PEDESTRIAN AND BICYCLE ACCOMODATIONS ON SUPERSTREETS

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Raleigh, NC

For the

North Carolina Department of Transportation

Final Report
Project: 2012 – 13

January, 2014

Technical Report Documentation Page

1. Report No. **FHWA/NC/2012-13**	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Pedestrian and Bicycle Accommodations on Superstreets**		5. Report Date **January, 2014** 6. Performing Organization Code
7. Author(s) **Dr. Joseph E. Hummer, Ph.D., P.E. (joseph.hummer@wayne.edu)** **Anne M. Holzem, P.E. (amholzem@ncsu.edu)** **Nagui M. Rouphail, Ph.D. (rouphail@ncsu.edu)** **Christopher M. Cunningham, P.E. (cmcunnin@ncsu.edu)** **Sarah W. O'Brien (skworth@ncsu.edu)** **Dr. Bastian J. Schroeder, Ph.D., P.E. (bastian_schroeder@ncsu.edu)** **Dr. Katy Salamati, Ph.D. (katy_salamati@ncsu.edu)** **Robert S. Foyle, P.E. (rsf@ncsu.edu)**		8. Performing Organization Report No.
9. Performing Organization Name and Address **North Carolina State University** **Department of Civil, Construction and Environmental Engineering** **208 Mann Hall** **Raleigh, NC 27695-7908**		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address **North Carolina Department of Transportation** **Research and Analysis Group** **104 Fayetteville Street** **Raleigh, North Carolina 27601**		13. Type of Report and Period Covered **Final Report** **August 2011 to August 2013** 14. Sponsoring Agency Code **2012-13**
Supplementary Notes:		

16. Abstract

The objective of this research was to consider the unique challenges for pedestrians and bicyclists at superstreet intersections and recommend crossing alternatives for both users. For pedestrians the options included the diagonal cross, median cross, two-stage Barnes Dance cross and midblock cross. For bicyclists the options included the bicycle U-turn, bicycles using the vehicle U-turn, the bicycle direct cross and the midblock cross. These options were analyzed through microsimulation based on average stopped delay per route, average number of stops per route, and average travel time per route. Furthermore, various parameters were analyzed per each of the crossing geometries including two signal cycle lengths, two signal splits, two signal offset designs, and two midblock distances. The results for pedestrians showed that the two-stage Barnes Dance crossing produced the lowest values for average stopped delay, average number of stops, and average travel time. However, since the Barnes Dance is designed for an intersection with high volumes of pedestrians, the pedestrian option recommended for most superstreets was instead a combination of the diagonal cross with the midblock cross. The levels that ultimately influenced travel time for pedestrians were a cycle length of 90 seconds rather than 180 seconds, a signal split of 60/40 rather than 75/25, and an offset signal design where the vehicle platoons arrived at different times rather than simultaneously. The results for bicyclists showed that the bicycle direct cross had the lowest average number of stops and the lowest average travel time. The bicycle option with the lowest stopped delay was the vehicle U-turn. The levels that produced lower travel time values for bicyclists included a cycle length of 90 seconds, a signal split of 75/25, and situations where the vehicle platoons arrived at different times rather than simultaneously. The recommended bicycle options for the superstreet were the bicycle direct cross and the midblock cross implemented together. Additionally, the research outcomes include suggestions for public outreach materials in the form of a brochure and discussions with public groups.

17. Key Words **Superstreet, restricted crossing U-turn intersection, pedestrian, bicycle**	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 789	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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ACKNOWLEDGEMENTS

The research team appreciates the North Carolina Department of Transportation for the support and funding of this project. We extend our thanks to the project Steering and Implementation Committee members:

Jim Dunlop, P.E. (Chair)
Ernest Morrison, P.E. (Project Manager)
Jay Bennett, P.E.
Kumar Trivedi, P.E.
Vickie Embry, P.E.
Dale McKeel, AICP
Carrie Simpson, P.E.
Timothy Williams, P.E.
Majed Al-Ghandour, Ph.D., P.E., CPM
Mrinmay Biswas, Ph.D., P.E.

The research team appreciates Mr. Jim Dunlop and Mr. Ernest Morrison of NCDOT for good communications throughout the project.

The research team also appreciates the help of everyone on the pedestrian and bicyclist expert panel for their input and communication throughout the project.

Additionally, acknowledgements go to Mr. Shreyas Bharadwaj and Ms. Chaithra Jagadish for their superb help with the data collection and help with data organization.

Agencies which helped with the implementation of the data collection include the Town of Chapel Hill, Charlotte Area Transit System (CATS), Charlotte Department of Transportation (CDOT), City of Raleigh, State Capitol Police Division, the Downtown District of the Raleigh Police Department, Greensboro Department of Transportation and Duke Energy.

Many people added valuable input to the discussion of current practices, including, Mr. Richard Kramer, Mr. Tim Barnett (ALDOT), Mr. Tom Thivener (ADOT), Mr. Robert Herstein (Maryland SHA), Mr. Joshua DeBruyn (MDOT), Ms. Georgina McDonald (MDOT), Mr. Dennis Eyler, Mr. Dirk Gross (ODOT), Ms. Elizabeth Hilton (USDOT), Mr. Gilmer Gaston, Mr. Mike Brown, and Mr. Mel Bodily.

Without the help of all the above individuals and groups, the project could not have been completed in such a successful manner.

EXECUTIVE SUMMARY

Superstreets, also known as J-turns or restricted crossing U-turns, have grown in popularity throughout North Carolina and other states in both rural and urban locations, primarily due to the benefits the intersection brings to motor vehicles, which include decreased delay and a reduction in collisions. However, the intersection poses unique challenges to pedestrians and bicyclists that need to be addressed so that all roadway users may benefit from this experience.

The objective of this research was to consider these unique challenges for pedestrians and bicyclists at signalized superstreet intersections and recommend crossing alternatives for both users. For pedestrians the options included the diagonal cross, median cross, two-stage Barnes Dance cross and midblock cross. For bicyclists the options included the bicycle U-turn as well as bicycles using the vehicle U-turn, the bicycle direct cross and the midblock cross. These options were analyzed through microsimulation based on average stopped delay per route, average number of stops per route, and average travel time per route. Furthermore, various parameters were analyzed per each of the crossing geometries including two signal cycle lengths, two signal splits, two signal offset designs, and two midblock distances.

The results for pedestrians showed that the two-stage Barnes Dance crossing produced the lowest values for average stopped delay, average number of stops, and average travel time. However, since the Barnes Dance is designed for an intersection with high volumes of pedestrians, the pedestrian option recommended for the typical signalized superstreet was instead a combination of the diagonal cross with the midblock cross. The levels that ultimately influenced travel time for pedestrians were a cycle length of 90 seconds rather than 180 seconds, a signal split of 60/40 rather than 75/25, and an offset signal design where the vehicle platoons arrived at different times rather than simultaneously. The results for bicyclists showed that the bicycle direct cross had the lowest average number of stops and the lowest average travel time. The bicycle option with the lowest stopped delay was the vehicle U-turn. The levels that produced lower travel time values for bicyclists included a cycle length of 90 seconds, a signal split of 75/25, and situations where the vehicle platoons

arrived at different times rather than simultaneously. The recommended bicycle options for the superstreet were the bicycle direct cross and the midblock cross implemented together.

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1.0 INTRODUCTION

1.1 Need Definition

Superstreets, also known as J-turns or restricted crossing U-turns, have grown in popularity throughout North Carolina and other states in both rural and urban locations, primarily due to the benefits the intersection brings to motor vehicles. A previous study completed for the North Carolina Department of Transportation concluded that superstreets decreased travel time for motorists and had an overall reduction in collisions by approximately 50 percent (1). Nevertheless, general public opinion about superstreets is mixed, specifically in the pedestrian and bicycling communities. The superstreet intersection poses unique challenges to pedestrians and bicyclists that need to be addressed so that all roadway users may benefit from this experience. For pedestrians, the superstreet requires a two stage crossing, and current practice for constructing pedestrian crossings through the superstreet requires a diagonal cross through the direct left turns (Figure 1.1). Both of these characteristics of a superstreet raise concern for pedestrians. In particular, the angled movement is foreign to most pedestrians who are accustomed to traditional right-angled crosswalks, and indeed, this alignment can pose serious safety considerations for people with vision impairments. However, a superstreet offers potential benefits to pedestrians with lower cycle lengths and increased safety through fewer conflict points than a conventional intersection.

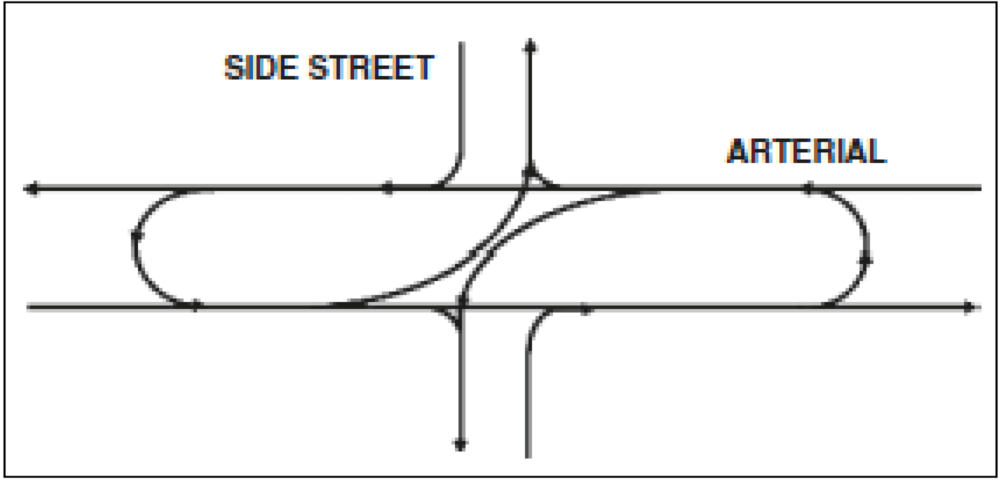

Figure 1.1. Superstreet intersection with direct left turns (1).

Bicyclists have concerns about the increased travel time to conduct a minor street through or left turn movement as this requires traveling some distance from the main intersection, utilizing a U-turn movement, and then traveling back to the main intersection. However, the bicyclists should benefit from the increased safety in addition to the improved signal progression compared to a conventional intersection.

1.2 Research Objectives

Researchers considered solutions to the unique challenges that pedestrians and bicyclists experience at superstreet intersections by examining two objectives: first to offer modifications to current superstreet design and operations in North Carolina to better accommodate bicyclists and pedestrians and second to develop materials to aid in the public outreach efforts. A large part of the modifications to the superstreet design was recommending alternative crossing patterns for bicyclists and pedestrians at superstreets. The objective was not to compare pedestrian and bicyclists crossing patterns at superstreets to crossings at a conventional intersection. The differences between superstreet and conventional intersection operations were demonstrated in previous research (1). In addition to crossing patterns, changes to the signal design and operation to improve overall pedestrian and bicycling crossing experiences by minimizing travel time and delay through the intersection were analyzed.

1.3 Scope

The scope of this research was limited to pedestrian and bicycling activities at signalized superstreet intersections in North Carolina. Specifically, the research sought to recommend crossing alternatives for pedestrians and bicyclists at superstreets and also to recommend modifications to signal design and superstreet operation. The models used for analysis were calibrated for pedestrians and bicyclists in North Carolina.

1.4 Organization of the Report

This report includes 7 chapters beginning with this introductory chapter. Chapters 2 and 3 cover the literature review and current practice, respectively. Chapter 4 discusses the research methodology including the analysis methods considered and detail about the microsimulation models that were ultimately used. Chapter 5 covers the results and Chapter 6 discusses the focus group and public outreach materials. Conclusions and recommendations are provided in Chapter 7.

2.0 LITERATURE REVIEW

The literature review focused on superstreet operations and safety, and general considerations for bicyclists, pedestrians, and transit users including considerations for persons with disabilities. The literature on superstreets is growing but somewhat limited at this point, thus the following literature review was broadened to include similar unconventional designs. However, there is an overabundance of literature on bicyclist and pedestrian issues, so the review was narrowed to focus on factors affecting these target users at unconventional designs similar to that of the superstreet.

