the Traditional crossing; however, the major street crossing is shifted to the “midblock” location from the main intersection, hence the term Midblock crossing. An advantage of this crossing is that it provides a very short travel path between the left corners of the NW and SW quadrant and between the right corners of NE and SE quadrant. Some routes, however, experience significant out of direction travel. Furthermore, sufficient signs and markings must supplement the design of this crossing type so that the users, particularly impaired pedestrians, are properly guided toward use it. In this setup, the vehicular signal timing can also be designed in such a way that the midblock crossing does not incur additional stops or delay to the vehicles as long as a median refuge is provided, as shown in Figure 3-3. It should be noted that a Midblock crossing can be used in conjunction with Traditional or Offset crossings, but for this effort was studied in isolation.

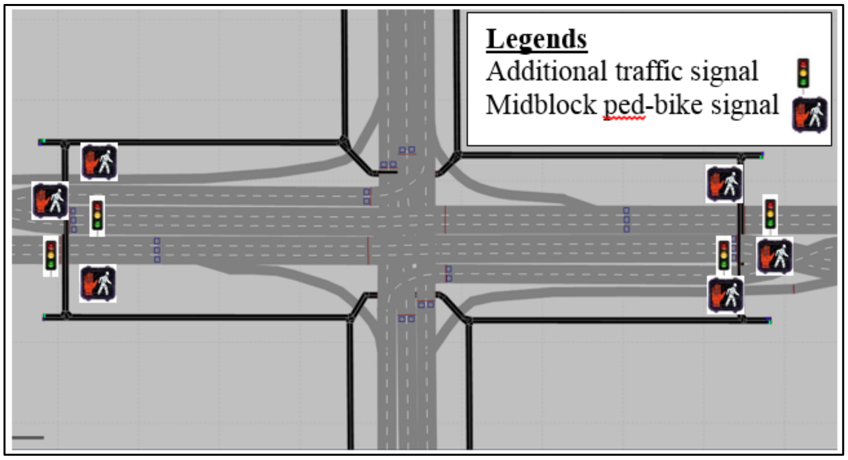


FIGURE 3-3: SCHEMATIC OF A MIDBLOCK CROSSING

3.2 Analysis Using Microsimulation

Microscopic simulation through PTV VISSIM 10.0 (PTV Group, 2019) was used to model the crossing alternatives of CFIs. The simulation run time was one hour, following a 15-minute warm-up period. Each treatment was replicated 25 times so that the results are statistically meaningful. The following paragraphs provide details of the analysis method using VISSIM.

3.2.1 Base CFI Geometry Model

The base model consisted of a four-legged CFI, which is located between two standard signalized intersections in order to replicate a coordinated system in an urban corridor. The major street (E-W direction in Figure 3-4) has three thru lanes, two displaced left-turn lanes, and one channelized right turn lane on each approach. The displaced left-turn intersections are located 500 feet upstream of the main intersection. The eastbound thru movements are progressed through the three intersections. The minor street (N-S in Figure 3-4) configuration varies for partial vs. full CFI models. For the partial model, each approach has two thru lanes, two standard left-turn lanes, and one channelized right turn lane. For the full CFI model, the minor street approach is identical to the major street approach.

All the left turns at the conventional legs of the partial CFI have a 250 feet exclusive pocket lane as shown by the green arrows in Figure 3-4. The distance between the stop bars at the main and Displaced Left Turn (DLT) intersection is 500 feet. These are shown by the yellow arrows in Figure 3-4. The right turn lanes are designed as channelized

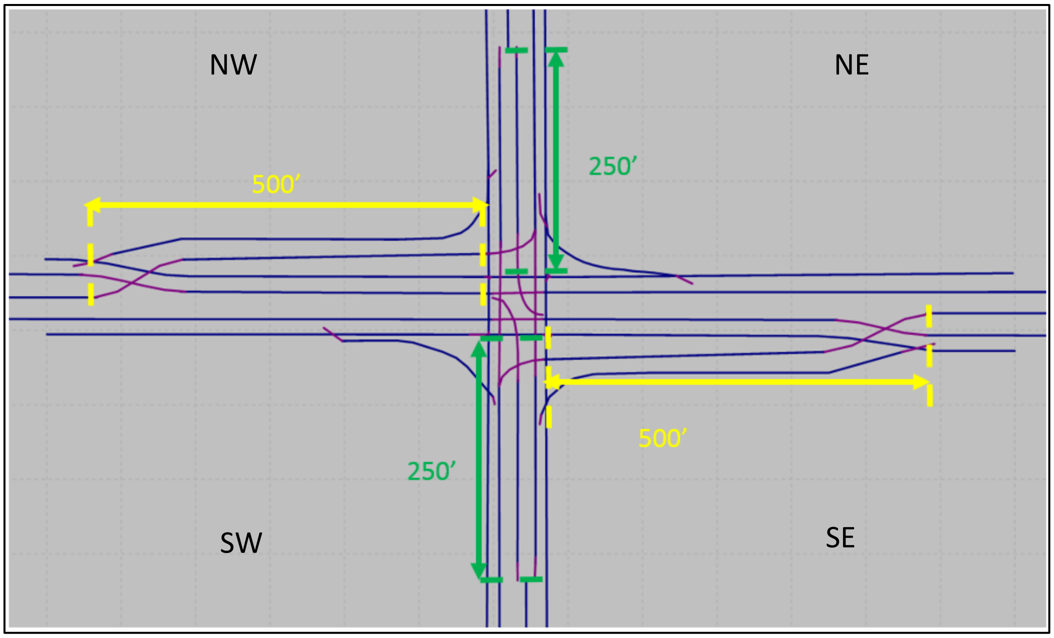


FIGURE 3-4: BASE GEOMETRY MODEL OF CFI

3.2.2 Adjacent Intersection Geometry

Since most CFIs are installed in urban areas (Hughes et al., 2010), their signal timing is coordinated with that of nearby intersections. As corridors with multiple consecutive CFIs exist mainly in Utah (U.S.), and are not very common in other locations, the upstream and downstream intersections are modeled as standard intersections. At these adjacent intersections, all left-turning movements have exclusive dual turning lanes, while right turning movements have exclusive single lanes. Two thru lanes are provided for the minor streets of the adjacent intersections. All left-turn lane pockets developed 250 feet upstream of the stop bar on the minor streets of the adjacent intersections, while on the major streets this distance was 300 feet. Figure 3-5 shows the schematic of one of the two adjacent intersections that are symmetric to each other.

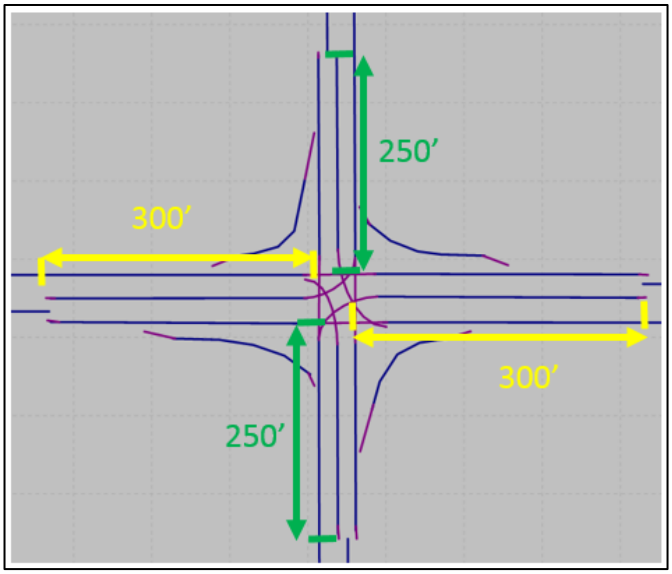


FIGURE 3-5: CONFIGURATION OF THE ADJACENT INTERSECTIONS

3.2.3 Pedestrian and Bicycle Model Construction

Similar to many past studies (Ishaque et al., 2005; Holzem et al., 2015), pedestrians and bicycles are modeled as "vehicles" in this experiment which allows interactions with vehicles. Sidewalks are modeled as "footpath" with a behavior type that allows the users to freely move without queueing, which is the default for vehicles. To ensure that all routes have statistically significant volume, a flow rate of 300 users per hour was used for pedestrians and bicycles on the shared-use path. Pedestrian volume is composed of two types of users, distinguished by their speed: walker (90 percent) and jogger (10 percent). The volume of exclusive bicycles was 100 users per hour. Being one-way in nature, the exclusive bicycle path does not have as many routes as the shared-use path; hence, a lower overall volume was sufficient to have a significant volume on each route. No pedestrian or bicycle crossing facility was included at the adjacent intersections.

To calibrate the speed distribution of pedestrians and bicyclists in VISSIM, field data were collected from six conventional intersections in North Carolina. These data were originally collected for a study of pedestrian and bicyclists crossing facilities at superstreets (Hummer et al., 2014). Details of the data collection technique are described in that study.

From the field data, pedestrians were classified into two categories: walkers and joggers. Figures 3-6 (a-c) show the histogram of speed for walkers, joggers, and bicyclists, respectively.

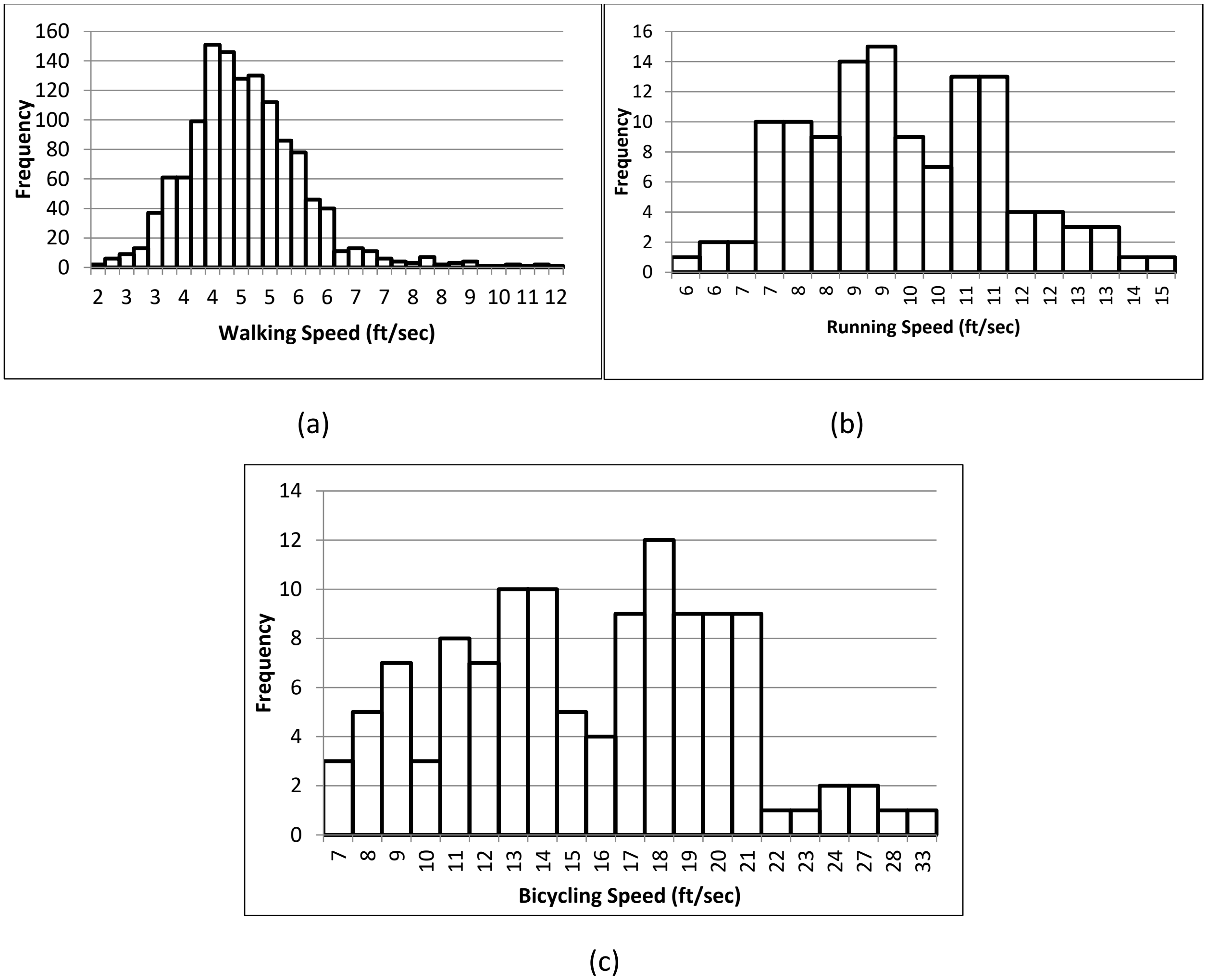


FIGURE 3-6: HISTOGRAMS OF (a) WALKER (b) JOGGER AND (c) BICYCLE SPEEDS

3.2.4 Scenario Generation

The simulation models of the aforementioned crossing options were set up with four input variables: bicycle path type, CFI type, right turn control type, and crossing geometry. The bicycle path type included exclusive lanes and shared use paths. CFI types included four displaced legs (full) and two displaced legs, one on each major approach (partial). Right turn control was either signalized or unsignalized. The three crossing geometries were as described earlier. In total, 24 scenarios for bicycles and 12 scenarios for pedestrians were generated by combining additional variables with these crossing options. Table 3-1 and the following subsections discuss these variables. Note that the column “Bicycle path type” applies to bicycles only.

TABLE 3-1: VISSIM MODEL COMBINATIONS BASED ON VARIABLE INPUTS

Combination no.	Bicycle path type	CFI type	Right turn control type	Crossing geometry
1	Exclusive	Full	Signalized	Traditional
2	Shared			
3	Exclusive	Partial		
4	Shared			
5	Exclusive	Full	Unsignalized	
6	Shared			
7	Exclusive	Partial		
8	Shared			
9	Exclusive	Full	Signalized	Midblock
10	Shared			
11	Exclusive	Partial		
12	Shared			
13	Exclusive	Full	Unsignalized	
14	Shared			
15	Exclusive	Partial		
16	Shared			
17	Exclusive	Full	Signalized	Offset
18	Shared			
19	Exclusive	Partial		
20	Shared			
21	Exclusive	Full	Unsignalized	
22	Shared			
23	Exclusive	Partial		
24	Shared			

Bicycle Path Types

Two types of bicycle paths were modeled: an exclusive bicycle lane alongside the vehicular lane and a shared-use path with pedestrians. The exclusive bicycle lane is a common cycle treatment in urban areas. It is a six-foot-wide lane adjacent to the rightmost vehicular lane and controlled by the vehicular signal at the intersection. The shared-use path is separated from traffic in a dedicated facility. It is common particularly in locations with recreational cyclists and is typically found in suburban and urban areas. Since the operation of these two path types is different, it was essential to test both at a CFI. It should be noted that to be consistent with design practice, the shared-use paths are modeled as two-way paths, while the exclusive bicycle lanes are modeled as one-way, causing some exclusive bicycle routes to be very long.

Number of Displaced Left Turn (DLT) Legs

Two types of CFIs were modeled: Full and Partial. Most four-legged CFIs built in the U.S. have DLT movements on two legs – most commonly along the major street – and conventional left turns on the remaining legs. Such a configuration is termed as a Partial CFI. A Full CFI is the one where all four legs have displaced left-turn movement. A few Full CFIs, like the one in SR 154 and 4100 S, Taylorsville, UT exist in the US as well as in other countries. Heavy left turn volume on all legs may demand the installation of a Full CFI, which would result in a large intersection footprint.

Right Turn Control Types

The control for pedestrians and bicycles crossing the right turn channelized lane is signalized only if the right turning vehicles are controlled by a signal. Otherwise, ped-bikes have the priority to cross a channelized right turn lane and vehicles yield to them. The control for the vehicles at channelized right-turning slip lanes of existing CFIs varies across locations. To further investigate, the research team randomly selected 12 CFIs in six different states in US. The control types for right-turning vehicles are listed for the DLT and conventional legs separately in Table 3-2. In most locations, right-turning vehicles have a channelized exclusive right turn lane with a "Yield to Pedestrian" sign (Figure 3-7 (a)). This control type is termed as "Unsignalized" in this table. The same intersection can have both control types at different legs which are tagged as "Mixed".