2.1 Superstreet Operations

Superstreets have a multitude of benefits over a conventional design, including improvements in capacity, travel time, and progression. A recent study in North Carolina examined travel time comparisons for seven newly constructed superstreets in the state and produced results from a saturation flow study (1). Field data were collected using video cameras to track turning movements, a GPS unit in a vehicle for travel times, and a laser speed gun to gather free-flow speeds. The travel times of the superstreet were compared to a conventional intersection using the simulation model VISSIM with field calibrated models. The report resulted in saturation flow adjustment factors and significant decreases in average travel times compared to a conventional intersection. Furthermore, the researchers also conducted a survey at the study sites to gain public opinion of residents, commuters and businesses. The residents felt that the superstreet was safer, while daily commuters expressed difficulty in navigation, but did note savings in travel time and a reduction in the number of stopped vehicles. The businesses reported a loss of customers due to access and confusion.

To address the concerns raised by businesses in proximity to newly implemented superstreets, Cunningham examined the effects of access management on North Carolina businesses (2). The study used a survey of businesses along sixteen study sites, of which, eight were treatment sites with recent access management applications and eight were comparison sites, which were similar in characteristic to the treatment sites without implementation of an access management project. This approach was used to simulate a before-after survey method. The research team also used the comparison sites to account for effects of local, regional, and national economic trends. Overall, 535 surveys were completed, and the consensus was that access management projects along treatment corridors had no considerable effect on revenues as reported by the respondents of the survey. Furthermore, safety at treatment sites seemed to improve, and the concerns about customer loss due to median installation were all but diminished by respondents at the treatment sites.

Reid and Hummer investigated the travel times of seven unconventional arterial intersection designs compared to a conventional design (3). Besides the superstreet median design, the median U-turn, quadrant roadway intersection, bowtie, jughandle, split intersection, and continuous flow intersection were also analyzed. For the scope of the paper, the researchers focused specifically on travel times and did not consider pedestrian movement. The intersections were studied using CORSIM for travel time and delay measures. The research found that the superstreet performed better than conventional for intersections with two-lane cross streets. Also, the researchers noted that the superstreet had optimum two-way progression independent of the signal spacing.

Richard Kramer invented the concept of the superstreet and first published it in a 1987 article of the ITE Journal (4). In this article, he proposed ten ideal concepts for arterial operations with the first being two-thirds to three-quarters green time for through movements. Also within his ten characteristics for the new design, he discussed the pedestrian traffic. He presented that pedestrians should be protected from conflicts with vehicles through protected signal phasing and that the spacing of the pedestrian path be convenient as to deter unprotected crossings. Protection for the pedestrians from vehicles should also include prohibiting right turn on red. Furthermore, the pedestrian crossing Kramer suggested was for a two stage diagonal crossing the major street from the southwest quadrant to the northeast quadrant when the superstreet runs west to east. When larger pedestrian volumes occur at the intersection, consideration should be made for bollards, splash panels and covered shelters. He also pointed out that the transit bus stops should coincide with the pedestrian crossings while not impeding traffic flow.

2.2 Superstreet Safety

The safety effects of superstreets are demonstrated by a recent report from North Carolina (5). The researchers gathered crash reports from NCDOT and used naïve and comparison group (C-G) analysis for rural signalized and unsignalized superstreets, and the Empirical Bayes (EB) method for rural unsignalized superstreets, as well as the Surrogate Safety Assessment Model (SSAM) to analyze signalized superstreet facilities. The report found that total, angle and right turn, and left turn collision types were reduced. Furthermore, a reduction in fatal and injury collisions were noted. In addition, the public opinion surveys found that residents felt that the superstreet was safer.

The safety advantage of superstreet design over conventional design was further illustrated by Hummer and Jagannathan (6). Hummer and Jagannathan examined collision data for rural superstreet applications in Maryland and North Carolina and of a suburban signalized superstreet in North Carolina. The researchers found a significant reduction in collisions at each study site, with the greatest reduction of angle collisions by 85.7% at one site. Furthermore, the paper suggested that the superstreet would benefit pedestrians by using signalized crosswalks, reducing the likelihood of getting struck by a vehicle due to fewer conflict points and relocating crosswalks away from some right-turning movements.

2.3 Pedestrian Considerations

2.3.1 Pedestrian Behavior

Sisiopiku and Akin studied pedestrian behaviors at a newly renovated corridor near Michigan State University (7). The data were collected from a survey resulting in 897 respondents and field observation through a series of videotaped intervals along the corridor. The researchers concluded that the location of the pedestrian crossing facility in relation to the destination is a major factor in a pedestrian’s decision to use the facility, with jaywalkers citing convenience as the main reason for not using the crosswalk. The midblock crossing was viewed favorably through survey results and observation. Crosswalks at signalized intersections were used often but compliance with the pedestrian signals was not strong. Turning vehicles often did not yield to pedestrians in the crosswalk, and the researchers suggested incorporating a lead pedestrian interval into the signal phasing of the intersection.

2.3.2 Pedestrian Safety

To understand the aspects of an intersection that impact the safety of pedestrians, Schneider *et al* examined pedestrian crashes in Alameda County, California (8). The research encompassed 81 intersections including arterials and collectors and considered several variables for the model including traffic crash counts, pedestrian counts, intersection site characteristics and the characteristics of the surrounding area. A model was created to predict pedestrian intersection crashes utilizing binomial regression and the variables were tested for collinearity. The study concluded that pedestrian crashes increased when the pedestrian volume and main-line vehicle volume increased. Also, right turn lanes increased pedestrian crashes, which may have been due to the longer crossing distance and the greater ability for right turn on red collisions. The presence of non-residential driveways and commercial retail properties increased the chance for pedestrian crashes due to an increase in driver distractions. Neighborhoods with a greater percentage of children also suffered from an increase in pedestrian crashes. The main factor that increased pedestrian safety at intersections was the presence of medians, allowing the pedestrians a refuge during crossing and the ability to cross in two stages.

2.3.3 Intersection Operations for Pedestrians

Jagannathan computed the pedestrian crossing times at continuous flow intersections with displaced left turns (9). The analysis utilized VISSIM to conduct microscopic time step and behavior-based simulation of three continuous flow intersections with fixed time signal control. The results showed the average delay per stop for all three cases had a pedestrian level of service B or C. The total delay time resulted in lower level of service for the uncoordinated pedestrian signal direction and when 10 seconds of green time was added to the right-turning phase. The research concluded that performance could be optimized through varying speeds, geometric features, and signal settings. Also, the continuous flow intersection performed better than a conventional intersection for the pedestrian due to tighter intersection geometries and shorter cycle lengths.

One option considered for pedestrian safety at a superstreet is a midblock crossing. The signal timing for this two-stage crossing is important to not deter the perfect progression.

Ma *et al* (10) studied ways to optimize two-stage midblock crossings. The paper examined simultaneous, progressive, and separate signalization. The signal was optimized and the model was tested using the case study of a popular pedestrian crossing in Shanghai, China. The study concluded that simultaneous and separate signalizations each decreased delay for vehicles and pedestrians. Also, the degree of saturation affects the green time and cycle length. Furthermore, the cycle length model helped to reduce traffic delay while the offset model decreased pedestrian delay and the number of pedestrians waiting on the median. The model was tested at the study site and the suggested improvements increased efficiency.

2.3.4 Microsimulation of Pedestrians

To analyze pedestrians at superstreets with the interaction of vehicles, microsimulation models will be performed, specifically, VISSIM. The calibration and interaction of vehicles and pedestrians through microsimulation was studied by Ishaque and Noland (11). The researchers collected vehicle and pedestrian data from a signalized network in London. The vehicle data included travel times, vehicle compositions, and queue discharge rates, while pedestrian data included speeds, queue discharge rate, and gap acceptance. The pedestrians were then modeled in VISSIM as vehicles using the program's settings for car following behaviors. This car following procedure was used over the pedestrian simulation option as simulated pedestrians otherwise would not interact with each other and are not affected by pedestrian densities. The simulations were then validated for both the vehicles and the pedestrians. The researchers concluded that the car-following algorithm in VISSIM was an effective approach to simulate pedestrian-vehicle interaction.

2.4 Bicyclist Considerations

2.4.1 Bicyclists Behavior

A 2010 study by Winters *et al* modeled the routes taken by cyclists and motorists and compared the actual route with the shortest distance (12). A survey of 150 Vancouver residents was completed to determine the origin, destination, mode, and purpose for a particular trip, as well as the details of the chosen route. The results showed that the novice cyclists were less likely to choose major roads. Also, three-quarters of the total trips were within 10% of the shortest route distance for both bicycle and car. The study mentioned similar results of cyclists detouring from shortest routes in Japan, Ontario, Phoenix, and Minnesota. The main emphasis with this study was on the built environment and analyzing why cyclists chose to detour. The study concluded that road infrastructure and bicycle aspects of the built environment influence the travel patterns. When asked, the cycling participants explained their route choices as being safer, away from traffic and well lit, and also comfortable, in areas of shade, pleasant aesthetics, adequate road surfaces and good topography.

Bicycle route selection was further discussed through literature on commuter bicyclists' opinions of route level factors and link-level factors (13). Route-level factors encompass travel time, bicycle facility continuity, and delays due to traffic controls; link-level factors involve the presence of bicycle facilities, vehicles including parked vehicles, the riding surface, and topography. The data were obtained through a stated preference survey, administered via the internet, which resulted in 3,000 responses. To analyze the data and determine the highest correlations between variables, a standard binary logit model was used. The results showed that when choosing a route, bicyclists prefer shorter travel times, residential roads, and bicycle facilities such as exclusive bicycle lanes, paths, or wider vehicle lanes. Furthermore, bicyclists are partial to flat or moderate changes in topography, continuous rather than interrupted bicycle facilities, fewer stop signs, and less delay from traffic signals.

2.4.2 Intersection Operations for Bicyclists

Bicyclists at superstreets currently have two route options, to either travel the roadway alongside the motor vehicles or to dismount and follow the pedestrian crossings. Several techniques can be utilized to accommodate bicycle progression (14). Ideas to consider in bicycle progression are bicycle speed variability, which can range from 8 mph to 20 mph and depend on the grade of the street and the presence of wind. Furthermore, other aspects to consider are signal cycle bandwidths, which are directly impacted by signal spacing, bicycle platooning, ability of the cyclists to clear a wide intersection, making lane changes or left turns, and other issues not associated with bicycle activities, such as peak times and street types. Bicycle speed variability was deemed as the most critical of the issues to consider.

The researchers presented a framework for solving specific cases of bicycle progression through a math programming formulation, which maximized vehicle and bicycle progression and minimized delay and total stops. Furthermore, the researchers suggested that the bicycle progression speed be posted as to inform the bicyclists of the most efficient speed for cycling through the signals.

The other option for the bicyclist at a superstreet is to follow a shared-use path. To aid designers, the level of service (LOS) for these types of paths can be quantified through the use of the 2010 Highway Capacity Manual (2010 HCM) (15). Similar research was performed for on-street bicycle facilities by Petritsch *et al* (16). The data collected for this study was from volunteers responding to videos of various paths and from field data obtained from the actual paths. The volunteer data were taken from the Video Ride for Science 2009 presented at the Museum of Science and Industry in Tampa, Florida. The eighty participants viewed 22 paths and gave a score to each based on the geometric and operational environment, which resulted in 1,709 segments rated. The field data collected from the paths included data for bicycle and pedestrian LOS, volume of other path users, and the number of interruptions. All of these data were used to create a model to determine a LOS score for a specific path. Stepwise regression was used to elucidate several significant variables including average speed of the motorized vehicles and the width of separation. The results showed that the highest scoring paths were ones with minimal influence from motorized vehicles. Conversely, the paths that received the worst grade were located on a road with no exclusive bicycle lanes, no paved shoulders and heavy traffic. The paths with LOS scores of B or C were paths separated from the roadway through a grass buffer or swale.

2.5 General Design Considerations for Bicyclists and Pedestrians

The California DOT released a report on complete streets in 2010 with emphasis on designs for bicyclists and pedestrians (17). The principles of the guide were to observe current pedestrian and bicyclist usage of intersections, improve existing conditions, and design with the assumption that pedestrians and bicycles will be present. The guide suggests decreasing the speed of turning motorists by constructing intersections with tighter curb radii and lower posted speeds. In addition, the guide emphasizes the importance of designing the intersection so that bicyclists and pedestrians need to make only one decision at a time.

These principles would reduce exposure, shorten the crossings, improve visibility, clarify right of way, use direct routes, provide adequate lighting and achieve access for all through ADA requirements. In addition, the intersection should accommodate bicyclists by clarifying the preferred bike path, while also considering bicycle detection and vehicular conflicts. Other treatments to be considered for bicyclists and pedestrians are bicycle push button signs, bike route guide signs, Pedestrian Hybrid Beacons (PHBs), rectangular rapid flashing beacons (RRFBs), countdown signals, slower walking speeds, and allowing pedestrians to activate additional crossing time by pressing an extended pushbutton for 2 seconds.

The FHWA released a report in 2010 on alternative intersections and interchanges and provided key concepts for accommodating bicyclists, pedestrians, and transit users (18). Similar findings were displayed in a chapter on intersection design from the Handbook of Transportation Engineering (19). Overall, the advantages for the pedestrians are 1) the use of (potentially) shorter signal cycle lengths, which allow improved pedestrian flow and a decrease in the number of signal phases and 2) conflicting traffic streams, which aid in the safety of the crossing pedestrian. The report emphasized that during the design of an unconventional intersection/interchange, there are several factors the designer should consider regarding pedestrians. One recommendation was to provide a median island refuge between crossing paths, which should make the crossing experience safer for the pedestrian. Furthermore, direct paths should be considered where feasible to reduce the amount of pedestrian exposure. Way finding signs are a necessity at unfamiliar crossings to encourage the pedestrians to use the given travel paths, and, in some cases, pedestrian pavement markings (“Look Right” or “Look Left”) to remind the pedestrian to look in the appropriate direction prior to crossing are a good idea. In addition, public information should be available to lessen the confusion of the unfamiliar pedestrian movements.

In addition to the accommodations discussed for pedestrians, the FHWA report also makes similar recommendations for bicycle facilities and transit users. For designs including U-turns, bicyclists may experience additional hazards from vehicles not staying within the indicated lane or from large vehicles experiencing off-tracking when the back tires encroach on the inner curb. For transit users, the bus stops should be placed away from the intersection either upstream or downstream of the left turn crossovers; however, prevention measures need to be considered to encourage pedestrians to use correct crossing paths instead of crossing at the bus stop. The installation of a breakaway barrier or plantings can help to channelize pedestrians to use the correct crossing location. Furthermore, the transit stop should not be placed in the loon of the U-turn as to conflict with the turning traffic movements. Also, some intersections may require more time for the transit system to perform left-turning movements, in which case additional time should be considered in the design of routes.

2.6 ADA Considerations

The FHWA gives guidelines for ADA approved street crossings (20). Constructing an aesthetically pleasing cross path for the pedestrians at superstreets may be desired; however, consideration must be made for pedestrians with disabilities by providing a smooth, slip resistant surface. Brick trim or colored concrete may help with the aesthetics of the intersection but must not hinder someone with a disability – for example if paint is applied it is to be slip resistant. Lining the median cross with shrubs or bushes will help with aesthetics and provide a traffic calming effect, however these applications must not decrease sight distances for the next crossing maneuver. Furthermore, the guide specifies that detectable warnings and contracting surface materials should be used at all crosswalks, and that pedestrian islands should have level landings.

A chapter from the Accessible Pedestrian Signals website addresses the basic practices for someone who is visually impaired to cross an intersection (21). The intersection needs to have ways for the visually impaired to detect the street and identify it through the slope of the curb ramp, detectable warnings and the presence of an intersecting sidewalk. For superstreets, detail will have to be implemented for a visually impaired person to detect the proper crossing location, align appropriately to an angled crosswalk, and maintain a proper heading while crossing through design details and the use of locator tones. Also, it will be important to inform the person crossing the street that there will be several crossings, each with a button to activate the accessible pedestrian signals.

2.7 Literature Review Summary

As demonstrated in the previous sections, thorough research has been performed on the operational and safety impacts of superstreet intersections as a whole in addition to various components of the intersection in relation to vehicular operations. Furthermore, the previous section discussed ways to improve pedestrian and bicycle facilities, primarily at conventional intersections. This report seeks to fill the missing gap between pedestrian and bicycle crossing facilities at unconventional intersections, specifically at the superstreet.

3.0 CURRENT PRACTICE

Superstreets are a relatively new concept as an alternative intersection design, and any pedestrian or bicycle crossings through the intersection require these users to potentially make non-traditional crossings or two-stage crossings. The researchers sought out current practice in several states to verify if another state or location had dealt with the crossing of pedestrians and bicyclists through a superstreet or similar design in a unique way that should be noted and included in this report. The states that were contacted included: Alabama, Arizona, Florida, Louisiana, Maryland, Michigan, Minnesota, Nevada, Ohio, Texas, Utah and Wisconsin. Of those states contacted, responses were received from all but Nevada and Wisconsin.

3.1 Alabama

Two sources were contacted in Alabama. The first was a telephone conversation with Richard Kramer, the founder of the superstreet design and the city engineer of Huntsville, and the second was Tim Barnett, a designer with the Alabama Department of Transportation (ALDOT).

Richard Kramer discussed the concept of the superstreet design as it relates to pedestrians and bicyclists through a phone conversation (22). His thoughts were that the diagonal crossing design, or as he refers to it as the “Z-crossing”, would be the best crossing pattern from the perspective of the vehicles. This crossing should be conducted with two pedestrian stages, using the median as a pedestrian refuge. All other designs that the research team has considered would have the ability to cross pedestrians in one stage (mostly through an exclusive pedestrian phase); however, this would take away from the point of the design, in Mr. Kramer’s opinion. He commented that the concept of having two one-way streets on the arterial or major street, with the benefit of separate signal operations, would diminish if the streets are tied together for a one-stage pedestrian crossing. Mr. Kramer mentioned that he would be willing to help the project team when additional questions arose, specifically with the signal timing. He also stated that the layout and signal timing of a superstreet are generally tasks that are not difficult as compared to conventional designs. Furthermore, the superstreet would work better as a corridor application for maximum progression since the timing of the signals can be coordinated with any upstream or downstream adjacent signalized intersection.

Being a big proponent of the superstreet design, Mr. Kramer has been able to incorporate certain aspects of this alternative design in a few locations in Alabama. The partial superstreets that have been constructed are along US Highway 231 near Boylston, AL.

For bicyclists, Mr. Kramer suggests these users follow the pedestrian path or a shared use path through the median when crossing the arterial from the minor street. Also, he mentioned that certain functions of the superstreet that bicyclists may find difficult would be similar at conventional designs. These pertain to bicyclists traveling on the main arterial and the difficulties with merging to make left turns. Transit users would benefit from the midblock crossing design; however, Mr. Kramer suggests that additional room should be provided for the bus to pull over and stop, thereby not blocking the through lane of traffic. Also, he reiterates that the midblock crossing would need to be a two-stage crossing for the pedestrians to maintain the separate progression for each direction of the major street.

Tim Barnett was the lead designer of Alabama's first superstreet and the person who initially presented the concept to ALDOT and the Federal Highway Administration (FHWA). Mr. Barnett was contacted, and he sent the plans for their superstreet which utilizes the diagonal crossing for pedestrians, see Figure 3.1 (23). Mr. Barnett also mentioned that this intersection did not have specific design features for bicyclists.

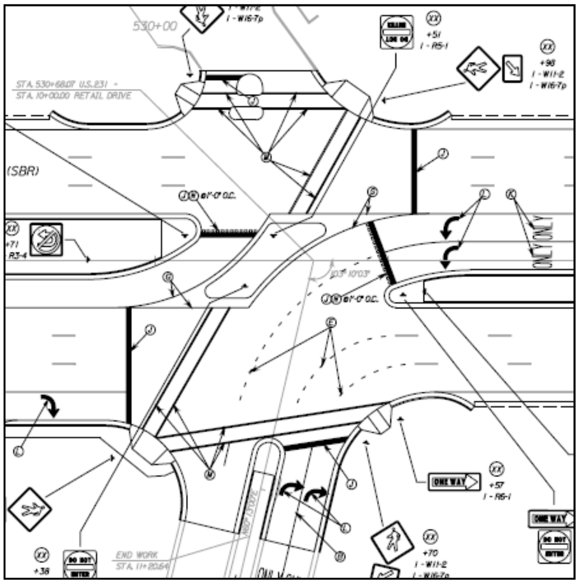

Figure 3.1. Pedestrian crossing at a signalized superstreet in Alabama (23).

3.2 Arizona

Arizona was not initially on the list of states to contact; however, after a request for current practice techniques was made at the 2012 Transportation Research Board (TRB) annual meeting, Tom Thivener responded (24). Mr. Thivener is the Bicycle & Pedestrian Program Manager in Tucson for the Arizona Department of Transportation (ADOT). He responded with a bicycle crossing technique at an indirect left turn intersection (or median U-turn), called the "bike spot". The indirect left turn, similar to the median U-turn, does not allow left turns at the main intersection; these turns would be made through U-turn crossovers downstream. The "bike spot" allows bicyclists to make left turns at the main intersection instead of traversing to the U-turns (Figure 3.2). While this technique may be a useful tool for bicyclists at the indirect left-turn, this approach may not be as effective at a superstreet crossing due to the raised median between the two channelized left turns from the major street.

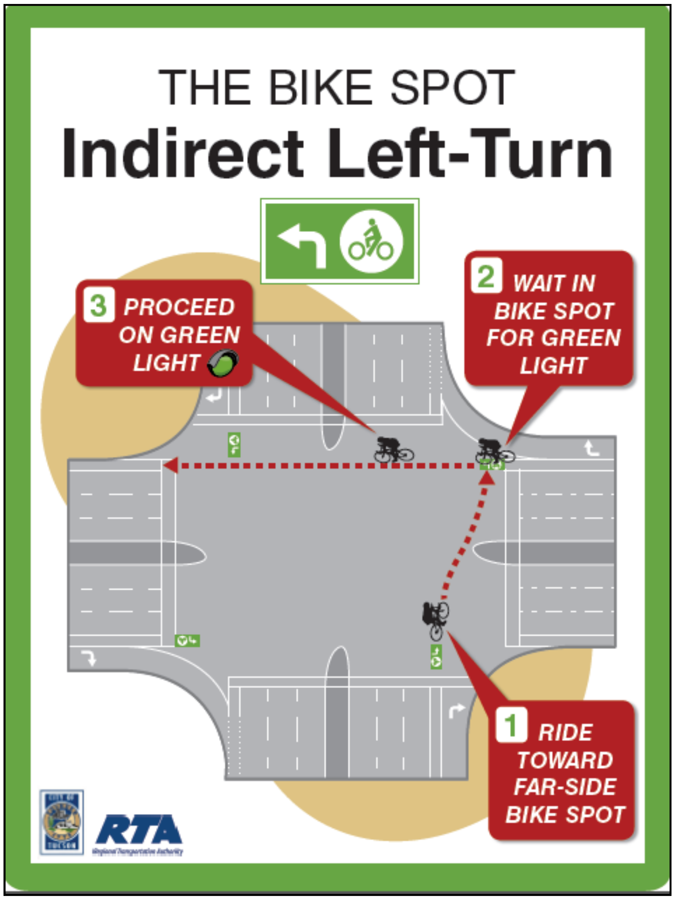

Figure 3.2. Instructions for a bicyclist using a bike spot at an Indirect Left-Turn intersection (24).

3.3 Maryland

In Maryland the superstreet is called the “J-turn”, and there are several of these intersections in rural (unsignalized) locations. For these locations, the state has made design considerations for bicyclists and pedestrians. Robert Herstein, a studies team leader for the Maryland State Highway Administration, reported that the state has made links connecting the bike lanes or sidewalk across the major street, usually with a paved path through the grassy median (25), see Figure 3.3. He also mentioned that at one location a space was created in the Jersey barrier to provide access for crossing pedestrians and bicyclists. Currently at a location with significant bicycle volumes the state is working on a way to inform the bicyclists of the option to either dismount and walk with the pedestrians, or to continue in the travel lane with the vehicles.

Figure 3.3. Pedestrian crossing through the median of a J-turn in Maryland (26).

3.4 Michigan

The median U-turn is a common design in Michigan; however, the superstreet design with direct left turns is not common in the state. Joshua DeBruyn, a Bicycle and Pedestrian Coordinator with the Michigan Department of Transportation (MDOT) in Lansing, sent location examples of crossings along an arterial with median U-turns (27). The crossings were located after a U-turn or between two sets of U-turns. Since this type of crossing is similar for a superstreet, Mr. DeBruyn was questioned about the effectiveness of these crossings for pedestrians. For this response, he recommended contacting a field office representative, Georgina McDonald (28). Ms. McDonald works for the Detroit section of MDOT, and she reported that one of the crossings she is familiar with was functioning fine and that there were no perceived changes to be made (29). Furthermore, she checked the crash history for that location and found no pedestrian crashes to date.