(a) (b)

FIGURE 3-7: CONTROL TYPES FOR RIGHT TURNING VEHICLES (a) CHANNELIZED YIELD CONTROL (b) CHANNELIZED SIGNAL CONTROL

TABLE 3-2: RIGHT TURN CONTROL TYPES AT DIFFERENT CFIS

Location	Right turning vehicle control	
	DLT leg	Conventional leg
US 34 & Madison Ave, Loveland, CO	Mixed	Unsignalized
US 550 & US 160, Durango, CO	No right turn	Unsignalized
SR 154 & 13400 S, Riverton, UT	Unsignalized	Mixed
University Pkwy & Sandhill Rd, Orem, UT	Signalized	Unsignalized
SR 154 & SR 171, West Valley City, UT	No slip lane	Unsignalized
SR 154 & 3100 S, West Valley City, UT	No slip lane	Signalized
Redwood Rd & Bennion Blvd, Salt Lake City, UT	No slip lane	Signalized
US 290 & W William Cannon Dr, Austin, TX	No slip lane	Unsignalized
US 290 & TX 71, Austin, TX	No slip lane	Unsignalized
Beechmont Ave & Five Mile Rd, Cincinnati, OH	Signalized	Signalized
US 1 & MD 200, Laurel, MD	Signalized	Unsignalized
William Floyd Pkwy & Dowling College, Shirley, NY	No right turn	Unsignalized

Since both signalized and unsignalized control types are common at right-turn slip lanes, a separate set of scenarios are modeled in VISSIM. Pedestrians and bicycles have the priority to cross the right-turn conflict area in the unsignalized control models. In the signalized models, additional signal heads are added to the signal controller as required.

Further, since pedestrians and bicycles do not always comply with the channelized right-turn signal, a 50 percent compliance rate is assumed based on the outcomes from past studies on pedestrian and bicycle compliance rates (Ren et al., 2011; Hummer et al., 2008). The priority rule in VISSIM enables the modeling of non-complying behavior as pedestrians and bicycles cross the channelized right turn during red only if any vehicle is far enough (14 feet) from the right turn crosswalk.

3.2.5 Traffic Volume

Our target was to simulate a peak-hour condition during which pedestrian and bicycle delay is expected to be very high. On the other hand, an excessively high traffic volume would result in signal failure. Hence, a trial and error process was executed using Cap-X (Lochrane and Bared, 2011) to select a volume for the given lane configuration such that the volume to capacity ratio (v/C) of any intersection remained in the range of 0.50 to 0.75. Based on that design, the directional traffic volumes in Table 3-3 were formulated.

TABLE 3-3: VEHICULAR VOLUME DATA USED IN THE CFI MODELS

CFI Type	Street type	Volume (vph)			Truck (%)
		Left Turn	Thru	Right turn	
Partial	Major	470	1250	200	2%
	Minor	310	880	180	2%
Full	Both	520	1470	250	2%

3.2.6 Signal Timing

All movements in the CFI are controlled using a single semi-actuated controller. For the given volume and lane configuration, the signal timing plan for the CFI intersection was developed by minimizing the cycle length while meeting the required green time so that the volume to capacity ratio (v/c) for any movement does not exceed 0.88. Figure 3-8 shows the ring-barrier diagram of 16 phases, their split times (colored green), and the movements in a Partial CFI with Traditional crossing.

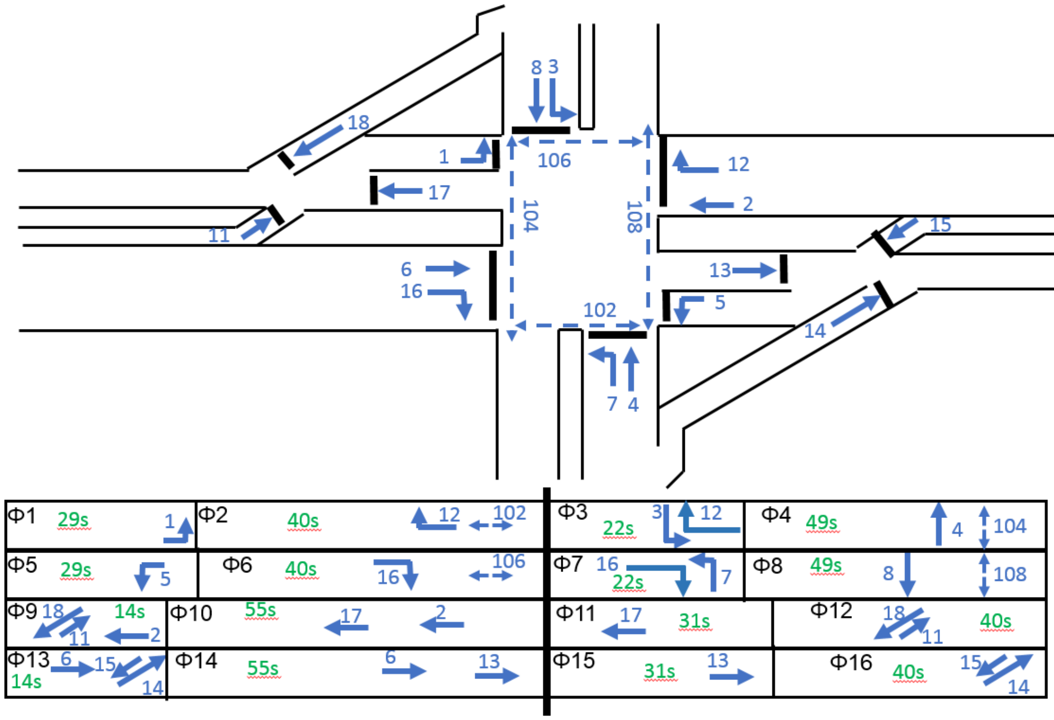


FIGURE 3-8: RING BARRIER DIAGRAM AND MOVEMENTS IN A PARTIAL CFI

It should be noted that in the case of Traditional and Midblock crossing, the full advantage of installing a CFI – namely, two critical movement operation – cannot be achieved as the displaced left-turn movements conflict with the parallel pedestrian-bicycle movements. Therefore, these two crossing types require a longer cycle length than the Offset crossing. For Partial CFI, the cycle lengths obtained for Traditional and Midblock crossing were 140 seconds, while that for Offset crossing was 110 seconds. For Full CFI, the Traditional and Midblock crossing cycle length increased to 170 seconds due to the increased volume and need for protected left turns. The Offset crossing design cycle length increased nominally to 115 seconds for the Full CFI.

The major street thru movements are coordinated in the CFI and adjacent intersections. The signals are operated in a semi-actuated mode with all three intersections having the same cycle length. The left turn movements have a minimum green time of 10 seconds. The selection of minimum green for the non-coordinated thru movements was dictated by the pedestrian crossing time. At the adjacent intersections, minimum green for the minor street thru movements was selected as 20 seconds based on judgment. A six-foot detector was used to detect vehicles with an extension time of two seconds. Given the speeds along the corridor, this was the suggested extension time from the Signal Timing Manual (Koonce and Rodegerdts, 2008) rounded up to the nearest second. However, for the coordinated thru movements at the CFI, the detectors are placed 300 feet upstream of the stop bar to allow vehicles to progress through this intersection. The extension time for these detectors was set at six seconds.

3.3 Equivalent Standard Intersection Modeling

In order to contrast the performance of pedestrian-bicycle mobility between a CFI and a standard intersection, geometries of standard intersections equivalent to both Partial and Full CFI are obtained using Cap-X (Lochrane and Bared, 2011). Keeping the volume similar to that of the Partial and a Full CFI models, different lane configurations of standard intersections were tested to achieve a similar v/C of the main intersection. The standard intersection equivalent to a Partial CFI consists of four thru and two left-turn lanes on the major street, and three thru and two left-turn lanes on the minor street, with one channelized right turn lane on each approach. The intersection v/C for the equivalent standard intersection was 0.65. In the case of Full CFI, the required number of lanes on each approach was found very high to achieve a similar v/C (~0.65) according to Cap-X. To model an intersection with a realistic footprint, a v/C of 0.85 was assumed to be acceptable to practitioners. Thus, the resulting equivalent standard intersection has four thru, two left-turn, and one channelized right turn lane on all approaches. The optimal cycle length for the standard intersection models equivalent to the Partial and Full CFI model generated by PTV VISTRO was 135 and 155 seconds, respectively.

3.4 Comparison of Crossing Alternatives

Three performance measures were selected to monitor the effects of various alternative scenarios on the pedestrian-bicycle crossing facilities: (1) average total delay, (2) average number of stops, and (3) average total travel time. Total travel time and delay are used by the Highway Capacity Manual to calculate the LOS score for pedestrians and bicycles. The number of stops was also considered as an indicator of level of comfort. Post Hoc Tukey test was conducted to estimate the difference in the average performance measures of each pair of CFI models and to determine its statistical significance (Williams, 2010).

To compare the routes of all pedestrians and bicycles among the various alternative scenarios, a set of origins and destinations were established as a standard for all models. Each of the four quadrants near the intersection was split into two origin and destination points as shown in Figure 3-9. The lettered boxes labeled A through D represent the four quadrants and the labels A1, A2, B1, etc. represent the origin and destination points. For consistency across the models, the origin and destination points were located 530 feet from the main intersection.

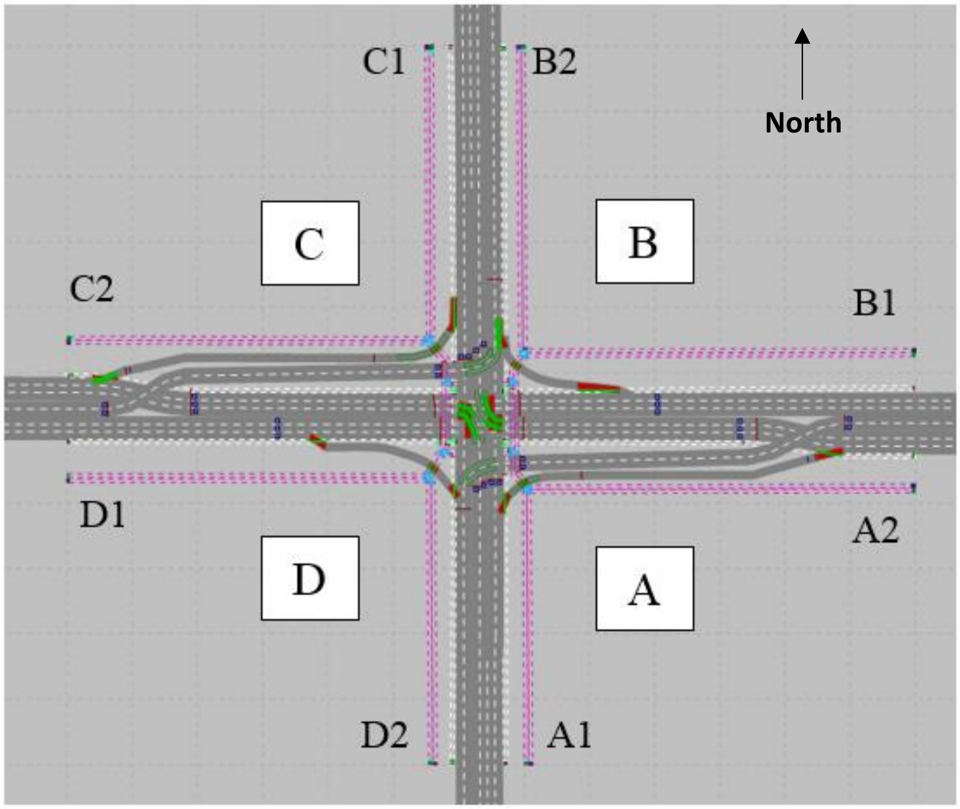


FIGURE 3-9: QUADRANTS AND ORIGIN-DESTINATION POINTS OF PEDESTRIANS AND BICYCLES (SHARED)

For the ease of discussion, pedestrian and bicycle routes are divided into four categories. As apparent from Figure 3-9, Diagonal (e.g., D to B and A to C), major street (e.g., C to D and B to A), minor street (e.g., D to A and C to B), and within the same quadrant are the most intuitive route types used to analyze any four-legged intersections. Here, the diagonal route type is further divided into two categories based on whether, in the Offset crossing, the route crosses the displaced lanes (e.g., A to C) or not (e.g., D to B). These route categories are listed in Table 3-4.

TABLE 3-4: CATEGORY OF PEDESTRIAN AND BICYCLE (SHARED) ROUTES

Route Category	End points of routes
Diagonal w/ DLT	A1 – C2, A2 – C2, A2 – C1
Diagonal w/o DLT	D1 – B2, D1 – B1, D2 – B1, A1 – C1, D2 – B2
Minor St. crossing	D2 – A1, C1 – B2, D1 – A1, D1 – A2, D2 – A2, C1 – B1, B2 – C2, C2 – B1
Major St. crossing	D1 – C2, A2 – B1, D1 – C1, A2 – B2, C2 – D2, B1 – A1, D2 – C1, B2 – A1

4. RESULTS

This chapter presents the results of the simulation runs. First, the route-level variations of the crossing alternatives are discussed. The common trend in terms of stopped delay, travel time, and number of stops across different route types are presented, followed by a discussion on some deviations from these trends. Then, the CFI crossing options and standard intersection crossing are contrasted based on the aggregated measures. The statistical significance of the difference in performance measures of the CFI crossing options is also determined.

4.1 Route Level Comparison of Crossing Alternatives

Figures 4-1 through 4-4 show the average stopped delay, travel time, and number of stops of three crossing alternatives for different user and route types. The error line on each bar represents ±1 standard deviation of the corresponding measure across the 25 simulation runs. The findings are discussed separately for each performance measure in the following subsections. Detailed findings from the route level analysis for all route types and alternative scenarios are provided in Appendix A.

4.1.1 Stopped Delay

Figure 4-1(a) shows the stopped delay for diagonal crossings across DLT legs at a Full CFI with signalized right turns (i.e., from quadrant B to C and vice versa, as labeled in Figure 3-9). Figure 4-1 (b) shows the stopped delay for diagonal crossings not facing any DLT leg at a Full CFI with yield-controlled right turns (i.e., from quadrant D to A and vice versa as labeled in Figure 3-9). Figure 4-1(c) shows the stopped delay for diagonal crossings across DLT legs at a Partial CFI with signalized right turns. Figure 4-1(d) shows the stopped delay for diagonal crossings across DLT legs at a Partial CFI with yield-controlled right turns.

It is apparent from Figure 4-1(a) to 4-1(d) that for pedestrians and bicycles on the shared-use path, Midblock and Offset crossing generated the highest and lowest stopped delay, respectively, in both Partial and Full CFI. In fact, this is the most common trend seen across the route categories. Offset crossings generated the lowest stopped delay for exclusive bicycles as well; however, the Traditional and Midblock crossing generated similar stopped delays for this user type. Further, Figure 4-1(a) and 4-1(b) show that diagonal crossings across DLT legs generated higher delay than diagonal crossings that do not cross any DLT leg due to the additional phases required to cross the DLT legs.