3.5 Minnesota

Minnesota also refers to superstreets as J-turns and these are unsignalized intersections located in rural areas. Dennis Eyler with SRF Consulting in Mankato reported that the J-turns do not see pedestrian activity (30). Mr. Eyler also reported that Minnesota has unsignalized restricted crossovers between intersections, but the pedestrian crosswalks are located at the intersections.

3.6 Ohio

The research team contacted Mr. Dirk Gross of the Ohio DOT, who was a traffic engineer involved in the design of the state's first superstreet intersection on Ohio Route 4 (31). The superstreet in Ohio is in a very rural area, so Mr. Gross stated that the designers did not consider pedestrian or bicycle accommodations at all. In fact, they have posted "No Pedestrian Crossing" signs on the cross street to make this point clear. Ironically, Mr. Gross stated that even where the DOT did not want crossing pedestrians they had to install curb cuts to meet Federal requirements.

Mr. Gross made an interesting observation that crossing farm equipment is a much more serious safety issue at the Ohio superstreet than crossing pedestrians or bicyclists. The research team has heard that comment from some places in North Carolina as well. Future studies may be needed to concentrate on that aspect of the design.

3.7 Texas

Two contacts were made in Texas: one with Elizabeth Hilton, an area engineer with the United States Department of Transportation (USDOT) in Austin, and Gilmer Gaston, the Vice President of Pape-Dawson Engineers, Inc. Ms. Hilton responded that the superstreets are relatively new in the state and that she did not have any new information to share (32).

Mr. Gaston worked on the design of the first superstreet in Texas, shown in Figure 3.4 & Figure 3.5. The crosswalk shown in the figures is the same diagonal cross used in this study.

Figure 3.4. Aerial view of a superstreet in Texas (33).

Figure 3.5. Diagonal pedestrian crossing through a signalized superstreet in Texas (33).

Mr. Gaston commented on this superstreet and the crossing pattern in an email message (33). He refers to the major street as having a "z-pattern crossing for pedestrians with a pedestrian path through the center island", and that the center island crossing is between 50 ft and 60 ft in length. Additionally, the minor streets have three right turn lanes, one being channelized, which gives a refuge to crossing pedestrians.

Mr. Gaston also described the daily individual timing plans for each direction (NB and SB) with varying cycle lengths from 60 seconds to 180 seconds. He compares the cross street green times from these plans to the green times from the previous conventional intersection and comments that the pedestrian walk sign is shown as frequently or in some cases more frequently during the superstreet cycles compared to the conventional cycles. He also acknowledged that even though the pedestrians could cross more frequently they still have a two-stage crossing compared to the previous one major cross at the conventional intersection.

As far as the effectiveness of this intersection for bicyclists and pedestrians, Mr. Gaston mentions seeing a bicyclist at the site on one occasion and describes the area as having potential for pedestrian activity, but that no significant increase in pedestrians has been noted at this time.

3.8 Utah

In Utah, Mike Brown a Transportation Engineer and Planner with MetroAnalytics was contacted (34). Mr. Brown is a big proponent of unconventional intersection designs, working mostly as a planner recommending projects. Although he could not offer much for pedestrians and bicyclists at superstreets, he did pass along an idea for a transit stop in the median, which for example, could be used in the large medians of median U-turns or superstreets. Mr. Brown referred to the transit stop as a “Transit Diverging Diamond” (Figure 3.6).

Figure 3.6. Transit stop option in a median (35).

Mr. Brown recommended speaking with Mel Bodily of Avenue Consultants in Salt Lake City. Mr. Bodily has been involved with the designs of ThrU-Turns in Utah, similar to a median U-turn or an indirect left intersection (Figure 3.7).

Figure 3.7. ThrU-Turn design from Utah (36).

Mr. Bodily discussed the pedestrians and bicyclists accommodations at the ThrU-Turn during a phone conversation (37). Although the ThrU-Turn intersection and a superstreet have many differences, a few key aspects of each may be similar for pedestrians. One similarity would be in the channelized free right-turning movement of motorists. The vehicles turning right would have to yield to pedestrians wanting to cross. Mr. Bodily discussed how the pedestrian in this instance would have to press a push button to cross the right turning vehicles, then reach a small refuge island and press another button to cross the through traffic. He believes this intersection would be friendlier to pedestrians as the crossing distance has shortened due to removing the left turn bays. When asked if he considered using a no Right Turn on Red (RTOR) policy at the locations of signalized right turns to aid the pedestrians, Mr. Bodily replied that the volume of right-turning vehicles was too high and this would impede on the overall design. For example, at one newly constructed ThrU-Turn intersection in the Salt Lake City area (12300 South and US-89), during the peak hour one approach required two right turn lanes to accommodate over 1300 vehicles wanting to travel either left or right. However, he did mention that the area has the potential for a high level of pedestrians as all four corners contain retail. As of now the intersection seems to be accommodating the pedestrians that are present. As for bicyclists at this intersection, the existing major street had bicycle lanes and the new construction kept the lanes. When asked how the major street bicyclists would turn left, he replied that they would use the U-turn, although he has seen many bicyclists use the pedestrian crossings. When asked about midblock crossings near the U-turn, he indicated that the intersection at 12300 South and US 89 does not have pedestrian crossings at the U-turns and he expressed that a crossing at this location would add delay for the vehicles.

3.9 Other States

One respondent from Florida said that the superstreet design was not currently being used (38) and another mentioned the presence of median openings in Florida, but no pedestrian accommodations are currently at these locations (39). In addition, the contact from Louisiana mentioned the construction of J-turns in the state, but that no additional accommodations were being made for pedestrians (40). Two other responses were received from the TRB annual meeting request, one from Colorado and one from Germany. The Colorado contact attached a standard specification for bicyclists at continuous flow intersections, but did not have a provision for superstreets (41). The respondent from Germany replied to the request for information by stating that superstreets are not currently in the country (42).

Overall, valuable information and ideas were gathered from current practitioners across the country, in particular, the bike spot for use at unconventional intersections similar to the indirect left turn or median U-Turn. However, a recurrent theme throughout this section was that further research is needed for pedestrian and bicycle treatments at superstreet intersections.

4.0 RESEARCH METHODOLOGY

The objective of the research was two-fold: first to offer modifications to current superstreet design and operations in North Carolina to better accommodate bicyclists and pedestrians and second to develop materials to aid in the public outreach efforts. A large part of the modifications to the superstreet design was recommending alternative crossing patterns for bicyclists and pedestrians at superstreets. To achieve this several steps were necessary and are described in the following sections.

4.1 Crossing Alternatives

Several crossing alternatives for both bicyclists and pedestrians were developed. The crossings considered effects to superstreet operations and user expectation. After thorough discussion of the alternatives amongst the research team, they were presented to a citizen panel of bicycle and pedestrian advocates and related working professionals from across the state.

4.1.1 Bicyclist and Pedestrian Panel

The research team gathered a list of eleven individuals to partake in the bicyclist and pedestrian panel. The list includes representation from official citizen boards, committees, and local or state advocacy/special interest groups (Figure 4.1). The individuals represent the Triangle area (Raleigh, NC, Durham, NC, and Chapel Hill, NC), as well as Wilmington, NC and Asheville, NC. They are professionals or extremely experienced and knowledgeable stakeholders.

Name	Organization	Title
Al Schroetel	Cape Fear Cyclists	*Advocacy Chair*
Claudia Nix	Asheville Bicycle and Pedestrian Task Force (Liberty Bicycles)	*Co-owner*
David Jerose	CAMPO Bicycle and Pedestrian Stakeholders Group	*Wake Forest Recreation Advisory Board Member*
Don Kostelec	Kostelec Planning	*Principal*
Erik Landfried	Durham Bicycle and Pedestrian Advisory Commission (Triangle Transit)	*Transit Service Planner*
Hanna Cockburn	Piedmont Triad COG	*Senior Planner*
Niel Brooks	Wilmington MPO Bicycle and Pedestrian Advisory Committee	*Represents Town of Leland*
Pete Schubert	North Carolina Coalition for Bicycle Driving (US EPA)	*Founding member*
Rainer Dammers	Town of Chapel Hill Bicycle and Pedestrian Advisory Board (IBM)	*Chair (Program Director)*
Steve Goodridge	NC Bike Club	*Advocacy Officer*
Steven Waters	City of Raleigh Bicycle and Pedestrian Advisory Commission	*Member (Computer Programmer)*

Figure 4.1. Pedestrian and bicyclists panel.

The research team met with the panel several times throughout the project. The first meeting was to introduce the panel to the superstreet intersection including presenting the current practice for maneuvering pedestrians and bicyclists through the superstreet. Details of the intersection were discussed and the panel expressed comments and concerns. The discussion progressed to related issues for pedestrians, bicyclists, transit users, and persons with disabilities at superstreets. Additionally, the research team presented several designs of alternative pedestrian crossing routes including explanations of the signal phasing for each. The panel commented on the designs and had a highly positive response to the midblock crossing option as an alternative crossing for pedestrians and as a suggested location for transit stops.

Communication between the panel and the research team continued between the first and second meetings. During these discussions, the panel had the opportunity to suggest locations for data collection (to record bicycle and pedestrian speeds) to be performed the first summer of the project and later use for calibration of simulation models. At the second meeting of the panel, bicycle crossing options were discussed as well as possible data collection sites in North Carolina. The panel offered valued input on the recommendations and had several suggestions for the data collection.

The research team met with the pedestrian and bicyclist panel a third time to discuss preliminary pedestrian simulation results. The panel made suggestions for future simulations and for the appearance of the simulation videos for the future use of public outreach. The fourth and final meeting with the panel was held to summarize the project, present findings of simulations for all crossing options (pedestrian and bicyclists separately) and to discuss the focus group outcomes and public outreach materials. Throughout the project, the research team thoroughly valued the unique perspective of the panel.

4.1.2 Selected Crossing Alternatives

The following section displays the bicycle and pedestrian crossing alternatives that were created and discussed with a panel of experts. These alternatives are for a signalized superstreet intersection with four vehicular approaches where the two minor street approaches are directly across from each other.

4.1.2.1 Pedestrian Crossing Alternatives

The first alternative offers a diagonal crossing for the pedestrians through the raised median between the two major street left turns (Figure 4.2). (The numbers in the figures represent the different pedestrian crossing segments and are used as a point of reference when describing each segment.) Each minor street will have a crossing and, depending on site geometry, this crossing may include a raised median or other crossing island. Crossing the major street would be done by utilizing a diagonal path through the median, creating an asymmetrical pedestrian crossing at the intersection. For example, a pedestrian wanting to cross from the southeast to the northwest would first cross westbound across the minor street (crosswalk 1), then cross diagonally in the northeast direction across both major streets (crosswalk 2 then 3), then move westbound to cross the minor street (crosswalk 4).

However, based on intersection geometry, crosswalks 2 and 3 could be placed perpendicular to the major street as opposed to the diagonal crossing shown in Figure 4.2. This crossing was first introduced for the superstreet by Richard Kramer in 1987 (4). Furthermore, advantages and disadvantages of the diagonal cross are shown in Table 4.1.

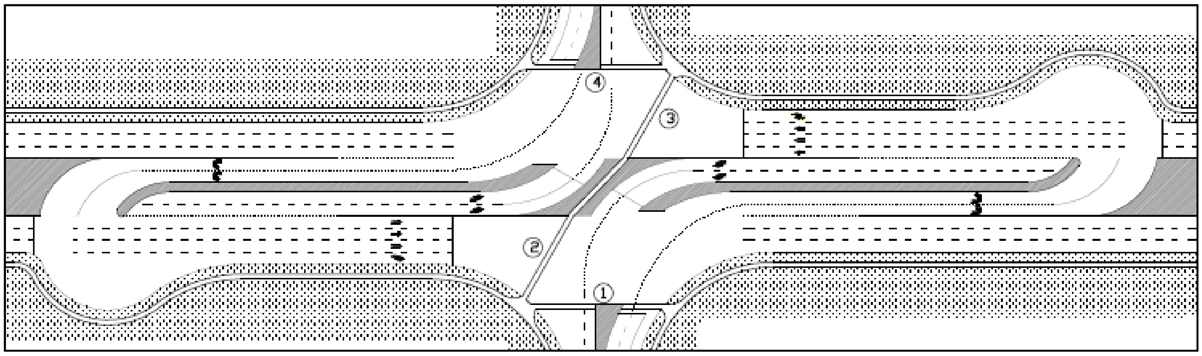

Figure 4.2. Diagonal cross.

Table 4.1. Assumed advantages and disadvantages to the pedestrian diagonal cross.

Advantages:	Disadvantages:
• Protected pedestrian movements. • Pedestrian phases work well with two-stage traffic crossings. • Expect no interruption to traffic flow. • Favors a direct path between the southwest and northeast quadrants. • Right turn on red from the minor street do not conflict with pedestrians any more than at a conventional intersection.	• Pedestrian movement from the southeast to the northwest quadrant will be longer due to the diagonal crossing length.

A more direct route across the major streets for the pedestrians is a median cross (Figure 4.3). Similar to the diagonal cross, the median cross utilizes the raised median between the two major street left turns. However, unlike the diagonal cross, the median cross is a symmetrical pedestrian crossing. This crossing allows pedestrians crossing from south to north, for example, to walk to the center of the minor street (crosswalk 1 or 2), and then cross the two major streets (crosswalk 3 then 4) directly to the center of the opposing minor street cross walk and then cross the minor street (crosswalk 5 or 6). Advantages and disadvantages to this crossing are discussed in Table 4.2.

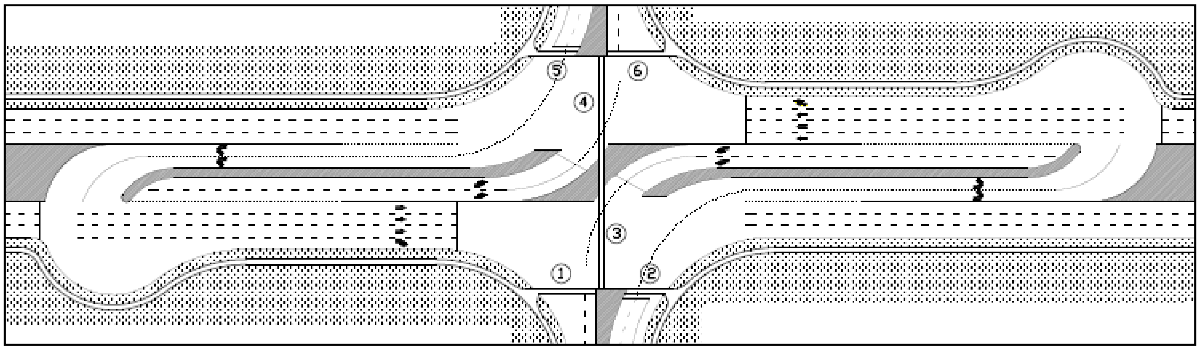

Figure 4.3. Median cross.

Table 4.2. Assumed advantages and disadvantages for the pedestrian median cross.

Advantages:	Disadvantages:
• Pedestrian paths at right angles, no angled paths. • Shorter crossing distances.	• The major street pedestrian path would conflict with the left turning vehicles from the major street. • An exclusive pedestrian signal phase would be required at each major street crossing, adding vehicular delay for the mainline left turn movement.

For a conventional crosswalk experience, Figure 4.4 offers users a more conventional way to cross the main street (crosswalks 3, 4, 8 and 9) in combination with two diagonal crossings, making this option symmetrical. One diagonal cross would function as described earlier (crosswalks 10 and 5 in Figure 4.4) and the second diagonal cross would be similar to the original diagonal cross (crosswalks 2 and 7), but in the opposing direction. This geometry would require an all-pedestrian (or “Barnes Dance”) phase to be implemented into the signals on each side of the major street. In addition, both major street directions could no longer operate independently. In addition, advantages and disadvantages to the two-stage Barnes Dance crossing are shown in Table 4.3.

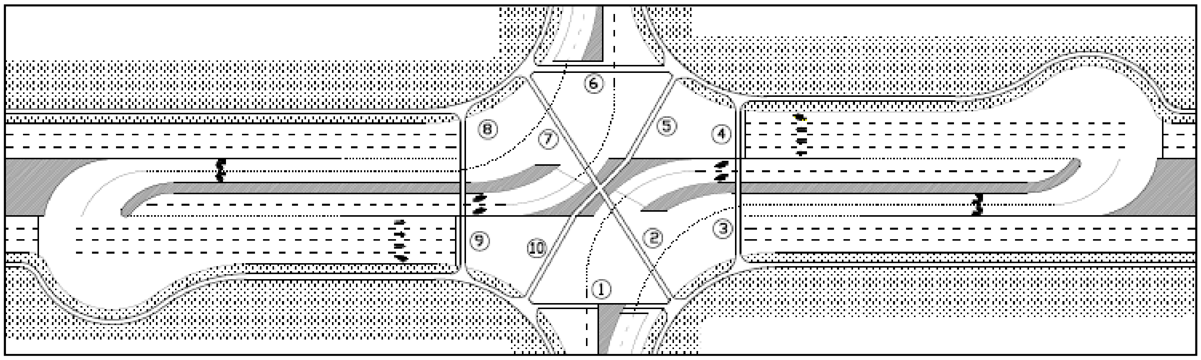

Figure 4.4. Two-stage Barnes Dance cross.

Table 4.3. Assumed advantages and disadvantages for the pedestrian two-stage Barnes Dance cross.

Advantages:	Disadvantages:
• Direct link between all quadrants increases pedestrian access.	• Major street pedestrian path would conflict with several vehicle paths and require an exclusive pedestrian signal phase. • The addition of the pedestrian signal phase would add to vehicular delay.

In addition to any of the above-mentioned crosswalks, a midblock crossing would add options for pedestrians as well as bicyclists at the superstreet (Figure 4.5). The midblock crossing would be placed at the U-turn crossovers, with one major street crossing already signalized for the U-turn vehicles (crosswalks 3 and 6). The second major street crossing (crosswalks 2 and 5) could utilize a conventional signal, pedestrian hybrid beacon (PHB), or a similar traffic control device that provides safe and (ideally) efficient crossings. This crossing would be symmetrical for both pedestrians and bicyclists. Additionally, the midblock crossings would offer a place for a transit stop away from the limited transit options near the intersection, as suggested by a member of the expert panel. Furthermore, advantages and disadvantages to the midblock cross are shown in Table 4.4.

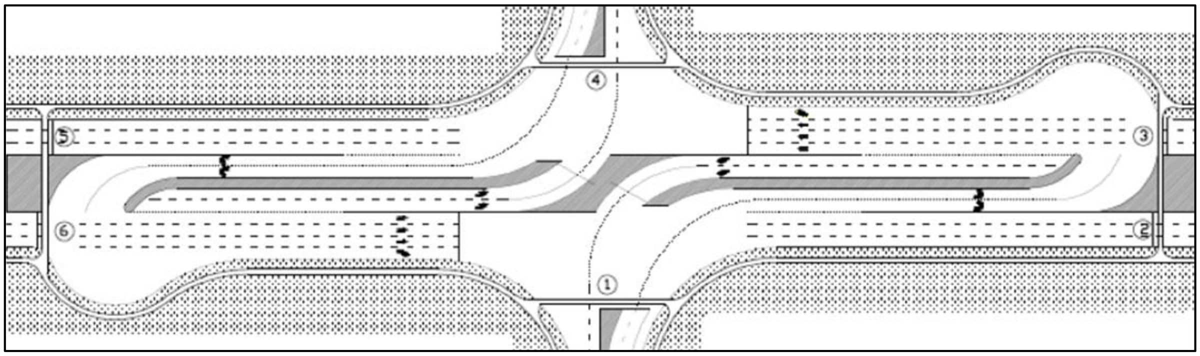

Figure 4.5. Midblock cross.

Table 4.4. Assumed advantages and disadvantages for the pedestrian midblock cross.

Advantages:	Disadvantages:
• Offers a crossing at the midblock, which may be in addition to a crossing at the main intersection. • One of the two crossings would work well with the current vehicle signal at the U-turn. • Midblock crossings would work well for closely spaced U-turns in a corridor of multiple superstreets. • Provides a crossing opportunity at a midblock location where transit could be incorporated.	• Possible added delay to the outbound vehicles from the side street movements at the midblock cross.

4.1.2.2 Bicycle Crossing Alternatives

Bicyclists have three options to choose for how they wish to travel through the superstreet. The bicyclist may choose to dismount and cross as a pedestrian, cycle in the vehicle lane and follow the vehicle paths, or to utilize a bicycle specific route.

Common complaints among bicyclists on the panel were that the superstreet U-turn crossovers are placed at a disproportionate length from the intersection for a bicyclist and that the U-turn crossovers are dangerous to bicyclists. One option would be to create a median cut exclusively for bicyclists at a shorter distance from the intersection than the vehicle U-turn crossovers (Figure 4.6). This median cut would be placed at the rear of the major street left turn bay to decrease vehicular conflicts for the bicyclists. A bicyclist traveling north on the minor street wanting to continue north or turn left onto the major street would move toward the center of the minor street to be positioned to the left of the right-turning vehicles (positions 1 then 2). When the signal dismisses the right-turning vehicles, the bicyclist would turn right onto the left side of the major street (position 3) to travel a short distance to the bicycle median cut. The bicyclist would then pause to cross the second half of the major street (position 4), waiting for either an acceptable gap in the vehicles or for the signals downstream to stop the major street vehicles and dismiss the U-turning vehicles. Table 4.5 lists the advantages and disadvantages of this crossing.

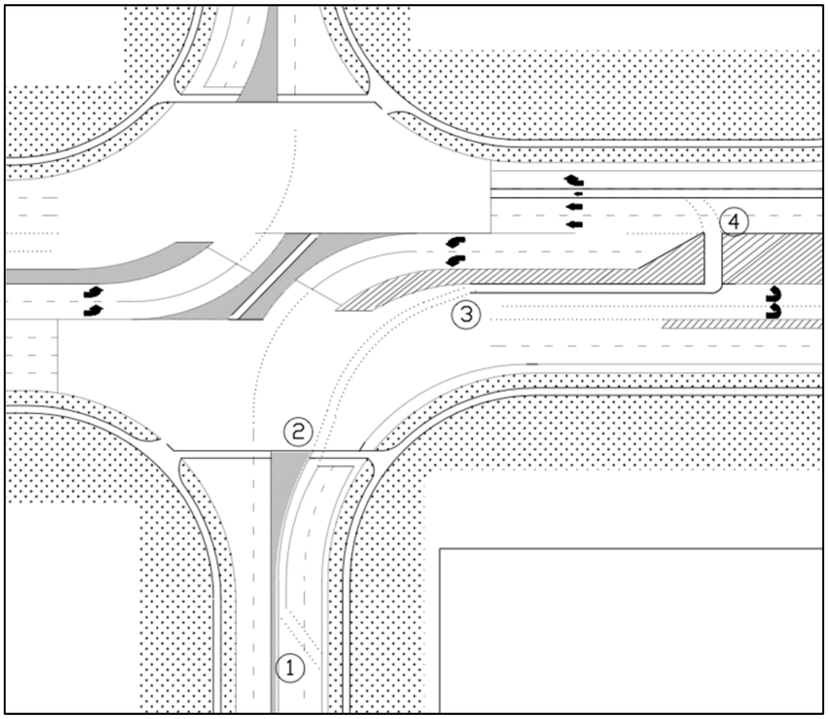

Figure 4.6. Bicycle U-turn option.

Table 4.5. Assumed advantages and disadvantages for the bicycle U-turn option.

Advantages:	Disadvantages:
• Bicyclists travel a shorter distance to the median cut as opposed to the vehicular U-turn. • Bicyclists' movements could work well with current vehicular signals. • The exclusive bicycle U-turn separates bicyclists from motorists, making the U-turn maneuver safer than when sharing the vehicular U-turn. • Favored by individuals on the expert panel who prefer to cycle with vehicles.	• Bicyclists traveling on the left side of the street is not common, making this movement unfamiliar to bicyclists as well as vehicles. • Possible storage concerns for multiple bicyclists traveling through the median cut at the same time. • May not be a viable option for extremely long mainline left turn bays

Another bicycle option would be to cross the bicyclists over the major street via a direct path (Figure 4.7). This more conventional approach would require two median cuts on either side of the major street left turn bay near the center of the intersection. This crossing differs from the pedestrian diagonal cross as this crossing has two paths for the bicyclists, one in each direction, and the paths cross over the major street left turn bays instead of crossing between them as in the pedestrian diagonal crossing. The bicyclist traveling north along the minor street would move to the center of the minor street prior to the intersection, similar to the bicycle U-turn option. However, instead of turning right with the motor vehicles, the bicyclist would continue traveling north, crossing the major street left turn bay and the second major street. Once across the second major street, the bicyclist could then continue traveling north along the minor street or turn left onto the major street. This crossing option would be direct but would require four different crossing movements. The advantages and disadvantages to this crossing are listed in Table 4.6.