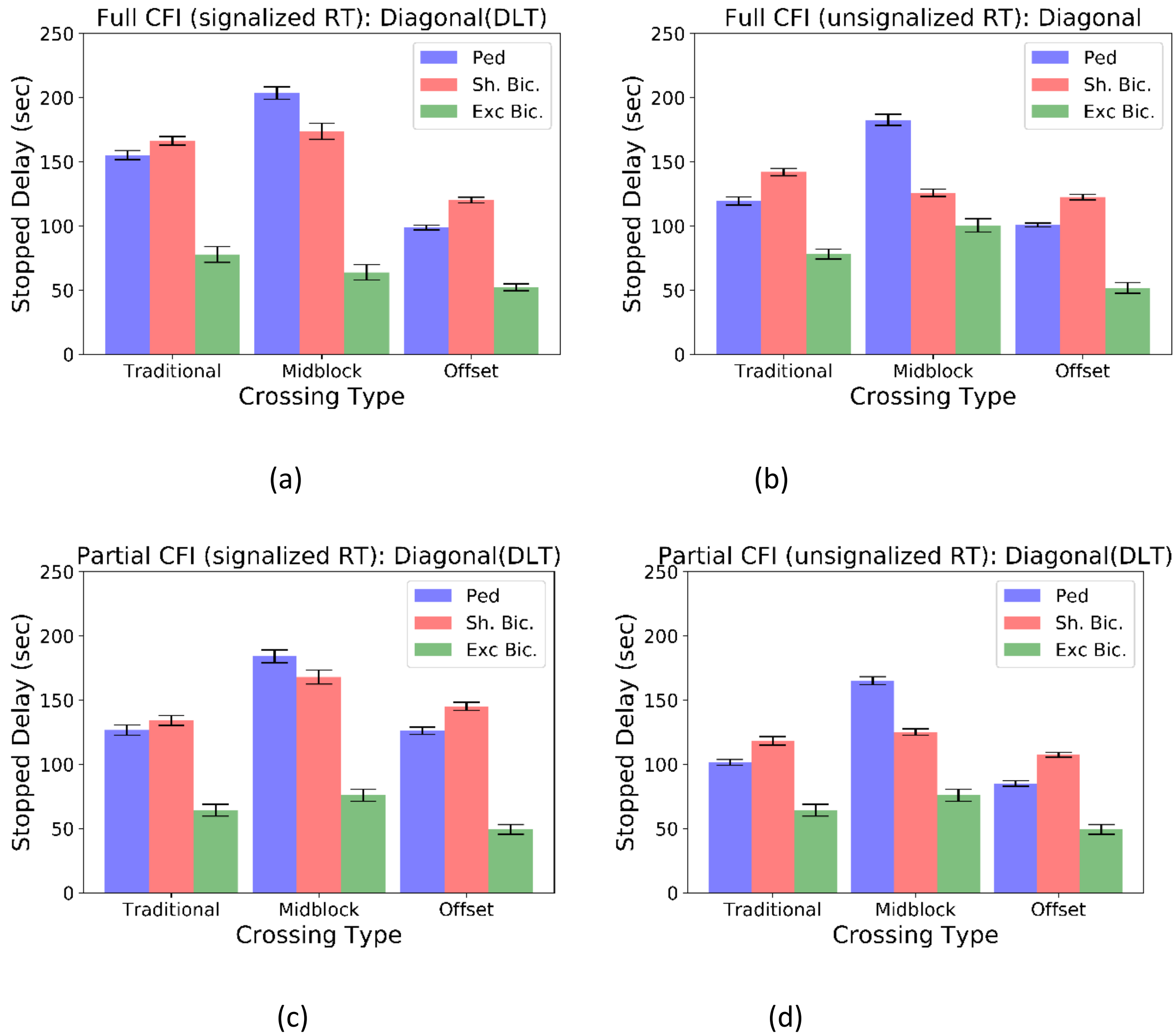


FIGURE 4-1: COMMON TREND OF STOPPED DELAY ACROSS DIFFERENT ROUTE TYPES AND CFI MODELS

The Offset crossing had the lowest stopped delay, which is likely due to its reduced number of phases, causing the intersection to operate at a shorter cycle length than the other two crossing types. The Midblock crossing generated the highest delay for pedestrians mostly because (a) it has four phases with a cycle length significantly higher than the Offset crossing and (b) the major street crossing requires two stages, whereas the Traditional crossing requires only one.

For bicycles on both shared and exclusive paths, the difference in stopped delay between Traditional and Midblock crossings is minimal for the diagonal route. This is because the higher speed of bicycles allows them to cross the multi-staged Midblock crossing in a single stage. The effect of such a progression opportunity is reflected in the number of stops as explained later.

A common trait observed in these figures is that exclusive bicycles experienced a significantly lower stopped delay than bicycles on sidewalks. In the following subsections, we showed that the same trend exists for different routes in terms of travel time and number of stops, with exceptions for a few routes. This is because exclusive bicycles follow vehicular traffic control which has a higher green time and lower clearance time than bicycles on shared-use path. Further, in the Offset and Midblock setup, the number of stages encountered on the exclusive path is lower than that of the shared-use path. It should be noted that exclusive bicycle lanes may create safety concerns unless physically separated from the roadway.

4.1.2 Travel Time

Figure 4-2(a) through 4-2(d) show the average travel time variation for four types of routes and CFI models: diagonal crossing across DLT legs at a Partial CFI with signalized right turns, diagonal crossing across DLT legs at a Full CFI with signalized right turns, major street crossing at a Partial CFI with yield-controlled right turns (i.e., routes between A and B, C and D as labeled in Figure 3-9), and diagonal crossing not facing any leg at a Partial CFI with yield-controlled right turns.

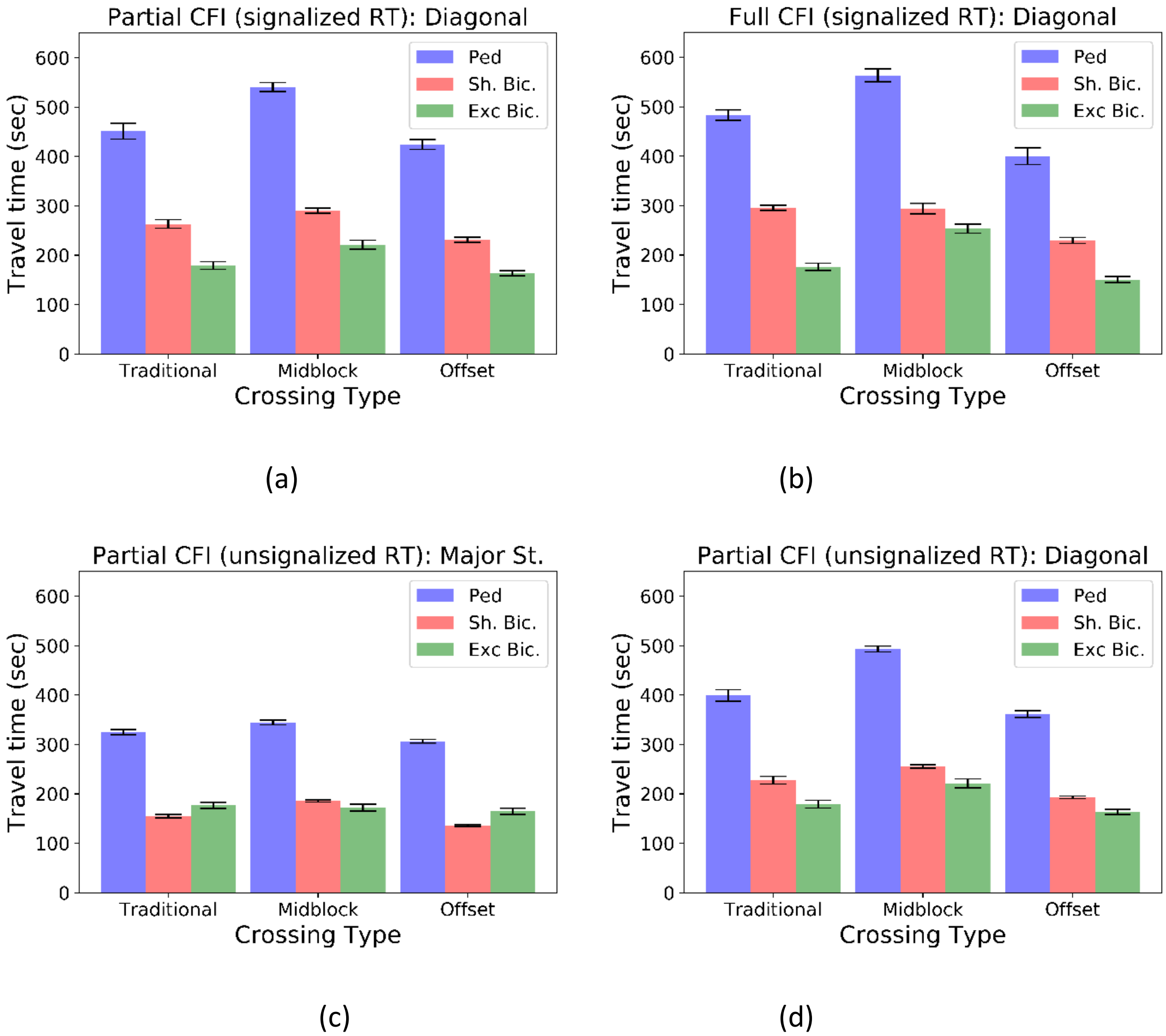


FIGURE 4-2: COMMON TREND OF TRAVEL TIME ACROSS DIFFERENT ROUTE TYPES AND CFI MODELS

It is clear from Figure 4-2(a) through 4-2(d) that the trend of travel time is similar to the stopped delay trend. Intuitively, the trend of travel time should generally follow the stopped delay trend with the exception of specific routes in the Midblock crossing. For instance, the path to travel from D1 to C2 or B1 to A2 is very short for the Midblock crossing as shown in Figure 3-9.

4.1.3 Number of Stops

Figure 4-3(a) to 4-3(d) show the average number of stops for four types of routes and CFI models: diagonal crossing across DLT legs at a Full CFI with yield-controlled right turns, major street crossing at a Full CFI with yield-controlled right turns, diagonal crossing across DLT legs at a Partial CFI with yield-controlled right turns, and major street crossing at a Partial CFI with signalized right turns.

For the scenarios and routes shown in Figure 4-3, both pedestrians and bicycles on the shared path exhibit a similar trend: the Offset crossing has the highest number of stops while the Traditional crossing has the lowest number of stops. This is attributed to the fact that all the crosswalks are multi-staged in the Offset crossing setup. In contrast, all crosswalks in the Traditional setup and minor street crosswalks in the Midblock setup are single-staged. Figure 4-3(a) and 4-3(c) also show that the number of stops does not vary much between Partial and Full CFI across the diagonal route.

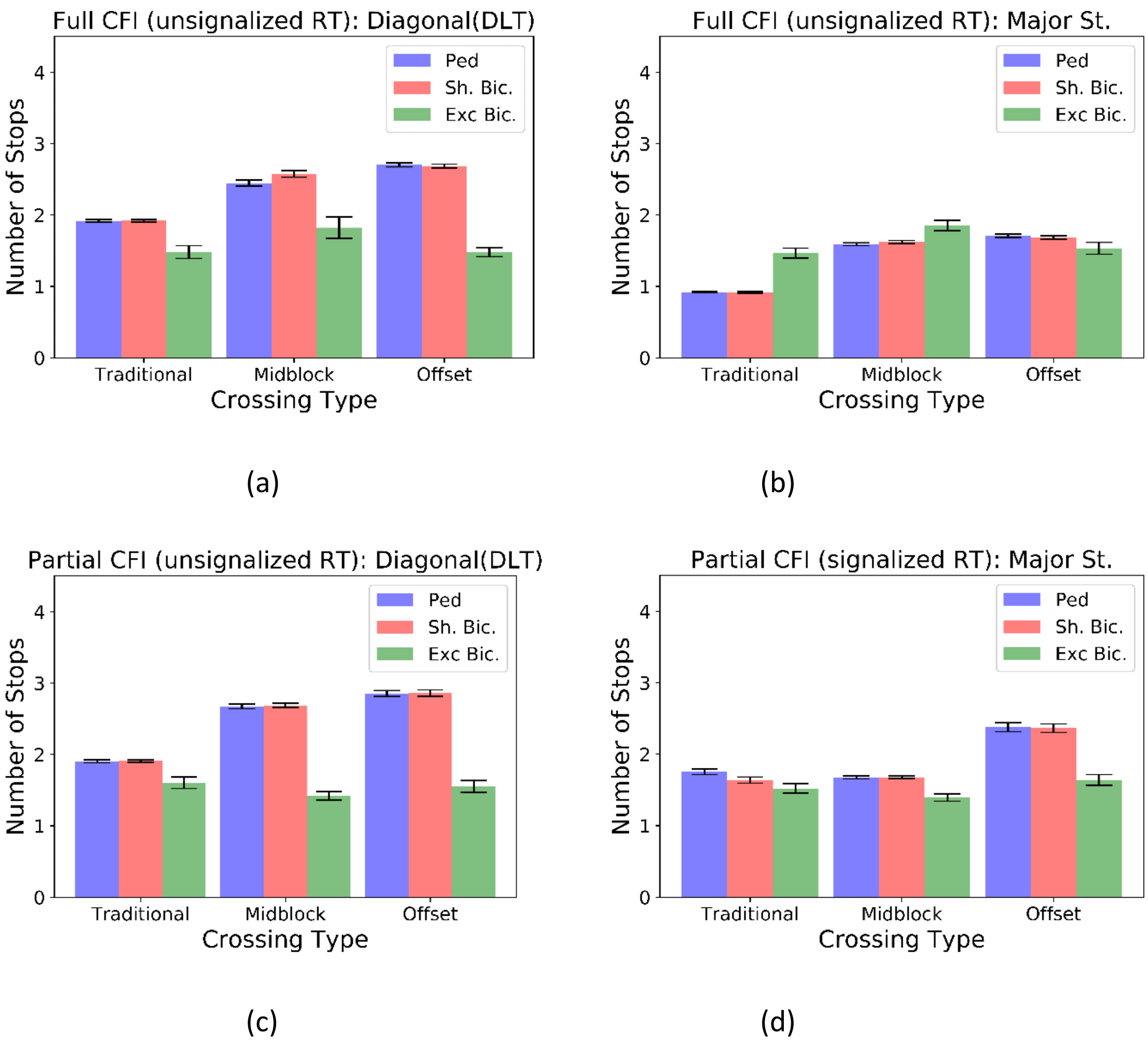


FIGURE 4-3: COMMON TREND OF NUMBER OF STOPS ACROSS DIFFERENT ROUTE TYPES AND CFI MODELS

4.1.4 Deviations from Common Trends

Figure 4-4(a) through 4-4(b) show some deviations from the common trends of stopped delay, travel time, and number of stops shown in Figure 4-1 to Figure 4-3. Figure 4-4(a) shows the variation in travel time for the major street crossing in a Partial CFI. Note that depending on the origin and destination, crossing the major street with the Midblock design may result in either a very direct or indirect path. When taken as a whole, the result is an average travel time that is similar to the Traditional crossing. In practice, a combination of Midblock and Traditional crossing designs may be recommended depending on local origin-destination patterns. Figure 4-4 (b) shows that the stopped delay to cross the minor street is almost similar in Traditional and Midblock crossing for all users since both have the same configuration for this route type. Figure 4-4(c) and 4-4(d) show two deviations from the common trends observed in Figure 4-3(a) through 4-3(d) in terms of the number of stops:

- The number of stops exhibited on the exclusive bicycle path relative to pedestrians and bicycles on the shared-use path is higher in these figures than what was shown in Figure 4-3 (a) through 4-3 (d). This is because this path type is one-way in these two models and has a long travel path for the major street route.
- The Offset crossing has a lower number of stops than the Midblock crossing since most pedestrians and bicycles on the shared-use path can progress through multiple stages in the Offset crossing while using the major street crosswalk.