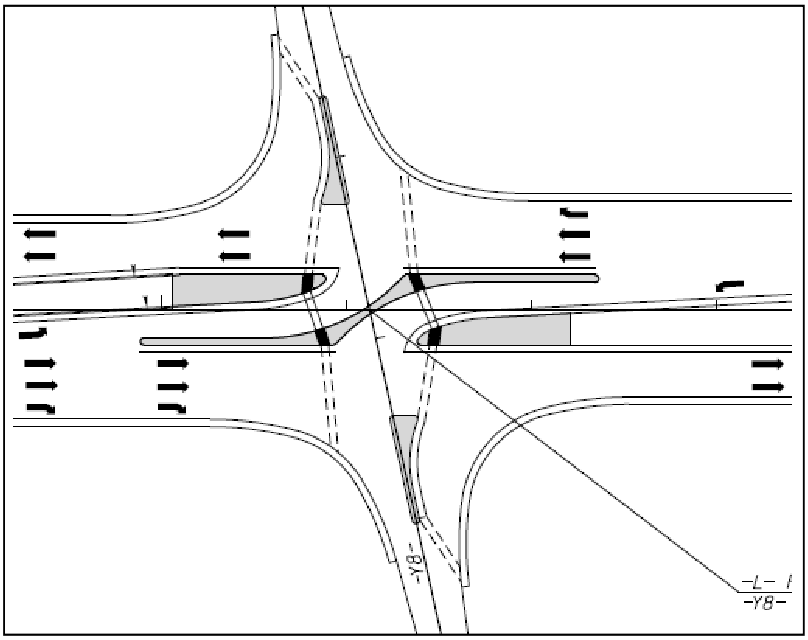

Figure 4.7. Direct cross.

Table 4.6. Assumed advantages and disadvantages to the bicycle direct cross.

Advantages:	Disadvantages:
• Directly crossing the major street offers the shortest distance to the bicyclists. • Bicyclists have less exposure to the major street traffic.	• Traveling on the left side is an unusual lane position for bicyclists and may be unexpected to motorists. • Additional signals exclusively for bicyclists need to be installed. • Additional design consideration needed for the bicyclists crossing the major street left turns. • Four different crossing movements.

4.1.2.3 Additional crossing alternatives

Several additional crossing alternatives were created for use at unique intersection geometries and land uses. However, these designs were not considered for final analysis. More detail into these designs can be found in Appendix A.

4.2 Analysis Methods Considered

Several methods were considered to analyze and compare the crossing alternatives outlined in the previous section. Methods considered included a pedestrian index, level of service through the Highway Capacity Manual, and microscopic simulation through PTV VISSIM.

4.2.1 Pedestrian Index

Pedestrian and bicycling advocates and city planners were contacted for methods to evaluate pedestrian and bicycle crossing facilities. Of the responses, the methods received were either too focused on aesthetics or difficult to modify from a conventional intersection method. For example, the Pedestrian Environmental Quality Index (PEQI) from the City of San Francisco helps communities identify ways to improve the walkability of a neighborhood (43). The PEQI considers the function of an existing intersection as well as the aesthetic characteristics of the surrounding area including traffic calming devices and the presence of public art and public use spaces. This method was not considered as a means to determine the appropriate crossing method for pedestrians and bicyclists as outlined in this report since it would not be able to clearly quantify a difference between alternative crossings at the same location. A more technical approach was considered by utilizing the level of service for pedestrians and bicyclists from the Highway Capacity Manual.

4.2.2 Level of Service Method in the Highway Capacity Manual

The level of service for pedestrians and bicyclists was computed by modifying the current level of service methodology from Chapter 18, Signalized Intersections, from the 2010 Highway Capacity Manual (HCM) (15). A spreadsheet was created to calculate the level of service (LOS) of pedestrians and bicyclists at a superstreet by modifying the conventional intersection calculations used in the HCM. The results of

4.2.2.1 Pedestrian Level of Service

All four of the pedestrian crossing alternatives were analyzed through the HCM LOS procedure, including the diagonal cross, median cross, Barnes Dance cross, and midblock cross. The route chosen for analysis was across the east-west superstreet, from south to north, specifically from the southeast quadrant to the northwest quadrant. Assumptions for the model included 50% minor street right turn on red, 10% major street right turn on red, and a pedestrian walking speed of 3.5 fps as found in the NCHRP-562 report (44). A 2-phase signal split of 70/30 was used for the model as well as the assumptions found in Table 4.7. The lane geometry and turning movement counts used for this model are shown in Table 4.8 and Table 4.9 respectively.

Table 4.7. Superstreet operational assumptions for HCM model.

Left Turn % of Cycle:	15	
Major/Minor yellow change interval, Y:	4	sec
Red clearance interval, R_c:	1	sec
Cycle Length:	90	sec
Additional time for Barnes Dance Phase:	30	sec
Major Street Speed:	45	mi/h
Minor Street Speed:	25	mi/h

Table 4.8. Superstreet lane geometry used for the HCM model.

	Approach	Left Lanes	Thru Lanes	Right Lanes	Channel Right	U-turn Lanes
Major Street	EB	1	2	1	0	2
Major Street	WB	1	2	1	0	2
Minor Street	NB	0	0	2	0	0
Minor Street	SB	0	0	2	0	0

Table 4.9. Turning movement counts used for the HCM model.

Input Turning Movement Counts:		veh/hr	Converted to Superstreet Geometry:		veh/hr
EB	LEFT	200	EB	LEFT	200
	THROUGH	2000		THROUGH	2000
	RIGHT	200		RIGHT	700
WB	LEFT	200	WB	LEFT	200
	THROUGH	2000		THROUGH	2000
	RIGHT	200		RIGHT	700
NB	LEFT	50	NB	LEFT	0
	THROUGH	500		THROUGH	0
	RIGHT	50		RIGHT	600
SB	LEFT	50	SB	LEFT	0
	THROUGH	500		THROUGH	0
	RIGHT	50		RIGHT	600

The LOS was determined for each crossing leg of the intersection, since the number of legs in a crossing varies among the geometries and the route taken. Thus one deviation from the current HCM calculations was to account for angled crosswalks as found in the diagonal cross option. For this option the 60^o crossing angle was utilized. Also, another modification to the current HCM LOS calculations was an increase in the delay function to account for the longer crossing distance in the median compared to a conventional intersection. The median crossing distances used are shown in Table 4.10.

Table 4.10. Median crossing distances per pedestrian crossing alternatives.

Pedestrian Geometry	Median Crossing Distance
Diagonal cross	40 ft
Median cross	28 ft
Two stage Barnes Dance cross	17 ft
Midblock cross	28 ft

The results were shown in the form of LOS per crossing as well as an overall travel time, which included delay time. The diagonal cross and the median cross each have four crossing legs for the intersection and thus were designated four LOS values. The two stage Barnes Dance cross and the midblock cross each have two crossing legs and were given two

LOS values. The results are shown in Table 4.11. Furthermore, the HCM spreadsheet created for this report is available and adaptable to other types of intersections.

Table 4.11. Results of pedestrian HCM model in LOS and travel time.

Pedestrian Geometry	Route	LOS	Travel Time to cross the intersection based on route (seconds per person)
Diagonal cross	SE to NW	C-C-C-C	120.5 s/p
Median cross	SE to NW	B-C-C-B	101.6 s/p
Two stage Barnes Dance cross	SE to NW	D-D	89.2 s/p
Midblock cross	S to N	C-C	88.5 s/p

4.2.2.2 Bicycle Level of Service

The three crossing alternatives for bicyclists, the bicycle U-turn cross, bicycle direct cross, and bicycle midblock cross, were also analyzed through the HCM LOS equations in Chapter 18. The bicycle crossing alternatives were analyzed separately from the pedestrian alternatives. The bicycling speed used for analysis was 12 mph or 17.6 fps from a study by William Hunter on bicycling speeds (45). The calculations also assumed a 5 ft bicycle lane and a bicycle flow rate of 40 bicycles per hour. The median crossing distances for the bicyclists were all the same at 28 feet. All other assumptions for the superstreet intersection were the same as for the pedestrian model.

The LOS calculations for the direct cross considered two major street crossings and the travel time considered the delay for crossing the two major streets as well as the delay for crossing the median. The midblock cross assumed that the bicyclist would be traveling on a shared use path adjacent to the major street, then upon reaching the midblock would cross the major street, then the median and finally the second major street. Thus the LOS calculations for the midblock cross included the two major streets, and the travel time included the delay for crossing the two major streets and the time spent crossing the median. As for the bicycle U-turn cross, the bicycles were assumed to be traveling positioned on the left side in the major street travel lane when utilizing the bicycle median cut, and then turn into the bicycle lane on the right of the (opposing) second major street. The LOS calculations were set up for crossing a street and not merging with traffic, thus a bicycle LOS could not be determined for the bicycle merging in both of the major streets. The travel time for the bicycle U-turn cross included the delay incurred for crossing the median and the time waiting to enter the second major street. Table 4.12 displays the results of the bicycle crossing alternatives for bicyclists crossing from the south to the north. The bicycle LOS spreadsheet is available and adaptable to other intersection types.

Table 4.12. Results of bicycle HCM model in LOS and travel time.

Bicycle Geometry	Route	LOS	Travel Time to cross the intersection based on route (seconds per person)
Bicycle direct cross	S to N	C-C	58.1 s/p
Bicycle midblock cross	S to N	C-C	72.4 s/p
Bicycle U-turn cross	S to N	N/A	72.4 s/p

4.2.3 Microscopic simulation through PTV VISSIM

The next method considered and ultimately chosen for analysis of the pedestrian and bicycle crossing alternatives was microscopic simulation through PTV VISSIM. Microscopic simulation allowed for an in-depth analysis of the crossing alternatives through various types of input scenarios and detailed output of results. The microscopic simulation procedure is outlined in the following section.

4.3 Calibration Data for the Simulation Model

The pedestrian and bicyclist crossing alternatives were tested separately through microscopic simulations to best replicate the vehicle interaction with bicyclists and pedestrians at superstreets in North Carolina. VISSIM was selected as the simulation program and several models were constructed based on previously calibrated superstreet microsimulation models while incorporating the alternative pedestrian and bicyclist crossing patterns. To calibrate the models in VISSIM for pedestrians and bicyclists of North Carolina, field data were needed.

4.3.1 Field Data Collection

To calibrate the VISSIM simulation models for pedestrians and bicyclists in North Carolina, data were recorded from the users of six sites within the state (Table 4.13). A video camera was mounted to a pole near the selected intersection and attached approximately 10 feet from the ground. Figure 4.8 is an example of a camera setup, displaying the camera mounted near the top of a pedestrian signal pole and the battery pack secured to the base of the pole with a cable and lock. At this height the cameras had a view of all the crosswalks located in the intersection. The cameras were timed to record during daylight hours for up to one week. Prior to placing the cameras on the poles, city engineers of each site were contacted for all the necessary approvals. In addition, at certain sites, the city police were also informed in advance of the camera placement, and at an intersection near a light rail station in Charlotte, approvals were gained from the Charlotte Area Transit System (CATS).

Figure 4.8. Camera mounted to a pedestrian signal pole with battery pack at the intersection of University City Blvd. and Broadrick Blvd. in Charlotte, NC.

4.3.1.1 Data Generated

The data generated from the video cameras at each site were walking and bicycling speeds. Specifically, for pedestrians, the walking speeds were divided into four subcategories based on pedestrian type: walkers, runners, electronic users, and manually operated wheelchair users. The electronic users included electronically operated wheelchairs as well as Segway users. For the bicyclists, the speeds were recorded for two users: bicyclists traveling in the bicycle lane or travel lane along the major street and bicyclists crossing at the crosswalks.

4.3.1.2 Selection of Sites

The sites were chosen for heavy pedestrian and bicycle usage as well as site characteristics similar to a superstreet. These characteristics included: signalized intersection with pedestrian accommodations; a lower speed minor street intersecting a higher speed major street or arterial; presence of a median on the major street, minor street, or both; channelized left turns; and/or channelized right turns. Table 4.13 depicts all the sites considered and the characteristics of the site that are similar to a superstreet intersection.

Table 4.13. Field data sites considered with corresponding site characteristics.

Site No.	Arterial (Major Street)	Cross Street	Location	Site Characteristics*
1	University City Blvd.	Broadrick Blvd	Charlotte, NC	Sig, Med
2	W. Lee St.	S. Chapman St.	Greensboro, NC	Sig, ChRT
3	South Blvd.	Sharon Rd. W.	Charlotte, NC	Sig, Med, ChRT
4	NC 54 (Raleigh Rd.)	Rogerson Dr.	Chapel Hill, NC	Sig, Med, ChLT, ChRT
5	Wilkinson Blvd.	Ashley Rd.	Charlotte, NC	Sig, Med, ChRT
6	W. Morgan St.	Fayetteville St.	Raleigh, NC	Sig
7	S. Salisbury St.	W. Cabarrus St.	Raleigh, NC	Sig

*Sig = Signalized
*Med = Median
*ChLT = Channelized Left Turn
*ChRT = Channelized Right Turn

4.3.1.3 Data Collection Sites Utilized

Of the seven sites shown in Table 4.13, six were ultimately used for data collection and a camera was placed at each of the six sites. Site No. 2, W. Lee St. and S. Chapman St. in Greensboro, NC was eliminated due to site conditions found upon inspection. The pedestrian facilities at this site were not as well-developed as the other sites, and camera placement on the approved poles would not have given a proper recording of all the crossing paths at the intersection.

Site 1, University City Blvd. and Broadrick Blvd. in Charlotte, NC, promised high volumes of pedestrian and bicyclist activity due to the location near the University of North Carolina – Charlotte (UNCC). Figure 4.9 shows the view of the two crosswalks observed from the height of the mounted camera.

Figure 4.9. View of crosswalks from mounted camera height at the intersection of University City Blvd. and Broadrick Blvd. in Charlotte, NC.

Site 3, South Blvd. and Sharon Rd. W. in Charlotte, NC, had high pedestrian activity due to the close proximity to the light rail station. With the approval of CATS, the camera was mounted to the pedestrian bridge connecting the observed intersection to the light rail station (Figure 4.10). From this camera placement, all five crosswalks at the intersection were clearly visible (Figure 4.11).

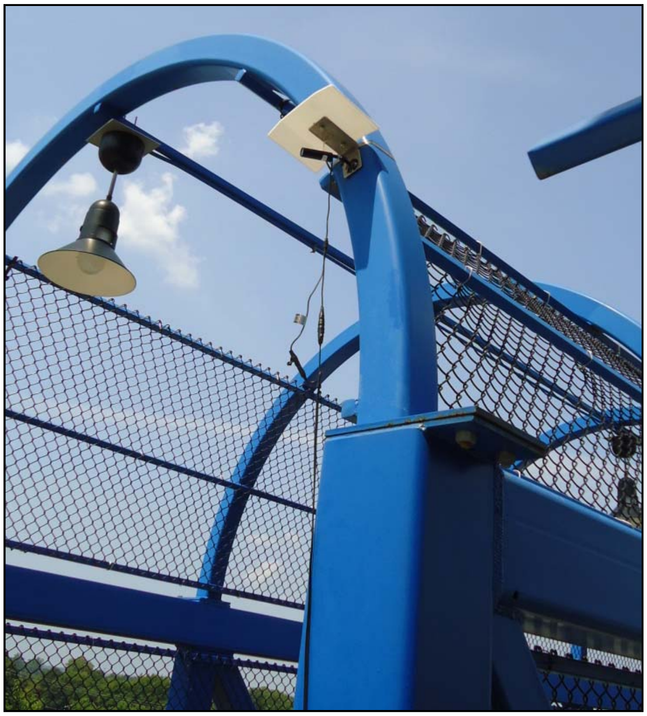

Figure 4.10. Camera mounted to the pedestrian bridge for the light rail station near the intersection of South Blvd. and Sharon Rd. W. in Charlotte, NC.

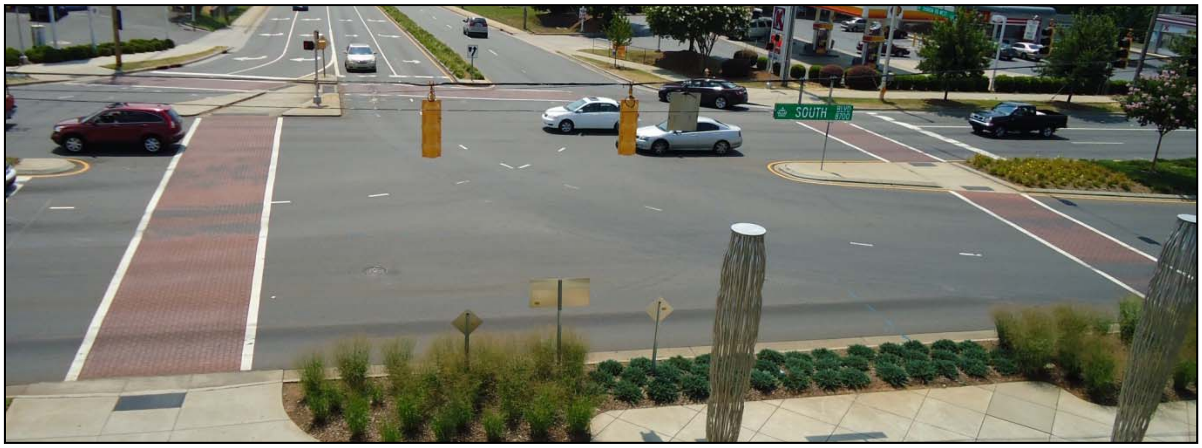

Figure 4.11. View of crosswalks from mounted camera height at the intersection of South Blvd. and Sharon Rd. W. in Charlotte, NC.

Site 4, NC 54 (Raleigh Rd.) and Rogerson Dr., had characteristics that best replicated a superstreet: signalization including pedestrian facilities, channelized left turn from an arterial, and a two stage crossing for the pedestrian with a path in the median to allow for a staggered crossing path similar to the diagonal crossing option of the superstreet. Due to the large footprint of this intersection and that the major street crossings were offset, two video cameras were mounted to produce the optimal views of all four crosswalks observed (Figure 4.12 and Figure 4.13).

Figure 4.12. Looking west along NC 54 (Raleigh Rd.) at Rogerson Dr. in Chapel Hill, NC from the base of the pole chosen to mount one of two cameras.

Figure 4.13. Looking east along NC 54 (Raleigh Rd.) at Rogerson Dr. in Chapel Hill, NC from the base of the pole chosen to mount the second camera.

Site 5, Wilkinson Blvd. at Ashley Rd. in Charlotte, NC, was chosen for high pedestrian and bicycle usage. Due to the camera placement on one of the few approved poles at this location, only two of the crosswalks were observed (Figure 4.14). These two crosswalks were located on the minor street, Ashley Rd.

Figure 4.14. View of crosswalks from the base of the pole at the intersection of Wilkinson Blvd. and Ashley Rd. in Charlotte, NC.

Site 6, W. Morgan St. at Fayetteville St. in Raleigh, NC, was chosen for the high pedestrian and bicycle activity at the intersection but also due to the one-way streets, which simulate a superstreet (Figure 4.15).

Figure 4.15. View of crosswalks from the base of the pole at the intersection of W. Morgan St. and Fayetteville St. in Raleigh, NC.

Site 7, S. Salisbury St. at W. Cabarrus St. in Raleigh, NC, was chosen for similar reasons as Site 6: high pedestrian and bicyclist activity and one-way streets. Due to limited allowable pole placement of the camera, only two of the three crosswalks were visible (Figure 4.16).

Figure 4.16. View of crosswalks from the base of the pole at the intersection of S. Salisbury St. and W. Cabarrus St. in Raleigh, NC.

4.3.2 Data Extraction

After the video cameras were removed, the data from the recordings were viewed manually and logged into a spreadsheet. The data were then summarized and formatted to be inserted into the VISSIM models. The user types that were used for the VISSIM models included walking pedestrians, running pedestrians and bicyclists on the main street. Observations were low for pedestrians using electronic devices and manual wheelchairs and thus were disregarded from input into the VISSIM models. Furthermore, the speeds that were produced from these two pedestrian users were within the range of speeds for the walking and running pedestrians. Additionally, the bicycle speeds used for simulation included only the main street bicycle speeds; the bicycles traveling on the crosswalks were considered walking pedestrians during simulation. Table 4.14 summarizes these findings with three speeds, average, 25th percentile and 75th percentile. Furthermore, Figure 4.17, Figure 4.18, and Figure 4.19 display the histograms for walking pedestrians, running pedestrians, and bicyclists, respectively.

Table 4.14. Summary of pedestrian and bicycle speeds inserted into VISSIM.

Type	Number of Observations	Average (fps)	Standard Deviation (fps)	25th Percentile (fps)	75th Percentile (fps)
Pedestrian (walk)	1277 (91%)	5.0	1.1	4.3	5.5
Pedestrian (runner)	121 (9%)	9.6	1.8	8.4	11.0
Bicyclist	118	15.6	4.9	12.0	18.9

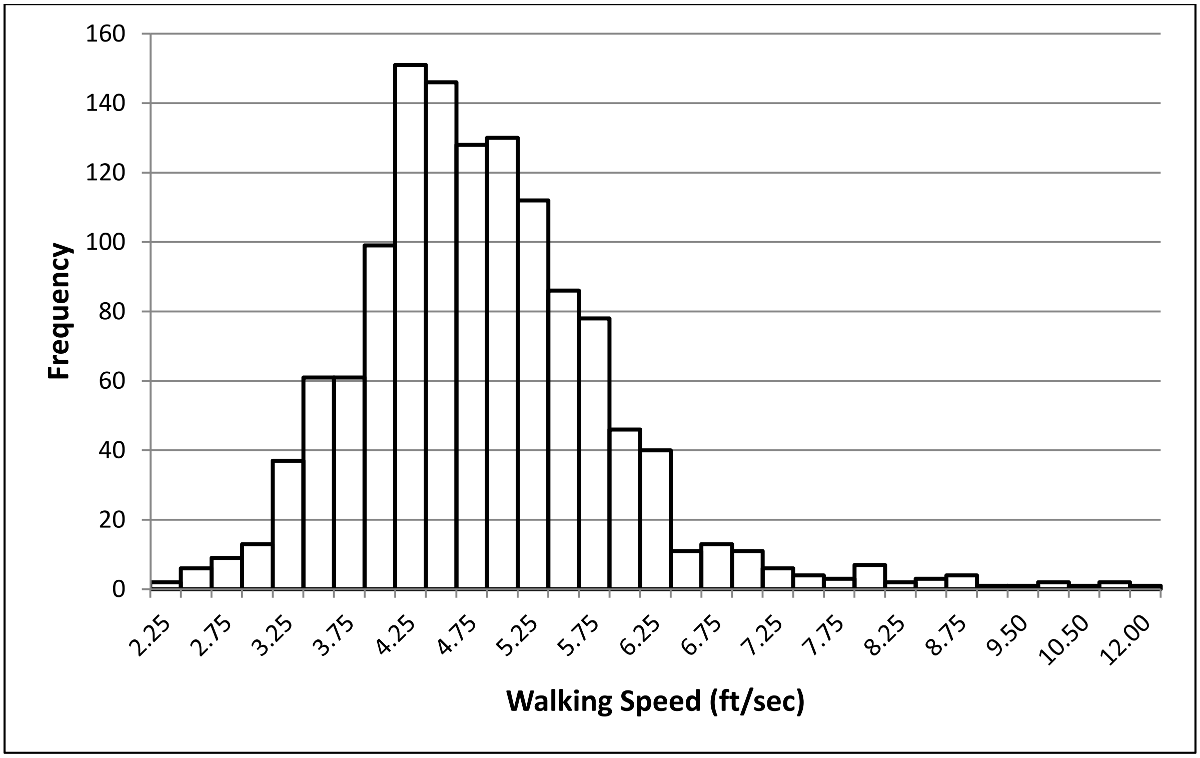

Figure 4.17. Histogram of walking pedestrian speeds.