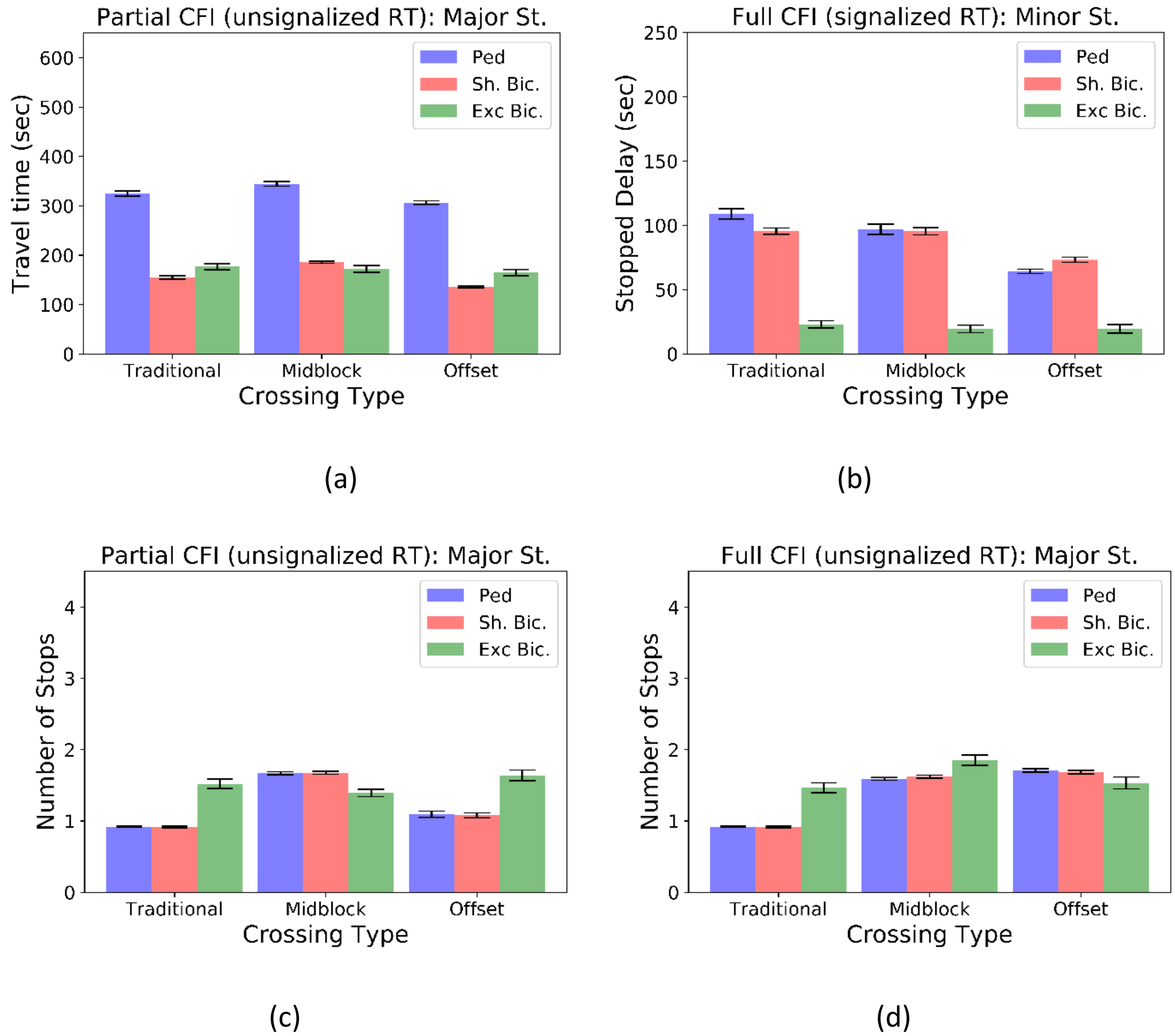


FIGURE 4-4: DEVIATIONS FROM THE COMMON TREND IN TERMS OF (a) TRAVEL TIME (b) STOPPED DELAY AND (c–d) NUMBER OF STOPS

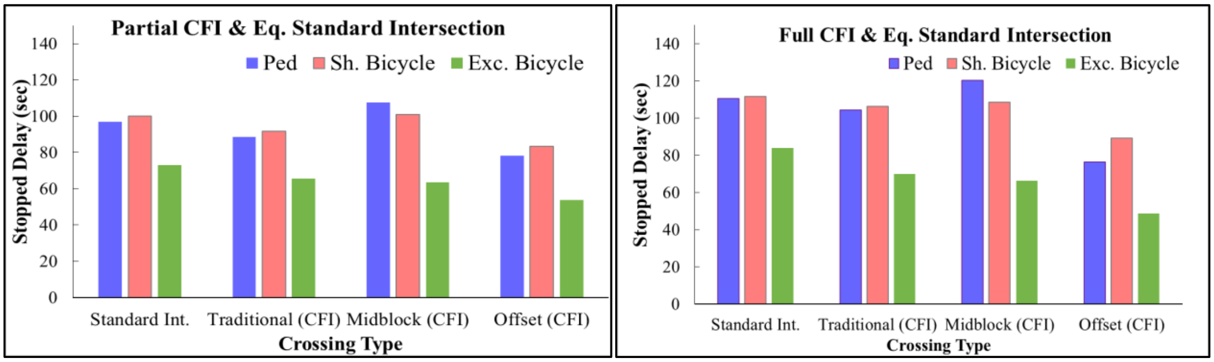
4.2 Aggregated Results

This section presents the comparison of the crossing alternatives based on the aggregated performance measures over all routes and all right turn control types for both continuous flow and equivalent standard intersections. The findings are discussed separately for each performance measure in the following subsections.

4.2.1 Stopped Delay

Figure 4-5 shows the overall average stopped delay for pedestrians and bicyclists for different crossing alternatives in (a) Partial and (b) Full CFI along with their equivalent standard intersection crossing. The standard intersection generated higher stopped delay for pedestrians and bicycles on the shared-use path than CFIs with Traditional and Offset crossing. Post Hoc Tukey test showed that these differences are statistically significant. However, the standard intersection equivalent to both Partial and Full CFI intersections exhibited a magnitude of stopped delay that is similar to the Midblock crossing. The stopped delay experienced by exclusive bicycles was higher in the equivalent standard intersection than in the CFI crossing options. This is attributed to the fact that exclusive bicycles move along with vehicular movements, which tend to have more green time in the CFI models.

The common trends observed in the route-level analysis of the CFI models are also reflected in these aggregated figures. For example, Traditional and Midblock crossing generated the highest stopped delays for all users, while Offset crossing generated the lowest. Bicycles in a Full CFI experienced the highest average delay of 103 seconds per bicycle. Bicycles on the exclusive path experienced the least stopped delay (42 seconds per bicycle) among the three users.



(a) (b)

FIGURE: 4-5 STOPPED DELAY AGGREGATED OVER ALL ROUTES (a) PARTIAL CFI (b) FULL CFI

To compare the performance among the three CFI crossing alternatives, Table 4-1 presents the difference in average, and upper and lower 95th percentile Confidence Intervals (CI) in terms of stopped delay *differences* for each pair of crossing alternatives and for each user type. Post-Hoc Tukey test shows the statistical significance of the pairwise comparison at the level of $p = 0.05$.

Table 4-1 Post Hoc Tukey Test Results on Difference of Stopped Delay between Different Pair of CFI Crossing Alternatives

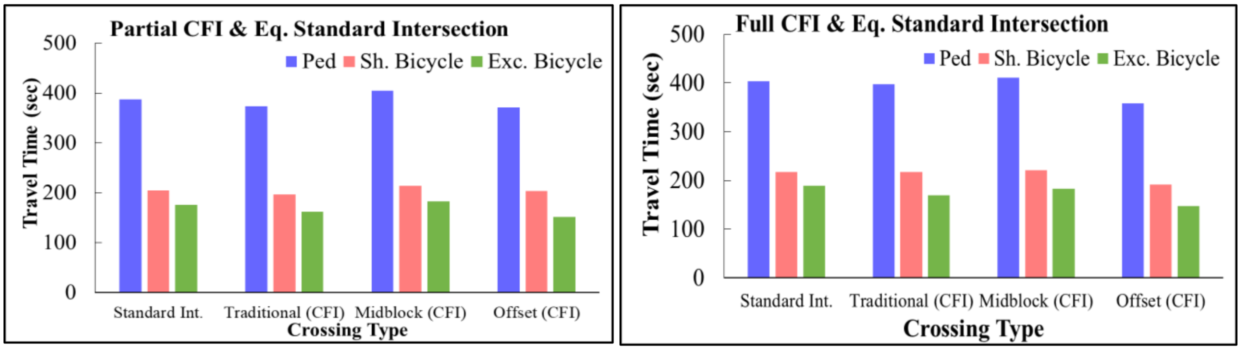
User type	CFI type	Crossing alternatives compared	Mean Difference (sec)	Lower 95th % CI (sec)	Upper 95% CI (sec)
Ped.	**Partial**	Midblock-Traditional	18.9*	16.4	21.4
		Offset-Traditional	-10.3*	-12.8	-7.8
		Offset-Midblock	**-29.2***	-31.7	-26.7
	Full	Midblock-Traditional	15.9*	13.3	18.5
		Offset-Traditional	-28.0*	-30.7	-25.4
		Offset-Midblock	**-44.0***	-46.6	-41.3
Bic.	**Partial**	Midblock-Traditional	9.16*	6.81	11.51
		Offset-Traditional	-8.32*	-10.67	-5.97
		Offset-Midblock	**-17.48***	-19.83	-15.13
	Full	Midblock-Traditional	2.12	-0.17	4.41
		Offset-Traditional	-17.07*	-19.36	-14.78
		Offset-Midblock	**-19.19***	-21.48	-16.90
Exc. Bicycle	**Partial**	Midblock-Traditional	-1.96	-8.72	4.80
		Offset-Traditional	**-11.72***	-18.48	-4.96
		Offset-Midblock	-9.75*	-16.51	-3.00
	Full	Midblock-Traditional	-3.58	-11.10	3.95
		Offset-Traditional	**-21.31***	-28.83	-13.79
		Offset-Midblock	-17.73*	-25.26	-10.21

** Indicates that the difference is statistically significant at a level of 0.05. The bold numbers show the highest difference in each cohort of CFI and user type.*

The contrast between Midblock and Offset crossing for pedestrians in a Full CFI is the most prominent in Table 4-1 as the former crossing type generated on an average 44 seconds higher stopped delay than the later. This is primarily attributed to the reduced number of phases in the Offset and the excess signals in the Midblock crossing. For exclusive bicycles, the difference in stopped delay between Traditional and Midblock crossing is not statistically significant. This is due to exclusive bicycles being controlled by the vehicular signal, which has very similar setting in these two setups.

4.2.2 Travel Time

Figure 4-6 shows the overall average travel time for pedestrians and bicycles for different crossing alternatives in (a) Partial and (b) Full CFI along with their equivalent standard intersection crossing. When comparing to the standard intersection, the difference in travel time is similar to what was seen in terms of stopped delay. However, these differences are much less pronounced than the stopped delay plots shown in Figure 4-5. Regarding the performance of the standard intersection, a similar magnitude of the difference is observed here as seen in the stopped delay analysis. Overall, the general trend of travel time across the three CFI crossing options follows the same trend as of the stopped delay. The difference between pedestrian and bicycle speed is obvious and reflected in these figures.



(a) (b)

FIGURE 4-6 TRAVEL TIME AGGREGATED OVER ALL ROUTES (a) PARTIAL CFI (b) FULL CFI

Table 4-2 presents the difference in average, and upper and lower CI in terms of travel time for each pair of CFI crossing alternative and for each user type.

TABLE 4-2 POST HOC TUKEY TEST RESULTS ON DIFFERENCE OF TRAVEL TIME BETWEEN DIFFERENT PAIR OF CFI CROSSING ALTERNATIVES

User type	CFI type	Crossing alternatives compared	Mean Difference (sec)	Lower 95th % CI (sec)	Upper 95th % CI (sec)
Ped.	Partial	Midblock-Traditional	31.2*	25.5	36.9
		Offset-Traditional	-2.8	-8.5	2.9
		Offset -Midblock	**-34.0***	-39.7	-28.3
	Full	Midblock-Traditional	14.3*	8.8	19.8
		Offset -Traditional	-38.7*	-44.2	-33.1
		Offset -Midblock	**-53.0***	-58.5	-47.4
Bic.	Partial	Midblock-Traditional	10.7*	6.9	14.5
		Offset -Traditional	-6.5*	-10.3	-2.6
		Offset -Midblock	**-17.1***	-21.0	-13.3
	Full	Midblock-Traditional	3.5*	0.0	7.0
		Offset -Traditional	-25.2*	-28.7	-21.7
		Offset -Midblock	**-28.7***	-32.2	-25.2
Exc. Bicycle	Partial	Midblock-Traditional	33.0*	24.9	41.1
		Offset-Traditional	-18.9*	-27.1	-10.7
		Offset-Midblock	**-51.9***	-60.1	-43.7
	Full	Midblock-Traditional	22.5*	14.8	30.1
		Offset-Traditional	-23.4*	-31.0	-15.7
		Offset-Midblock	**-45.8***	-53.5	-38.2

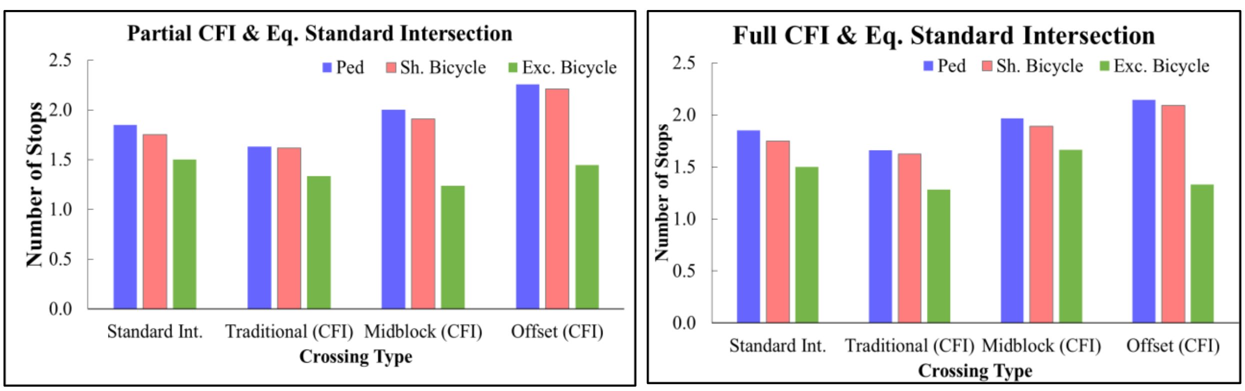
** Indicates that the difference is statistically significant at a level of 0.05. The bold numbers show the highest difference in each cohort of CFI and user type.*

Table 4-2 shows that with one exception, all the differences observed in Figure 4-2 are statistically significant. The most notable differences observed are between the Offset and Midblock crossing, since the former has fewer phases than the latter. Note that the differences are higher in the Full CFI than in the Partial CFI for both pedestrians and bicycles on the shared-use path because the Offset crossing can handle additional displaced left turns without needing to add exclusive left-turn phases.

4.2.3 Number of Stops

As shown in the route-level analysis, the number of stops per user has an entirely different trend than the other two performance measures. Figure 4-7 shows the variation in the number of stops across different scenarios. An interesting observation from Figure 4-7 is that the equivalent standard intersection generated a number of stops that is higher than the CFI with Traditional crossing, but lower than the ones with Offset and Midblock crossing. In fact, the Post-Hoc Tukey test revealed that these differences are statistically significant. The average number of stops generated by the standard intersection was as much as 0.45 stops per pedestrian less than Offset crossing.

The aggregated trend across the three CFI crossing alternatives is similar to what was observed for individual route types – Offset crossing having the highest while Traditional crossing the lowest average number of stops for pedestrians and bicycles on the shared path for both Partial and Full CFI. Midblock crossing generated the highest number of stops with 1.43 stops on average for bicycles on the exclusive path in a Full CFI.



(a) (b)

FIGURE 4-7 NUMBER OF STOPS AGGREGATED OVER ALL ROUTES (a) PARTIAL CFI (b) FULL CFI

Table 4-3 shows the average with the upper and lower CI differences in the number of stops for each pair of CFI crossing alternative and for each user type with the significance test result obtained from the Post Hoc Tukey Test.

TABLE 4-3 POST HOC TUKEY TEST RESULTS ON DIFFERENCE IN NUMBER OF STOPS BETWEEN DIFFERENT PAIR OF CFI CROSSING ALTERNATIVES

User type	CFI Type	Crossing alternatives compared	Mean Difference (sec)	Lower CI (stops/user)	Upper CI (stops/user)
Ped.	Partial	Midblock-Traditional	0.37*	0.32	0.43
		Offset -Traditional	**0.62***	0.57	0.68
		Offset -Midblock	0.25*	0.20	0.31
	Full	Midblock-Traditional	0.31*	0.26	0.35
		Offset -Traditional	**0.49***	0.44	0.53
		Offset -Midblock	0.18*	0.13	0.23
Bic.	Partial	Midblock-Traditional	0.29*	0.24	0.34
		Offset -Traditional	**0.59***	0.54	0.65
		Offset -Midblock	0.30*	0.25	0.35
	Full	Midblock-Traditional	0.27*	0.22	0.31
		Offset -Traditional	**0.47***	0.42	0.51
		Offset -Midblock	0.20*	0.16	0.24
Exc. Bicycle	Partial	Midblock-Traditional	-0.10	-0.23	0.03
		Offset-Traditional	0.11	-0.02	0.24
		Offset-Midblock	**0.21***	0.08	0.34
	Full	Midblock-Traditional	**0.38***	0.24	0.52
		Offset-Traditional	0.05	-0.09	0.19
		Offset-Midblock	-0.33*	-0.47	-0.19

** Indicates that the difference is statistically significant at a level of 0.05. The bold numbers show the highest difference in each cohort of CFI and user type.*

Table 4-3 shows that the difference in the number of stops is most noticeable between the Offset and Traditional crossing for both pedestrians and bicycles on the shared path. The difference peaks at 0.62 stops per pedestrian in a Partial

CFI. Other contrasts which appeared in Figure 4-3 are also statistically significant for these two user types. Note that for bicycles on the exclusive path, the number of stops across different crossing alternatives is generally not statistically significant.

One anomaly in Table 4-3 is that the Exclusive bicycles have a higher number of stops in the Midblock crossing than in the Offset crossing for Full CFI. This is due to additional stages exclusive bicycles face in a Full CFI Midblock crossing that are not experienced in a Full CFI Offset or Traditional crossing.

4.3 Summary

The analysis results provided a detailed assessment of the performances of different CFI crossing alternatives along with the standard intersection crossing. These results indicate (a) a Traditional crossing would generate the least number of stops for pedestrians and bicyclists; (b) Midblock crossing would incur very short travel times only along some routes that start and end near the midblock locations, and (c) an Offset crossing would perform best in terms of stopped delay. The most notable differences observed are between the stopped delays in Offset and Midblock crossing. If adequate space is available, an exclusive bicycle path is operationally preferable to the shared-use path in most cases.

Regarding the tradeoffs between a standard intersection and a CFI, a CFI with Traditional or Offset crossing would incur less stopped delay because of the reduced number of phases. However, a CFI with an Offset or a Midblock crosswalk would generate a higher number of stops than a standard intersection because of the increased number of stages.

5. CONCLUSIONS

The primary objectives of this research were to evaluate pedestrian and bicycle crossing alternatives at Continuous Flow Intersections (CFIs) and to compare the CFI crossing options with equivalent standard intersection crossings. VISSIM microsimulation tool was used to develop the models. Pedestrians and bicycles in VISSIM were modeled as vehicles to allow interaction with vehicular traffic. Three types of CFI crossing alternatives – Traditional, Offset, and Midblock crossing – were tested in this study. In total, 24 alternative scenarios were generated by varying the CFI type, right-turn control type, and the bicycle path type. Two types of CFIs, one with two DLT legs on the major street approaches called Partial CFI, and another with DLT legs on all approaches called Full CFI were modeled. Models with signalized and yield-controlled right turn were considered since both control types are common at CFIs. Two types of bicycle paths – shared-use and exclusive – were modeled in this study.

Traffic volumes were obtained from the capacity analysis tool Cap-X to ensure a v/C of about 0.6-0.7 at the main intersection. A signal timing plan for each model was developed by minimizing the cycle length while meeting the required green time so that the volume to capacity ratio (v/c) for any movement did not exceed 0.88. In addition, the performances of the CFI crossing options were contrasted against that of an equivalent standard intersection crossing. All these crossing alternatives were compared in terms of stopped delay, travel time, and number of stops.

Rest of this chapter presents the summary of the results and recommendations for future research.

5.1 Summary of the Simulation results

The route-level and aggregated results from the simulation runs are listed below

- For most route types, Midblock crossing generated the highest stopped delay, while the Offset crossing the lowest among the three crossing alternatives. Travel time showed the same trend as the stopped delay for most route types. Deviations from the common trend were observed for some scenarios. For instance, Traditional crossing exhibited the highest stopped delay on the minor street crossing at a Full CFI with signalized right-turn.
- Offset crossing generated the highest number of stops compared to the other two crossing types primarily due to the increased number of stages. Traditional crossing exhibited the least number of stops due to its straightforward configuration. A few eccentric trends were observed in the case of number of stops as well. For instance, Midblock crossing had the highest number of stops for the major street crossing at a Full CFI with yield-controlled right turn.

- Overall, exclusive bicycles generated significantly lower stopped delay, travel time, and number of stops than bicycles on the shared-use path. However, it experienced higher performance measures for some route types (e.g., major street crossing) because exclusive lanes are one-way, resulting in out of direction travel, whereas shared-use paths allowed for more direct two-directional travel.
- Post-Hoc Tukey test revealed that the difference in stopped delay incurred by Midblock and Offset crossing was prominent and statistically significant. The differences in stopped delay incurred by exclusive bicycles in Traditional and Midblock crossing were not statistically significant. Additionally, the difference in number of stops experienced by exclusive bicycles in a Traditional and Offset crossing was not statistically significant. All other differences in measures between pair of crossing alternatives were statistically significant.
- When comparing an equivalent standard intersection crossing with a CFI crossing, a CFI with Traditional or Offset crossing incurred less stopped delay and travel time because of the reduced number of phases. However, a CFI with an Offset or a Midblock crosswalk generated a higher number of stops than a standard intersection because of the increased number of stages.

5.2 Recommendations

Although the study was conducted with careful consideration of all factors related to the goals and tasks, several critical issues deserve further attention. Following are the limitations of this study to be addressed in any future study related to this topic.

- It was evident from the simulation runs that the Midblock crossing generated the highest performance measures among all crossing alternatives, although it generated a very short travel time for some routes. Traditional crossing, while exhibiting a significantly high stopped delay and travel time, generated the least number of stops. Therefore, it is expected that having both Midblock and Traditional crossing in a CFI would result in a minimal number of stops and reasonable stopped delay and travel time. It is recommended to test this option in a future study.
- While this study focused on the effects of crossing alternatives on pedestrian-bicycles, it is also imperative to consider the impact on vehicular traffic.
- While considering the benefit and cost of installing a pedestrian-bicycle crossing at a CFI, grade-separated crossing options should be considered if the pedestrian-bicycle volume is significant and likely to use the crossing. Topography of the intersection may play a role in pedestrian and bicycle use of the grade-separated crossing.

- Additional operational analyses should consider methods to provide simultaneous progression for bicycles, pedestrians, and vehicles between Midblock crossings and those at the main intersection
- An exploration of how performance measures for any one specific crossing type vary with cycle length could provide more signal timing guidance to practitioners.
- Local preference and dominant user type will likely dictate which performance measures are of most importance for any specific project. Additional operational analyses should consider methods to provide simultaneous progression for bicycles, pedestrians, and vehicles between Midblock crossings and those at the main intersection. Additionally, an exploration of how performance measures for any one specific crossing type varies with cycle length could provide more signal timing guidance to practitioners.

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7 APPENDICES

7.1 APPENDIX A – Performance Measures by Route Type and Alternative Scenarios

This appendix shows the aggregated results by route type from each alternative scenario model. Table A.1 through Table A.3 show the stopped delay, travel time, and number of stops results for the CFI models. Table A.4 through Table A.6 show the stopped delay, travel time, and number of stops results for the equivalent standard intersection models.

Table A.1: Stopped Delay Results for CFI models

Route Type	Scenarios (CFI type -RT control-Crossing type)	Pedestrian stopped delay (s)		Shared-use Bicycle stopped delay (s)		Exclusive Bicycle stopped delay (s)	
		Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Diagonal	Full-sgnlzd-traditional	151.6	4.0	164.6	3.2	78.2	3.8
	Full-sgnlzd-midblock	205.8	4.0	150.1	5.5	100.5	5.3
	Full-sgnlzd-offset	100.0	1.9	121.4	3.0	51.7	4.2
	Full-unsgnlzd-traditional	119.4	3.2	142.0	2.8	78.2	3.8
	Full-unsgnlzd-midblock	182.7	4.3	125.9	2.9	100.5	5.3
	Full-unsgnlzd-offset	100.8	1.5	122.6	2.1	51.7	4.2
	Partial-sgnlzd-traditional	134.2	4.3	140.3	2.6	87.1	4.9
	Partial-sgnlzd-midblock	177.2	5.4	149.4	5.8	68.2	5.4
	Partial-sgnlzd-offset	107.4	3.4	100.1	2.5	67.0	4.9
	Partial-unsgnlzd-traditional	106.5	2.6	120.9	2.1	87.1	4.9
	Partial-unsgnlzd-midblock	152.5	5.2	130.6	5.7	68.2	5.4
	Partial-unsgnlzd-offset	76.3	2.1	88.4	1.7	67.0	4.9
Diagonal with DLT	Full-sgnlzd-traditional	155.3	3.5	166.4	3.4	77.9	6.1
	Full-sgnlzd-midblock	203.5	4.8	173.8	6.3	63.9	6.0
	Full-sgnlzd-offset	98.9	1.8	120.3	2.2	52.2	2.7
	Full-unsgnlzd-traditional	120.2	2.9	140.7	2.6	77.9	6.1
	Full-unsgnlzd-midblock	169.1	4.6	136.7	4.6	63.9	6.0
	Full-unsgnlzd-offset	99.1	2.2	121.2	2.2	52.2	2.7
	Partial-sgnlzd-traditional	126.7	4.1	134.2	3.9	64.4	4.6
	Partial-sgnlzd-midblock	184.2	4.9	168.0	5.5	76.0	4.7
	Partial-sgnlzd-offset	126.2	2.8	145.2	3.2	49.3	3.8
	Partial-unsgnlzd-traditional	101.5	2.3	118.3	3.2	64.4	4.6
	Partial-unsgnlzd-midblock	165.1	3.1	125.2	2.6	76.0	4.7
	Partial-unsgnlzd-offset	85.1	2.2	107.4	1.9	49.3	3.8

Table A.1: Stopped Delay Results for CFI models (Contd.)

Route Type	Scenarios (CFI type -RT control-Crossing type)	Pedestrian stopped delay (s)		Shared-use Bicycle stopped delay (s)		Exclusive Bicycle stopped delay (s)	
		Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Major St. Crossing	Full-sgnlzd-traditional	102.0	3.3	94.6	2.5	85.4	5.0
	Full-sgnlzd-midblock	87.9	2.0	96.6	2.4	74.1	4.1
	Full-sgnlzd-offset	65.2	2.0	73.0	1.8	60.0	4.5
	Full-unsgnlzd-traditional	70.6	2.0	69.9	1.4	85.4	5.0
	Full-unsgnlzd-midblock	86.9	2.3	96.8	2.1	74.1	4.1
	Full-unsgnlzd-offset	65.3	1.9	72.8	1.9	60.0	4.5
	Partial-sgnlzd-traditional	89.6	2.7	88.9	3.0	78.1	4.4
	Partial-sgnlzd-midblock	81.6	2.3	89.9	2.1	76.6	3.9
	Partial-sgnlzd-offset	66.1	1.9	77.5	2.0	64.1	3.9
	Partial-unsgnlzd-traditional	60.5	1.3	59.6	1.7	78.1	4.4
	Partial-unsgnlzd-midblock	81.6	1.8	90.5	1.8	76.6	3.9
	Partial-unsgnlzd-offset	41.4	1.3	39.5	0.9	64.1	3.9
Minor St. Crossing	Full-sgnlzd-traditional	108.9	4.0	95.6	2.5	22.9	2.8
	Full-sgnlzd-midblock	97.0	4.0	95.3	2.8	19.5	2.9
	Full-sgnlzd-offset	64.3	1.7	73.3	2.1	19.5	3.3
	Full-unsgnlzd-traditional	72.1	2.2	70.8	1.8	22.9	2.8
	Full-unsgnlzd-midblock	70.0	2.1	68.6	1.7	19.5	2.9
	Full-unsgnlzd-offset	64.1	1.6	73.7	1.7	19.5	3.3
	Partial-sgnlzd-traditional	86.5	3.1	86.2	2.7	19.7	3.3
	Partial-sgnlzd-midblock	82.6	3.1	80.0	2.2	20.2	3.4
	Partial-sgnlzd-offset	106.3	4.1	96.2	1.9	24.3	3.8
	Partial-unsgnlzd-traditional	59.8	1.3	59.2	1.6	19.7	3.3
	Partial-unsgnlzd-midblock	58.9	1.3	58.5	1.6	20.2	3.4
	Partial-unsgnlzd-offset	57.9	1.3	67.1	1.6	24.3	3.8

Table A.2 Travel Time Results for CFI models

Route Type	Scenarios (CFI type -RT control-Crossing type)	Pedestrian number of stops		Shared-use Bicycle number of stops		Exclusive Bicycle number of stops	
		Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Diagonal	Full-sgnlzd-traditional	483	11	296	5	176	4
	Full-sgnlzd-midblock	564	13	294	11	253	8
	Full-sgnlzd-offset	400	17	230	6	150	3
	Full-unsgnlzd-traditional	399	5	228	4	176	4
	Full-unsgnlzd-midblock	493	10	256	8	253	8
	Full-unsgnlzd-offset	362	4	193	3	150	3
	Partial-sgnlzd-traditional	541	16	290	9	180	8
	Partial-sgnlzd-midblock	451	9	263	5	221	4
	Partial-sgnlzd-offset	425	10	231	5	163	3
	Partial-unsgnlzd-traditional	521	12	250	8	180	8
	Partial-unsgnlzd-midblock	422	6	250	4	221	4
	Partial-unsgnlzd-offset	398	7	232	3	163	3
Diagonal with DLT	Full-sgnlzd-traditional	489	10	297	5	181	3
	Full-sgnlzd-midblock	563	15	338	9	216	5
	Full-sgnlzd-offset	395	14	232	5	153	3
	Full-unsgnlzd-traditional	392	5	224	3	181	3
	Full-unsgnlzd-midblock	526	14	256	5	216	5
	Full-unsgnlzd-offset	383	5	216	3	153	3
	Partial-sgnlzd-traditional	564	14	348	7	165	6
	Partial-sgnlzd-midblock	448	9	266	6	234	4
	Partial-sgnlzd-offset	465	9	320	4	150	3
	Partial-unsgnlzd-traditional	512	13	262	6	165	6
	Partial-unsgnlzd-midblock	423	5	250	4	234	4
	Partial-unsgnlzd-offset	396	5	229	3	150	3

Table A.2: Travel Time Results for CFI models (Contd.)

Route Type	Scenarios (CFI type -RT control-Crossing type)	Pedestrian stopped delay (s)		Shared-use Bicycle stopped delay (s)		Exclusive Bicycle stopped delay (s)	
		Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Major St. Crossing	Full-sgnlzd-traditional	397	6	210	4	185	2
	Full-sgnlzd-midblock	343	10	189	6	167	3
	Full-sgnlzd-offset	341	10	171	4	161	2
	Full-unsgnlzd-traditional	325	5	155	2	185	2
	Full-unsgnlzd-midblock	345	4	186	3	167	3
	Full-unsgnlzd-offset	307	3	136	2	161	2
	Partial-sgnlzd-traditional	348	10	186	6	177	3
	Partial-sgnlzd-midblock	388	5	197	4	172	2
	Partial-sgnlzd-offset	359	5	212	2	165	2
	Partial-unsgnlzd-traditional	347	5	192	3	177	3
	Partial-unsgnlzd-midblock	337	5	166	2	172	2
	Partial-unsgnlzd-offset	338	4	173	2	165	2
Minor St. Crossing	Full-sgnlzd-traditional	402	8	212	4	119	3
	Full-sgnlzd-midblock	370	8	207	4	115	2
	Full-sgnlzd-offset	339	11	172	5	114	2
	Full-unsgnlzd-traditional	318	5	152	3	119	3
	Full-unsgnlzd-midblock	316	4	151	2	115	2
	Full-unsgnlzd-offset	325	4	164	2	114	2
	Partial-sgnlzd-traditional	359	6	188	5	111	2
	Partial-sgnlzd-midblock	368	6	189	5	113	2
	Partial-sgnlzd-offset	420	5	231	4	116	2
	Partial-unsgnlzd-traditional	329	4	163	2	111	2
	Partial-unsgnlzd-midblock	337	3	167	2	113	2
	Partial-unsgnlzd-offset	338	3	173	2	116	2

Table A.3: Number of Stops Results for CFI models

Route Type	Scenarios (CFI type -RT control-Crossing type)	Pedestrian number of stops		Shared-use Bicycle number of stops		Exclusive Bicycle number of stops	
		Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Diagonal without DLT	Full-sgnlzd-traditional	2.72	0.04	2.68	0.05	1.47	0.07
	Full-sgnlzd-midblock	3.40	0.04	3.03	0.07	2.30	0.10
	Full-sgnlzd-offset	2.90	0.03	2.80	0.05	1.48	0.08
	Full-unsgnlzd-traditional	1.92	0.02	1.92	0.01	1.47	0.07
	Full-unsgnlzd-midblock	2.68	0.03	2.29	0.03	2.30	0.10
	Full-unsgnlzd-offset	2.72	0.03	2.70	0.02	1.48	0.08
	Partial-sgnlzd-traditional	2.59	0.05	2.66	0.04	1.47	0.07
	Partial-sgnlzd-midblock	3.42	0.06	2.88	0.05	1.42	0.09
	Partial-sgnlzd-offset	2.70	0.05	2.50	0.04	1.68	0.08
	Partial-unsgnlzd-traditional	1.92	0.02	1.92	0.01	1.47	0.07
	Partial-unsgnlzd-midblock	2.73	0.05	2.26	0.04	1.42	0.09
	Partial-unsgnlzd-offset	1.90	0.02	1.89	0.02	1.68	0.08
Diagonal with DLT	Full-sgnlzd-traditional	2.71	0.05	2.65	0.03	1.48	0.09
	Full-sgnlzd-midblock	3.44	0.06	3.13	0.05	1.82	0.15
	Full-sgnlzd-offset	2.91	0.03	2.81	0.05	1.48	0.06
	Full-unsgnlzd-traditional	1.92	0.02	1.92	0.02	1.48	0.09
	Full-unsgnlzd-midblock	2.45	0.04	2.58	0.05	1.82	0.15
	Full-unsgnlzd-offset	2.70	0.03	2.69	0.03	1.48	0.06
	Partial-sgnlzd-traditional	2.76	0.05	2.62	0.05	1.61	0.08
	Partial-sgnlzd-midblock	3.50	0.07	3.32	0.06	1.42	0.06
	Partial-sgnlzd-offset	4.22	0.11	4.24	0.07	1.55	0.08
	Partial-unsgnlzd-traditional	1.90	0.02	1.91	0.02	1.61	0.08
	Partial-unsgnlzd-midblock	2.68	0.03	2.69	0.03	1.42	0.06
	Partial-unsgnlzd-offset	2.85	0.04	2.86	0.05	1.55	0.08

Table A.3: Number of Stops Results for CFI models (Contd.)

Route Type	Scenarios (CFI type -RT control-Crossing type)	Pedestrian stopped delay (s)		Shared-use Bicycle stopped delay (s)		Exclusive Bicycle stopped delay (s)	
		Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Major St. Crossing	Full-sgnlzd-traditional	1.71	0.03	1.65	0.04	1.47	0.07
	Full-sgnlzd-midblock	1.60	0.02	1.62	0.02	1.85	0.07
	Full-sgnlzd-offset	1.93	0.03	1.83	0.03	1.53	0.08
	Full-unsgnlzd-traditional	0.92	0.01	0.91	0.01	1.47	0.07
	Full-unsgnlzd-midblock	1.59	0.02	1.62	0.02	1.85	0.07
	Full-unsgnlzd-offset	1.71	0.02	1.68	0.03	1.53	0.08
	Partial-sgnlzd-traditional	1.75	0.04	1.64	0.04	1.52	0.07
	Partial-sgnlzd-midblock	1.68	0.02	1.68	0.02	1.39	0.05
	Partial-sgnlzd-offset	2.38	0.06	2.37	0.06	1.64	0.08
	Partial-unsgnlzd-traditional	0.92	0.01	0.92	0.01	1.52	0.07
	Partial-unsgnlzd-midblock	1.67	0.02	1.68	0.02	1.39	0.05
	Partial-unsgnlzd-offset	1.09	0.04	1.08	0.03	1.64	0.08
Minor St. Crossing	Full-sgnlzd-traditional	1.76	0.04	1.68	0.03	0.53	0.06
	Full-sgnlzd-midblock	1.71	0.04	1.68	0.03	0.49	0.06
	Full-sgnlzd-offset	1.91	0.03	1.83	0.04	0.63	0.10
	Full-unsgnlzd-traditional	0.93	0.01	0.92	0.01	0.53	0.06
	Full-unsgnlzd-midblock	0.91	0.02	0.91	0.02	0.49	0.06
	Full-unsgnlzd-offset	1.70	0.02	1.70	0.02	0.63	0.10
	Partial-sgnlzd-traditional	1.62	0.04	1.67	0.03	0.56	0.08
	Partial-sgnlzd-midblock	1.60	0.03	1.61	0.03	0.56	0.08
	Partial-sgnlzd-offset	2.57	0.05	2.39	0.03	0.72	0.07
	Partial-unsgnlzd-traditional	0.91	0.01	0.91	0.01	0.56	0.08
	Partial-unsgnlzd-midblock	0.90	0.01	0.91	0.01	0.56	0.08
	Partial-unsgnlzd-offset	1.65	0.02	1.68	0.02	0.72	0.07

Table A.4: Stopped Delay Results for Equivalent Standard Intersection models

Route Type	Standard Intersection Model (Equivalent CFI type -RT control)	Pedestrian stopped delay (s)		Shared-use Bicycle stopped delay (s)		Exclusive Bicycle stopped delay (s)	
		Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Diagonal without DLT	Full-sgnlzd	166.1	7.5	174.8	5.2	92.2	6.2
	Full-unsgnlzd	111.7	3.8	131.9	2.6	92.4	6.1
	Partial-sgnlzd	140.4	5.9	156.9	6.1	79.5	6.5
	Partial-unsgnlzd	97.0	3.1	116.3	3.2	79.5	6.6
Diagonal with DLT	Full-sgnlzd	166.5	7.0	177.0	6.7	96.8	6.5
	Full-unsgnlzd	111.6	4.1	131.0	3.2	96.7	6.5
	Partial-sgnlzd	150.3	5.8	160.7	5.7	82.0	5.3
	Partial-unsgnlzd	96.3	3.2	115.8	3.4	82.1	5.2
Major street	Full-sgnlzd	125.1	3.3	112.7	2.8	96.0	4.7
	Full-unsgnlzd	69.3	2.2	67.4	2.4	96.1	4.7
	Partial-sgnlzd	109.1	3.8	105.9	3.4	84.7	4.5
	Partial-unsgnlzd	59.7	1.9	60.4	2.1	84.7	4.5
Minor street	Full-sgnlzd	123.9	4.4	113.2	4.3	37.9	4.9
	Full-unsgnlzd	68.8	2.5	67.8	2.3	37.9	4.9
	Partial-sgnlzd	110.3	3.6	96.9	3.1	33.6	5.2
	Partial-unsgnlzd	59.7	1.9	59.4	2.4	33.7	5.2

Table A.5: Travel Time Results for Equivalent Standard Intersection models

Route Type	Standard Intersection Model	Pedestrian travel time (s)		Shared-use Bicycle travel time (s)		Exclusive Bicycle travel time (s)	
	(Equivalent CFI type -RT control)	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Diagonal without DLT	Full-sgnlzd	485	17	291	9	201	9
	Full-unsgnlzd	427	9	247	4	201	9
	Partial-sgnlzd	457	15	271	9	185	8
	Partial-unsgnlzd	409	9	230	5	185	8
Diagonal with DLT	Full-sgnlzd	482	11	291	7	203	10
	Full-unsgnlzd	424	7	244	6	203	10
	Partial-sgnlzd	460	10	273	7	187	8
	Partial-unsgnlzd	404	9	227	5	187	8
Major street	Full-sgnlzd	407	6	215	4	205	6
	Full-unsgnlzd	349	6	170	4	205	6
	Partial-sgnlzd	392	6	208	5	192	6
	Partial-unsgnlzd	341	6	161	3	192	6
Minor street	Full-sgnlzd	407	6	216	5	132	8
	Full-unsgnlzd	350	4	168	3	132	8
	Partial-sgnlzd	389	6	198	4	126	7
	Partial-unsgnlzd	336	4	158	2	126	7

Table A.6: Number of Stops Results for Equivalent Standard Intersection models

Route Type	Standard Intersection Model	Pedestrian number of stops		Shared-use Bicycle number of stops		Exclusive Bicycle number of stops	
	(Equivalent CFI type -RT control)	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Diagonal without DLT	Full-sgnlzd	3.00	0.09	2.82	0.05	1.66	0.08
	Full-unsgnlzd	1.95	0.02	1.95	0.02	1.71	0.07
	Partial-sgnlzd	2.98	0.07	2.83	0.06	1.69	0.10
	Partial-unsgnlzd	1.94	0.02	1.94	0.02	1.69	0.10
Diagonal with DLT	Full-sgnlzd	3.02	0.08	2.83	0.06	1.71	0.08
	Full-unsgnlzd	1.94	0.02	1.96	0.01	1.71	0.09
	Partial-sgnlzd	3.06	0.07	2.87	0.04	1.66	0.08
	Partial-unsgnlzd	1.94	0.02	1.94	0.02	1.67	0.07
Major street	Full-sgnlzd	2.04	0.04	1.83	0.03	1.67	0.07
	Full-unsgnlzd	0.95	0.01	0.95	0.02	1.69	0.07
	Partial-sgnlzd	2.04	0.05	1.88	0.03	1.68	0.09
	Partial-unsgnlzd	0.94	0.01	0.94	0.01	1.69	0.08
Minor street	Full-sgnlzd	2.01	0.05	1.83	0.04	0.69	0.09
	Full-unsgnlzd	0.95	0.01	0.94	0.02	0.69	0.09
	Partial-sgnlzd	2.02	0.05	1.81	0.03	0.70	0.08
	Partial-unsgnlzd	0.94	0.02	0.94	0.01	0.73	0.08

7.2 Appendix B – Pedestrian, Bicycle and Transit Considerations for RCUT Intersections

Background

Addressing bicycle and pedestrian safety in conjunction with traffic operation and motor vehicle efficiency is a critical concern in the design and configuration of transportation infrastructure. Pedestrian and bicyclists have higher risks and safety concerns at signalized intersections due the concentrated number of conflict points with motorized traffic flows and other factors related to vehicle speed and levels of congestion (Pulugurtha, Imran, 2015). In 2017, 5,977 pedestrian fatalities occurred as a result of traffic crashes, comprising a disproportional 15.8 percent of all traffic fatalities in the U.S, and 852 fatal bicycle crashes, equating to 2.2 percent of U.S. traffic fatalities (NHTSA, 2018). Furthermore, the number of pedestrian and bicycle fatalities occurring in urban areas have increased, respectively, by 46 percent and 13 percent since 2008, while overall urban traffic fatalities have increased by 17.4 percent and urban vehicle miles traveled (VMT) have increased by 13.3 percent during the same period. Correspondingly in 2017, 193,866 pedestrians and 329,831 bicyclists were treated for non-fatal crash related injuries in medical emergency departments across the U.S. (CDC, 2017). In response to these rising concerns, an implementation strategy of routine accommodation is recommended for roadway and intersection projects to provide space, facilities and amenities for pedestrian and bicycles as an integral part of transportation capital projects (BikeSafe, 2014).

Given adopted USDOT goals to achieve an 80 percent reduction in pedestrian and bicycle fatalities and serious injures within 15 years, and 100 percent reduction in pedestrian and bicycle fatalities within 20 years (FHWA, 2016), all roadway and intersection improvement and innovation projects must incorporate effective design solutions to address prevalent safety concerns of vulnerable highway users. Safety goal actions identified in FHWA's strategic agenda pertaining specifically to pedestrians, bicycles and intersection design include: improving high-risk pedestrian and nonmotorized areas; creating a multimodal transportation system that provides travelers with viable mobility choices; conducting before/after safety studies, consistent with AASHTO Highway Safety manual, for innovative pedestrian and bicycle facilities; and using design methods and procedures that promote Vision Zero aspirational goals and outcomes.

Another approach to evaluating pedestrian and bicycle safety is use of a scalable risk assessment method that is determined based on speed limit, traffic control, alignment, land use, exposure, pedestrian/bicycle crash records, and risk indicators to provide an estimated measure of the probability of a crash to occur for site specific conditions (FHWA, 2018). Application of this method evaluates pedestrian and bicyclist risk at a specific site, or at multiple sites, using eight sequential steps to develop risk values at desired geographic scales. Based on desired geographic scales, three analytical methods can be used to estimate pedestrian and bicyclist exposure: 1) site counts, 2) travel demand estimation, and 3) travel surveys. Of the four geographic scales identified, facility specific points are used to evaluate intersection locations, which are frequently determined as high-risk facility types for pedestrian and bicyclists.

As a result of undesirable and concerning national pedestrian and bicycle safety trends, many local jurisdictions are placing a concentrated emphasis on creating more walkable communities. Walking and bicycling can provide valuable physical activity, however, both are limited in the U.S. as a result of car-centric planning of the past, which has led to creation of a transportation network that makes driving convenient and cheap, while creating many obstacles to walking, bicycling and public transit use (ALR, 2016). Urban planners attribute walkable urban environments with positive health benefits, cost-efficient mobility infrastructure, improved quality of life, and smaller sustainability impacts (Hermann, et al, 2017). Higher levels of walkability are also associated with quantifiable increases in walking and bicycling, however, these relationship are complex and nonlinear (Caspi, Smart, 2019). Furthermore, improved walkability and street-level urban design qualities supporting walking and bicycling, have a positive effect on residential property values (Hamidi, et al, 2019). Lastly, many communities are using pedestrian and bicycle facilities as an intervention to revitalize struggling areas by improving access to commercial and retail developments located along busy roadway corridors and across other need-based and opportunity-oriented urban areas (Bartlett, et al, 2012).

Another prevalent response to addressing non-motorized traffic safety and community walkability concerns is taking the form of community action and grass roots safety initiatives such as Walkwise Florida to provide innovative pedestrian safety education to citizens in a variety of spatial contexts and land use environments (Walkwise, 2018). These efforts are being further supported by formal institutionalized programs such as

Florida's Pedestrian and Bicycle Focused Initiative, a collation of governmental partners including engineering, law enforcement, education and outreach, promoting a multidisciplinary approach to improve safety, led by the Florida Department of Transportation Traffic Safety Office (FDOT, 2018).

Equity is yet another issue of considerable importance in non-motorized traffic safety in that lower income neighborhoods experience the highest per-capita rate of pedestrian fatalities (Lin, Kourtellis, 2019). Additionally, across the U.S. urban landscape, arterial roadways, which are the most likely candidates for implementation of RCUT treatments, are often in close proximity to lower income residential areas. According to Lin and Kourtellis, from analysis of 712 low-income block groups located in Broward and Palm Beach Counties, other effects of lower socio-economic status (SES) land use and demographic indicators on pedestrian safety correlating to increased pedestrian related crashes occur in areas exhibiting: 1) increased public transit, or bike to work, 2) lower education levels, 3) lower car ownership, 4) higher concentrations of low-income minority populations, and 5) increased number of intersections, traffic signals and bus stopes per mile in low-income block group areas. In a broader sense, transportation equity refers to providing to affordable and reliable mobility that fairly meets the needs of the community with specific emphasis on traditionally underserved populations including low income, minorities, older adults, limited English proficiency, and persons with disabilities (Sandt, Combs, Cohn, 2016.) Furthermore, U.S. national framework for transportation equity is focused on ensuring communities have access to safe, accessible, convenient and comfortable pedestrian and bicycle infrastructure that is well connected to the broader mobility network, as well as to the transit systems, supporting the goal of collectively creating Ladders of Opportunity (FHWA, 2016). Advancing ideals of equitable transportation access to jobs, essential services, healthy food, parks and community resources, are substantially advanced through designing roadways and streets for everyone in accordance with the philosophy of complete street principles, especially for the growing sector of the public who are unable to travel by privately owned motorized vehicles (FHWA, 2016). Additionally, equity goal actions identified in FHWA's strategic agenda pertaining specifically to pedestrians, bicycles and intersection design include: creating well-connected pedestrian and bicycle facility networks to support equity, empowerment, and community cohesion; reducing unintended consequences in facility design that create barriers to mobility for nonmotorized travel; and embracing USDOT Every Place Counts Design Challenge principles to implement design solutions that bridge the infrastructure divide to reconnect people with opportunity.

The need for, and benefit of, transportation related physical activity is a topic that has been widely studied by public health researchers. From 1953 to 2015 there were nearly 70,000 studies of physical activity and health outcomes (Varela, et al, 2018; Ding, Gebel, 2011). Chronic conditions, such as heart disease, and risk factors for chronic disease, such as overweight and obesity, can be mitigated by achieving recommended amounts of physical activity. Growing body of research shows built environment conditions are key factors for individuals in promoting regular physical activity and preventing chronic disease (Sallis, 2012). Evidence from physical activity research suggest that adults tend to be more physically active when they live in more walkable communities (Sallis 2016). There is also evidence that in general, people who live in urban areas walk more and are less sedentary than those residing in rural areas (Sallis, Anderson 2015). In a Canadian study involving 3,727 adults, evaluations determined that living in more walkable neighborhoods is positively correlated with higher levels of utilitarian walking and a higher number of total daily steps (Hajna, et al, 2015). Supportive built environment and transportation infrastructure, referred to as activity space walkability, are strongly associated with transportation physical activity as determined from a study of 12,152 university students in Toronto, Canada (Howell, et al, 2018). Cycling as a day-to-day means of travel in urban areas provides measurable health benefits including a 52 percent lower risk of dying from heart disease and a 40 percent lower risk of dying from cancer, as shown in a recent 5-year study from the United Kingdom (Celis-Morales, et al, 2017). The need for well-connected network of bicycle-specific infrastructure in urban areas, including multiuse paths and on-street facilities is critical to encourage more bicycling among adults and achieve the potential of positively influencing health outcomes (Dill, 2009).

Safety Benefits of RCUT Intersections

Safety benefits of RCUT intersections are well documented, include a reduction in the number of conflict points by 87 percent, and as studied at implementation sites located in Maryland, Minnesota, Missouri and North Carolina, resulted in 35 percent to 59 percent reduction in total crashes, as well as considerable reductions in severe and fatal crashes (FHWA, 2018). In a study of 11 RCUT implementation sites located in Alabama, North Carolina, Ohio, and Texas, analysis determined values of estimated crash modification factors of 0.85 for overall crashes and 0.78 for injury crashes (FHWA, 2017). A study of six RCUT intersection in Louisiana demonstrated safety benefits using a comparison of crash modification factors (CMF) with aggregate reduction in total crashes of 28.6 percent, accompanied by 100 percent reduction in fatal crashes (Sun et al, 2019). Using VISSIM simulation for rural locations with two way stop control intersections, along major multilane roadways, RCUT intersections were determined to significantly reduce societal costs due to crashes, and furthermore user costs resulting from delay and increased travel time were minimal (Adams, Sangster, 2019). At a congested at-grade, signalized intersection site location in the northern suburbs of San Antonio, TX, a strategic RCUT implementation resulted in a 25 percent reduction in peak hour traffic delay and correspondingly increased safety by reducing the number of conflict points between high-volume traffic flows (TAMU, 2014).

Pedestrian and Bicycle Safety at RCUT Intersections

RCUT configurations provide a considerable reduction in the number of conflict points in comparison to a conventional at-grade, four-leg intersection, which entails six conflict points for each of the four typical crosswalks, totaling 24 conflict for the entire intersection. RCUT intersections can reduce the number of conflict points for pedestrians to as few as eight (FHWA, 2014). Based on before and after studies of 8 sites where reduce conflict intersections improvements were implemented in Minnesota, findings determined a 100 percent reduction of fatal and serious injury right angle crashes and 50 percent reduction in injury crashes (Leuer, Fleming, 2017). As RCUT intersection configurations commonly incorporate medians and traffic islands providing refuge for pedestrians, resulting safety benefits include shorter crossing distances, and reduced need to cross multiple traffic movements at the same time, whereas these design features are similarly advantageous for motor vehicle safety as well (FHWA, 2010, 2011).

For pedestrians crossing the major street at RCUT intersections, using VISSIM simulations, a diagonal crosswalk, extending along the center channelization island, was identified as an optimal configuration, and if signalized, would also likely necessitate a 60/40 traffic signal cycle split to accommodate walking distance and clearance periods needed for pedestrians (NCDOT, 2014). It should be noted that the diagonal crosswalk extending across the major roadway is also accompanied by crosswalks on both of the minor crossing street legs, creating a configuration referred to as a “Z” crossing. The diagonal crosswalk extending across the major roadway could also be designed to accommodate a multiuse path. Additionally, pedestrian crossing signals are beneficial, when warranted, and Americans with Disability (ADA) requirements, and Public Rights-of-Way Accessibility Guidelines (PROWAG) must be considered, specifically with regard to landings, slopes, widths, curb ramps, accessible/audible signals, and detectable delineation. If site conditions necessitate, the diagonal crosswalk could be designed for a two-stage crossing of the major roadway. In Orange Beach, AL, implementation of an RCUT intersection along a busy beach front arterial roadway where 70 percent of crashes were related to left turns, incorporated a center crosswalk into a raised concrete center channelization island to provide a countermeasure for pressing pedestrian and bicyclist safety concerns, where four fatalities occurred between 2012-14, of which two were pedestrians (FHWA, 2018).

For bicyclists traveling along the minor crossing street, an innovative approach to allow a direct cross through opening in the center channelization island was identified as a functional solution, using VISSIM simulation, for rural RCUT intersection locations (FHWA, 2014). Furthermore, for bicyclists who opt to use the U-turn crossings, bicycle signal detectors, signing, and sharrows should be included in the design and implementation of RCUT intersections. For bicyclists traveling along the major roadway there will be no difference from a conventional intersection with the exception of left turns to access the minor cross street. In the event buffered multiuse paths are provided along the major roadway, bicyclists would most likely use a multiuse path "Z" crossing configuration, as described for pedestrians. If accel/decel lanes are present, this can create a difficult condition to for bicyclists to navigate, as motor vehicle drivers generally do not anticipate having to yield the right-of way to bicyclists, when traveling along major roadways. If bicycle lanes are present along the major roadway, this problematic condition can be mitigated by shifting the right turn/decel lane to the right of the bicycle lane, through a transition zone delineated with dashed pavement markings, using a lane marking layout detail, which is specifically covered under AASHTO guidelines (AASHTO, 2012).

Transit User Safety at RCUT Intersections

As public transit is primary accessed by pedestrians, all of the previous identified safety benefits of RCUT intersection configurations related to reduced conflict points, median/island refuges and "Z" pedestrian crossing configuration would be similarly advantageous to transit users, regardless of near-side, far-side, exclusive bus lane, bus pullout, or curbside public transit variations (FHWA, 2014). When bus stops are situated at the nearside of the intersection approaches along the major roadway, this will provide transit users with the benefit of being located closest to the diagonal crosswalk extending along the center channelization island, providing access across the major roadway. Furthermore, for minor crossing streets, if bus stops are located on the far-side, passengers will similarly be closest to the diagonal crosswalk and additionally, buses will not be required to make a weaving maneuver to change lanes to access curbside or pullout transit stop locations in the right most lane. Key elements for access to bus rapid transit or light rail transit systems located adjacent to RCUT intersections should similarly consider right-of-way controls, route alignment, station location, passenger ingress/egress, and pedestrian network connectivity.

Summary of Multimodal Considerations for RCUT Intersections

The reduction of the number of conflict points to as few as eight provided by RCUT intersection configurations is beneficial to all roadway users including, motor vehicle traffic, pedestrians, bicyclists, and transit users. While some concerns for non-motorized users have been identified (MnDOT, 2016), the net result of reducing conflict points, providing median/island refuges and including multimodal considerations in the design of RCUT intersections outweigh the list of concerns including: user unfamiliarity, reduced convenience, perceived wayfinding difficulties, two-stage crossings of the major roadway, longer walking distances, possible increased delay, and difficulty in meeting ADA/PROWAG design requirements. Determination of optimal configurations for candidate RCUT intersection implementation sites will require careful consideration of all roadway user needs, mobility demands, site conditions, location constraints, network connectivity, traffic operations, and comprehensive safety performance to individually customize this innovative design treatment for each community to best address the needs of the traveling public.

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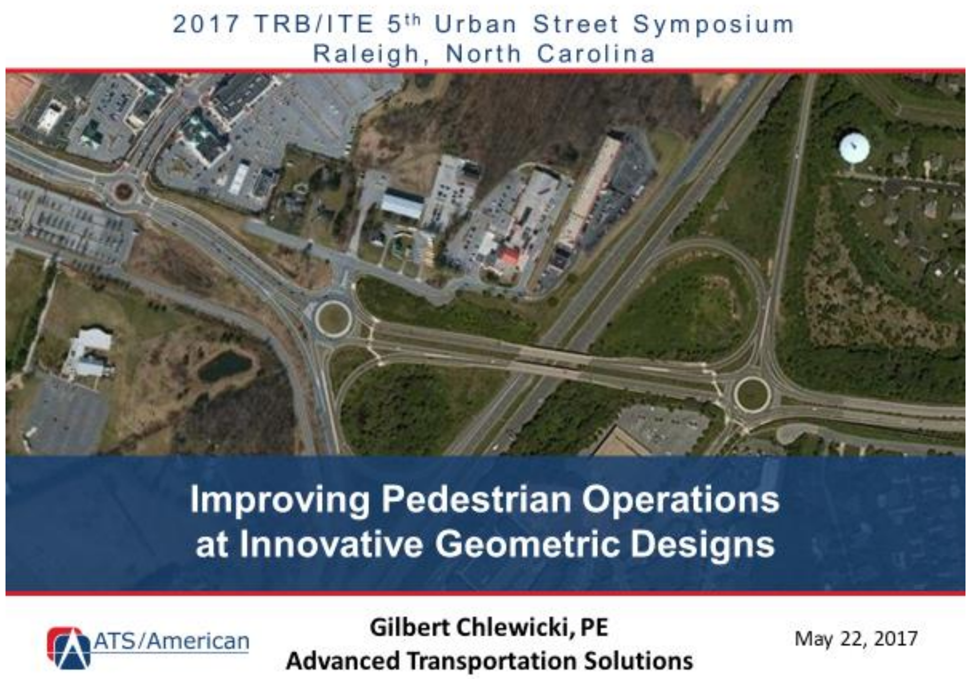
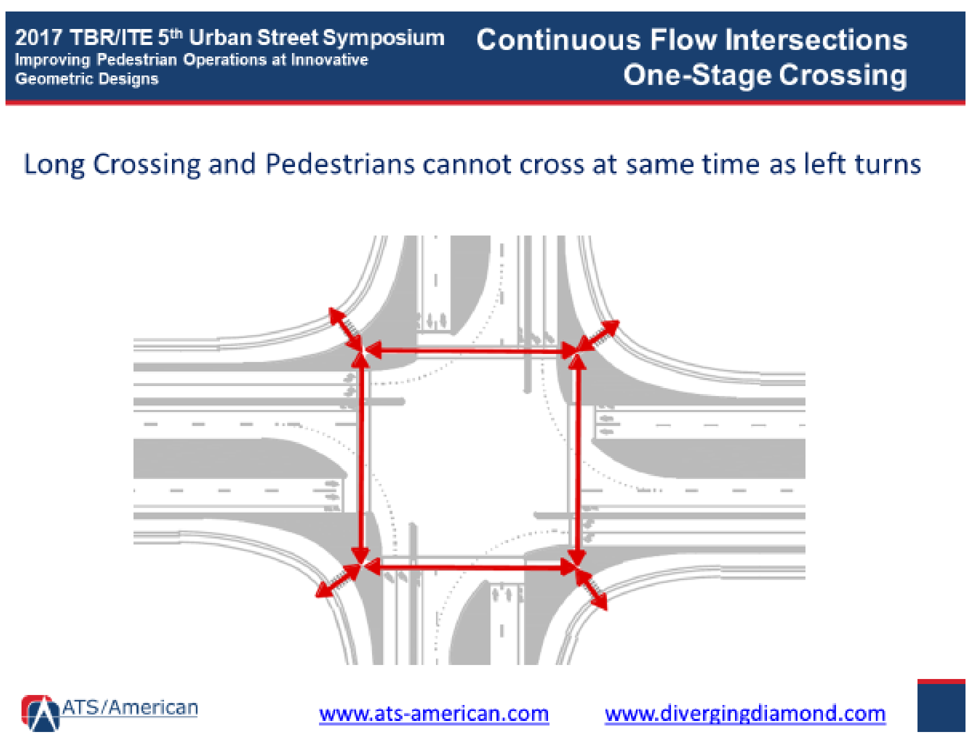
7.3 Appendix C – Supplementary Diagrams of Pedestrian Crossings at Innovative Geometric Designs

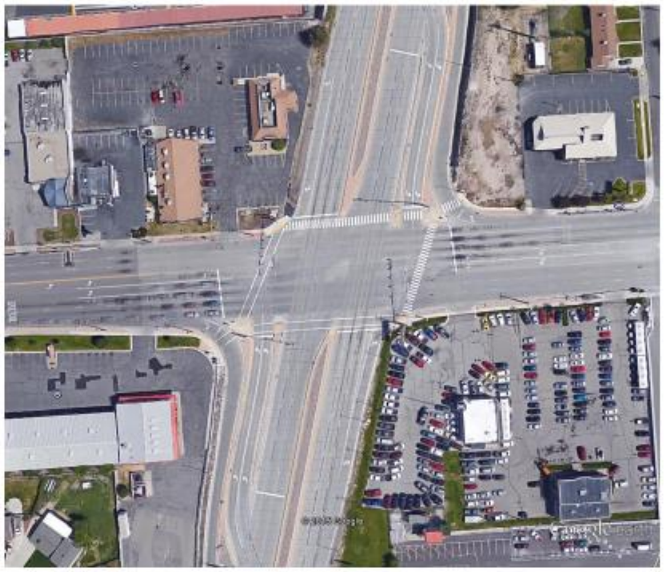
The following images are from a presentation given on 2017 TRB/ITE 5th Urban Street Symposium, Raleigh, NC (Chlewicki, 2017)





2017 TBR/ITE 5th Urban Street Symposium
Improving Pedestrian Operations at Innovative Geometric Designs

Continuous Flow Intersections
One-Stage Crossing



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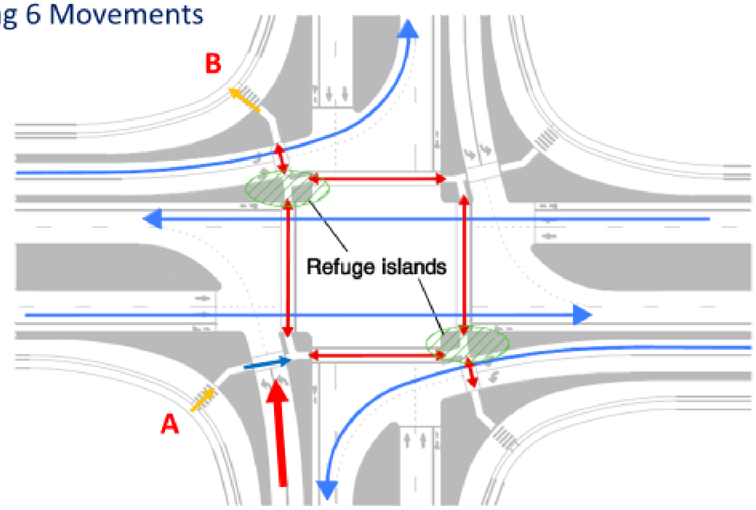
2017 TBR/ITE 5th Urban Street Symposium
Improving Pedestrian Operations at Innovative Geometric Designs

Continuous Flow Intersections
Multiple Stage Crossings

Shorter Crossings, No Left Turn Conflict, Poor Pedestrian Progression, Crossing 6 Movements



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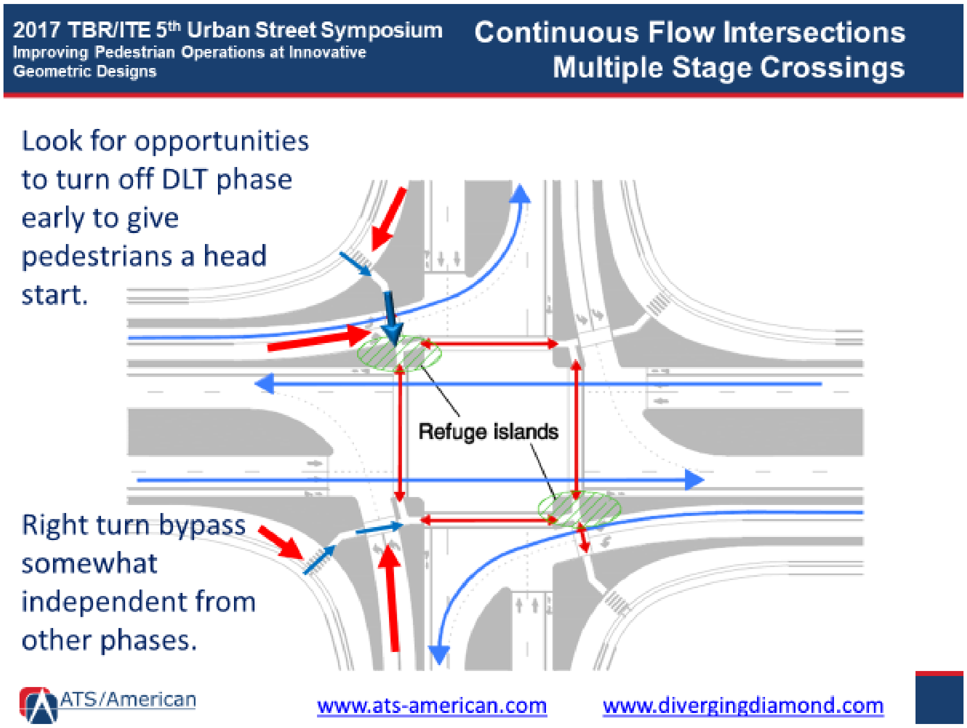
2017 TBR/ITE 5th Urban Street Symposium
Improving Pedestrian Operations at Innovative Geometric Designs
Continuous Flow Intersections
Multiple Stage Crossings
Look for opportunities to turn off DLT phase early to give pedestrians a head start.
Refuge islands
Right turn bypass somewhat independent from other phases.
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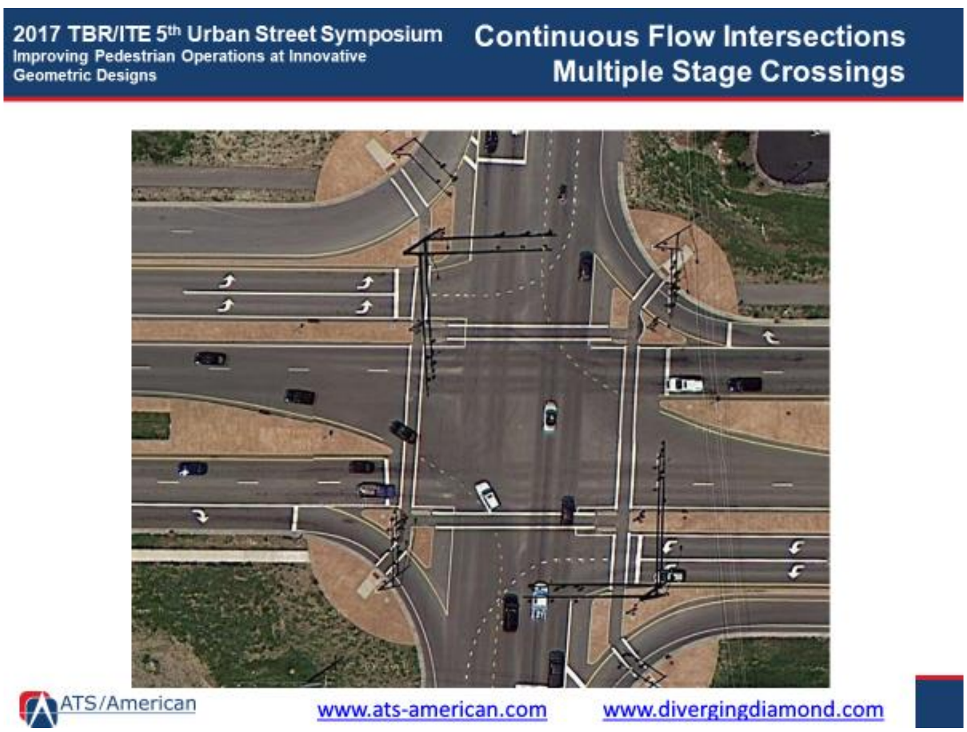
2017 TBR/ITE 5th Urban Street Symposium
Improving Pedestrian Operations at Innovative Geometric Designs
Continuous Flow Intersections
Multiple Stage Crossings
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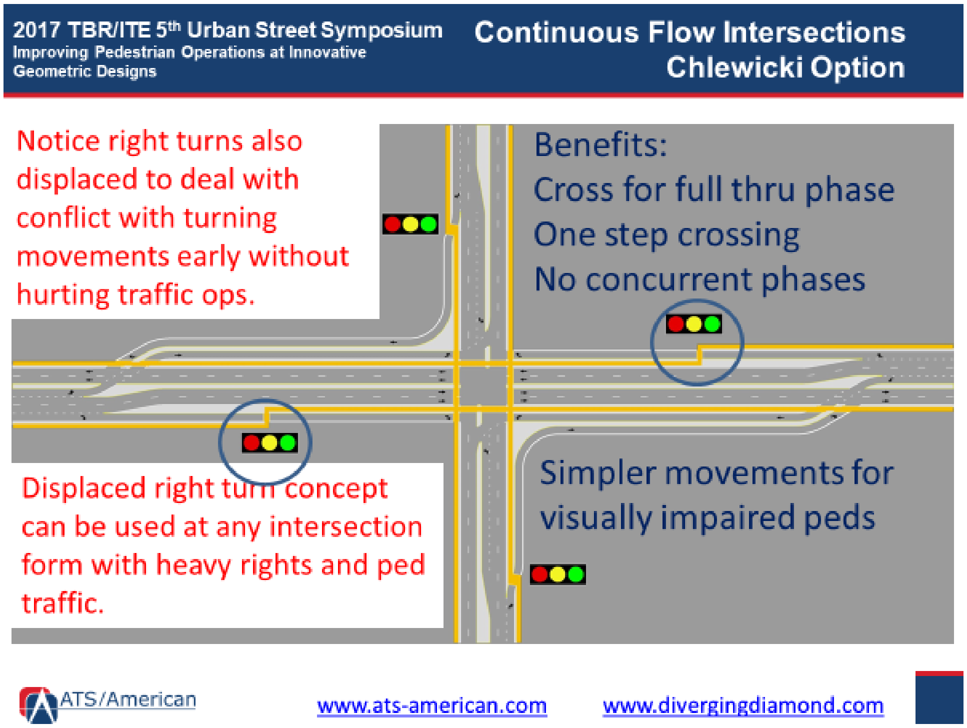
2017 TBR/ITE 5th Urban Street Symposium
Improving Pedestrian Operations at Innovative Geometric Designs
Continuous Flow Intersections
Chlewicki Option
Notice right turns also displaced to deal with conflict with turning movements early without hurting traffic ops.
Benefits:
Cross for full thru phase
One step crossing
No concurrent phases
Displaced right turn concept can be used at any intersection form with heavy rights and ped traffic.
Simpler movements for visually impaired peds
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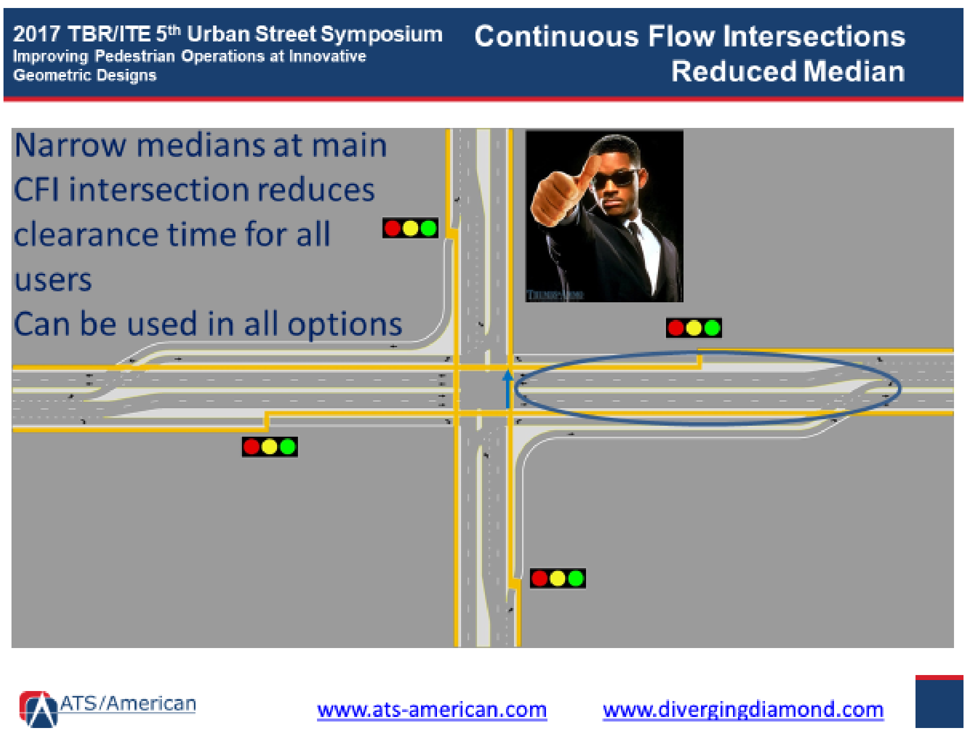
2017 TBR/ITE 5th Urban Street Symposium
Improving Pedestrian Operations at Innovative Geometric Designs
Continuous Flow Intersections
Reduced Median
Narrow medians at main CFI intersection reduces clearance time for all users
Can be used in all options
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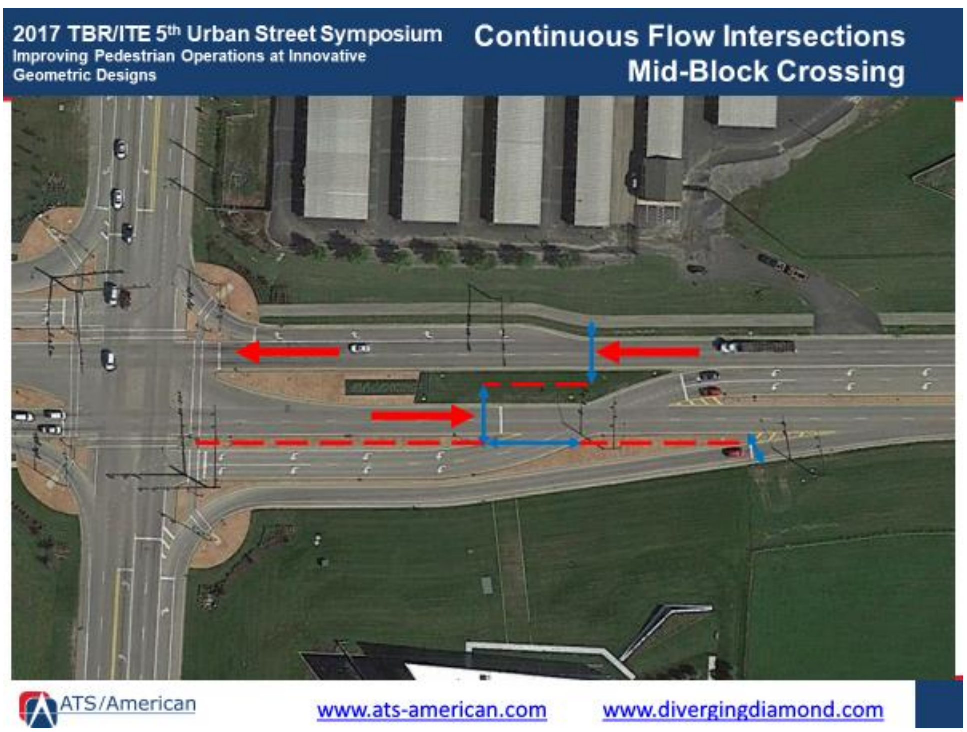
2017 TBR/ITE 5th Urban Street Symposium
Improving Pedestrian Operations at Innovative Geometric Designs
Continuous Flow Intersections
Median Sidewalk
ATS/American
www.ats-american.com
www.divergingdiamond.com


2017 TBR/ITE 5th Urban Street Symposium
Improving Pedestrian Operations at Innovative Geometric Designs
Continuous Flow Intersections
Mid-Block Crossing
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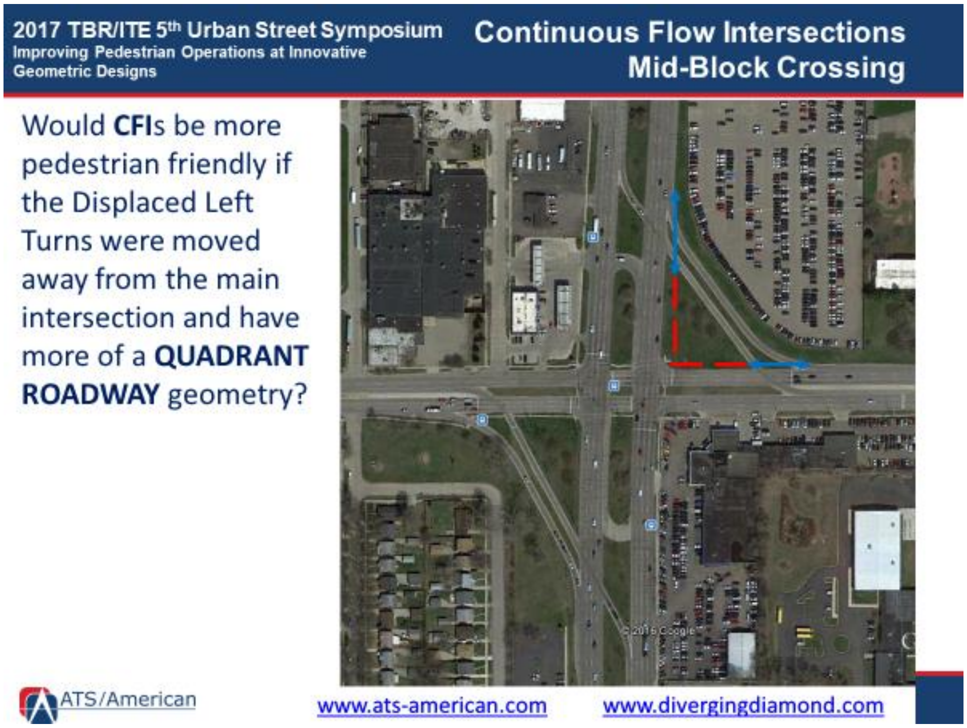
2017 TBR/ITE 5th Urban Street Symposium
Improving Pedestrian Operations at Innovative Geometric Designs
Continuous Flow Intersections
Mid-Block Crossing
Would **CFI**s be more pedestrian friendly if the Displaced Left Turns were moved away from the main intersection and have more of a **QUADRANT ROADWAY** geometry?
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7.4 Appendix D – Summary of Accomplishments

Date	Type of Accomplishment	Detailed Description
8/20/19	International Conference	Abstract submitted to the International Symposium on Highway Geometric Design (Amsterdam, June 2020) has been accepted for a full paper submission
7/31/19	Journal and Presentation	Submitted a paper for presentation and publication at TRB 2020 annual meeting
5/7/19	Poster Presentation	The project team presented the findings from this project in the North Carolina Department of Transportation Research and Innovation Summit.
5/30/19	Compendium Presentation	The project team presented the findings from this project in the North Carolina Section of ITE's Midyear Meeting.
12/31/2018	Products Developed	Developed 24 microsimulation models of different CFI geometries and pedestrian-bicycle crossing facilities.
07/23/2018	Award	Dr. Nagui Rouphail, PI has been awarded the title "Distinguished University Professor" this quarter, by the Provost and dean of Engineering
07/23/2018	Presentations	Davis, Jeff; SC Section ITE meeting, presentation on STRIDE UTC research projects and capacity building activities, Charleston, SC, April 20, 2018. Davis, Jeff; ASCE Eastern Branch Meeting, presentation on STRIDE UTC research projects and capacity building activities, Charleston, SC, May 11, 2018. Davis, Jeff; SC Governor's School, organized and conducted 1-week Summer Camp on multimodal mobility, connected vehicles and congestion mitigation, Hartsville, SC, June 17-23, 2018. Davis, Jeff; Statewide ASCE/ITE Section meeting, 2-hour workshop on connected vehicles and congestion mitigation, Greenville, SC, June 26, 2018.