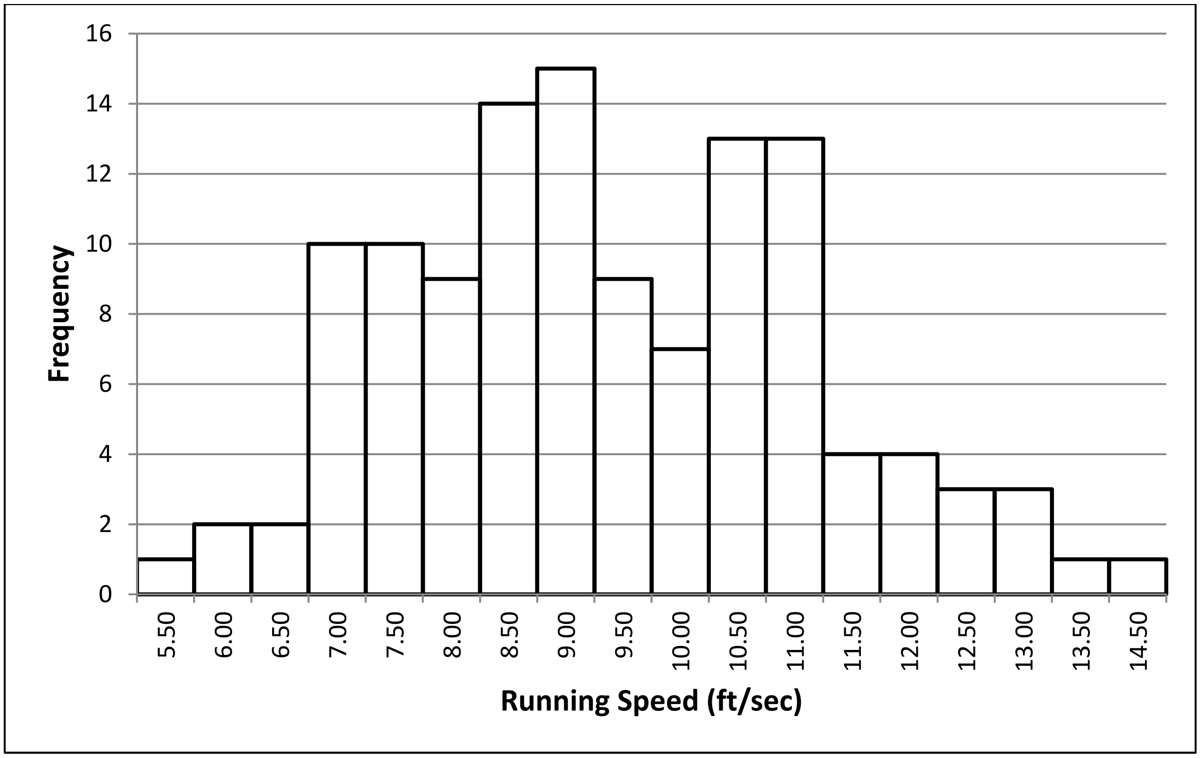

Figure 4.18. Histogram of running pedestrian speeds.

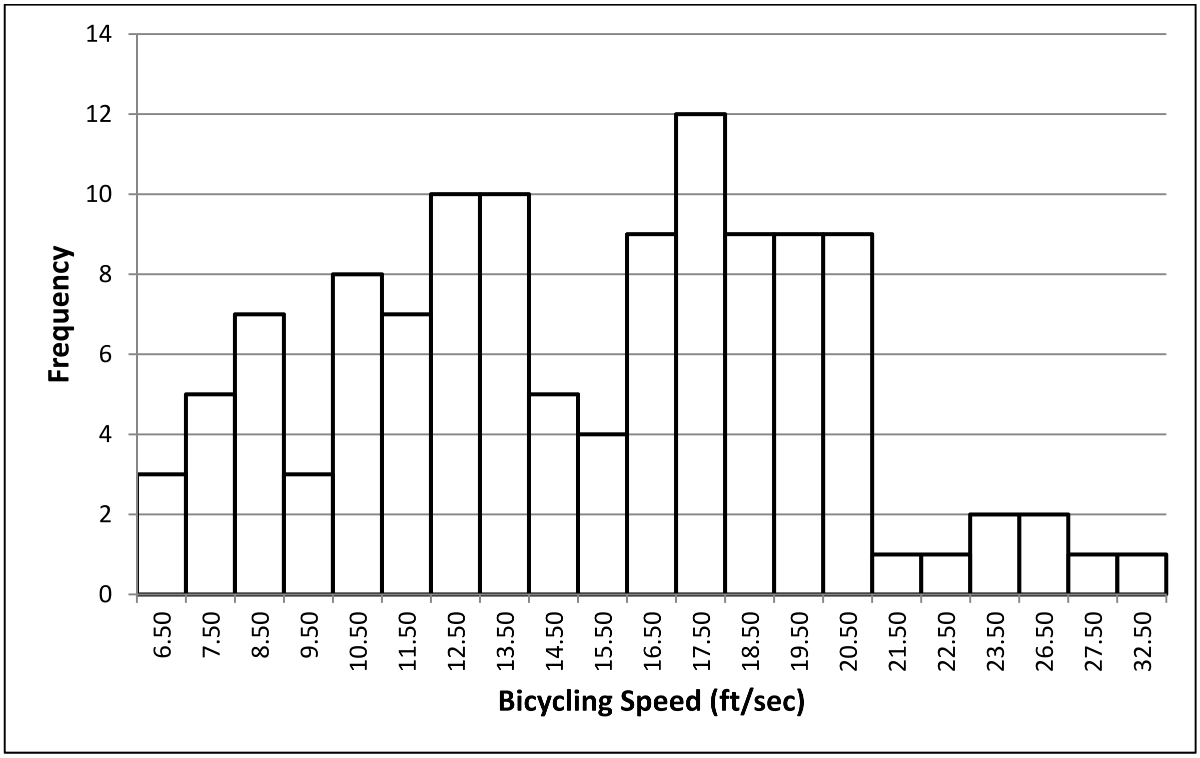

Figure 4.19. Histogram of bicycle speeds.

The speeds were inserted into the VISSIM models as speed distributions as shown in Figure 4.20, Figure 4.21, and Figure 4.22. Furthermore, the observed speeds were compared to a normal speed distribution using the Chi-Square test. The statistical results are shown in Table 4.15. The Chi-Square test resulted in a failed hypothesis for the walking pedestrian speeds and the bicycling speeds. The hypothesis for the Chi-Square test assumed that the observed speeds were similar to a normal distribution of speeds. However, upon further inspection of the walking speeds in Figure 4.20 and the bicycling speeds in Figure 4.22, the observed speeds follow the normal distribution with small differences and a few outlying data points.

Table 4.15. Summary of Chi-Square test results.

	Chi-Square Test Results		
	Walking Pedestrians	Running Pedestrians	Bicyclists
Degrees of Freedom:	25	15	13
α:	0.05	0.05	0.05
$\chi^2_{calc} =$	374.4	16.04	26.36
$\chi^2_{table} =$	37.65	25	22.36
Pass/Fail:	Fail	Pass	Fail

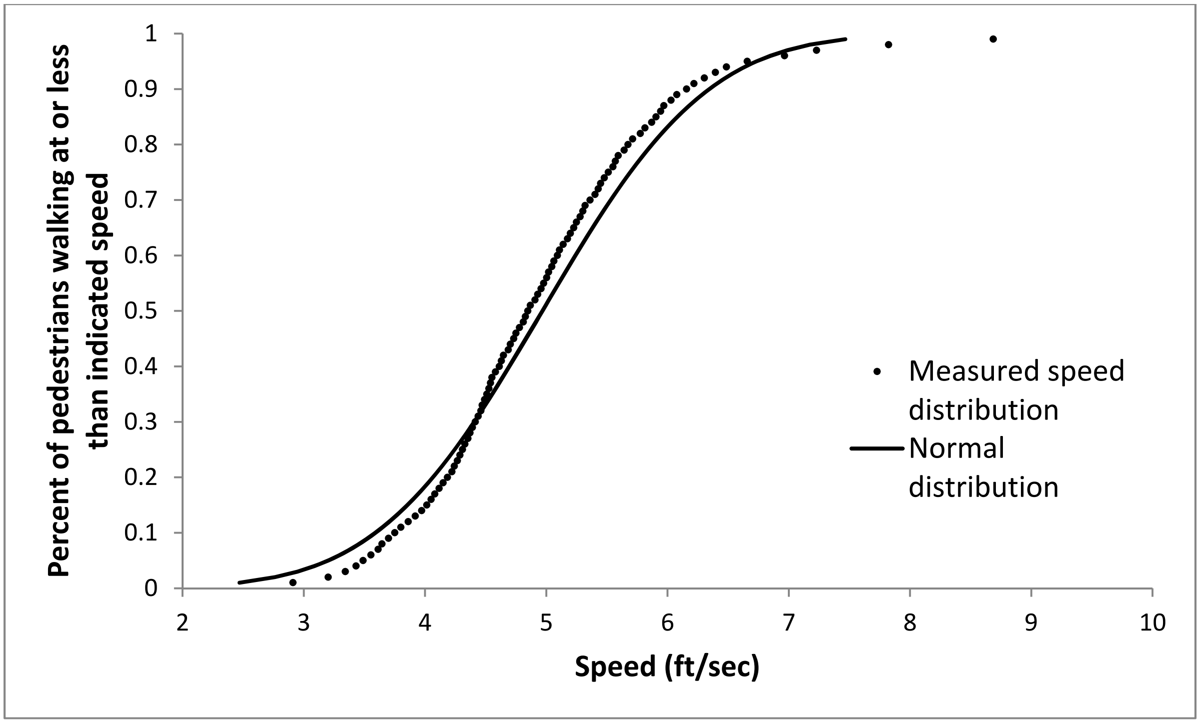

Figure 4.20. Measured speed distribution of walking pedestrians.

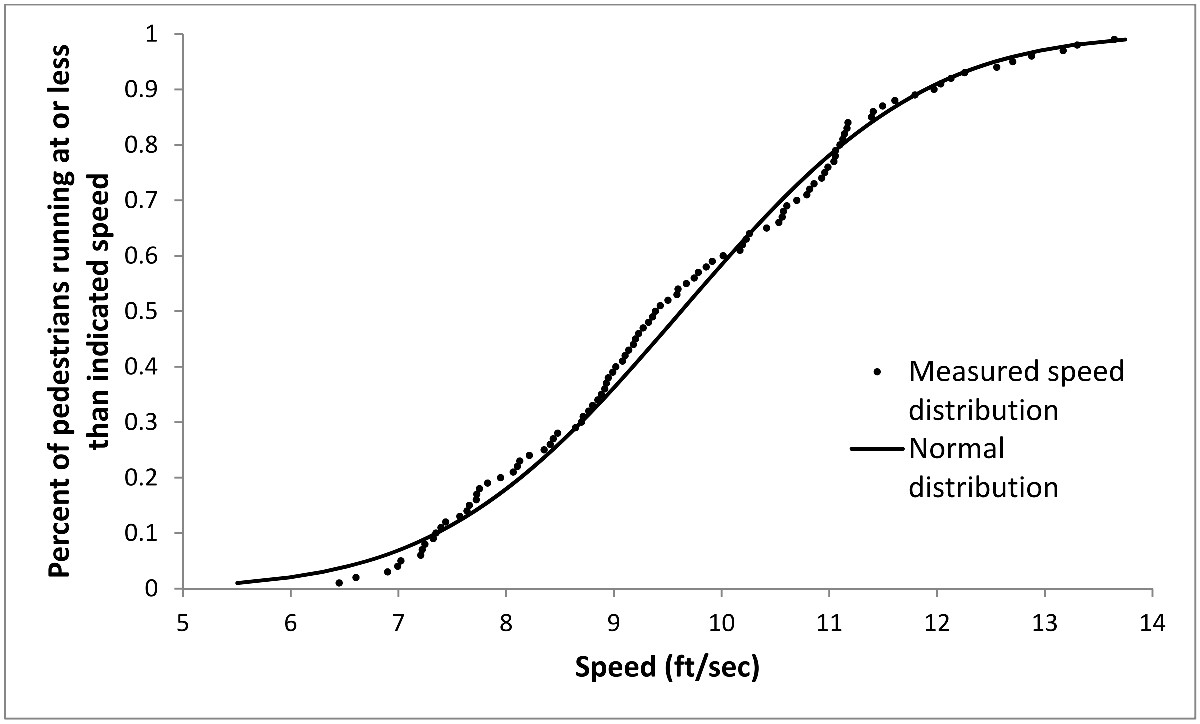

Figure 4.21. Measured speed distribution of running pedestrians.

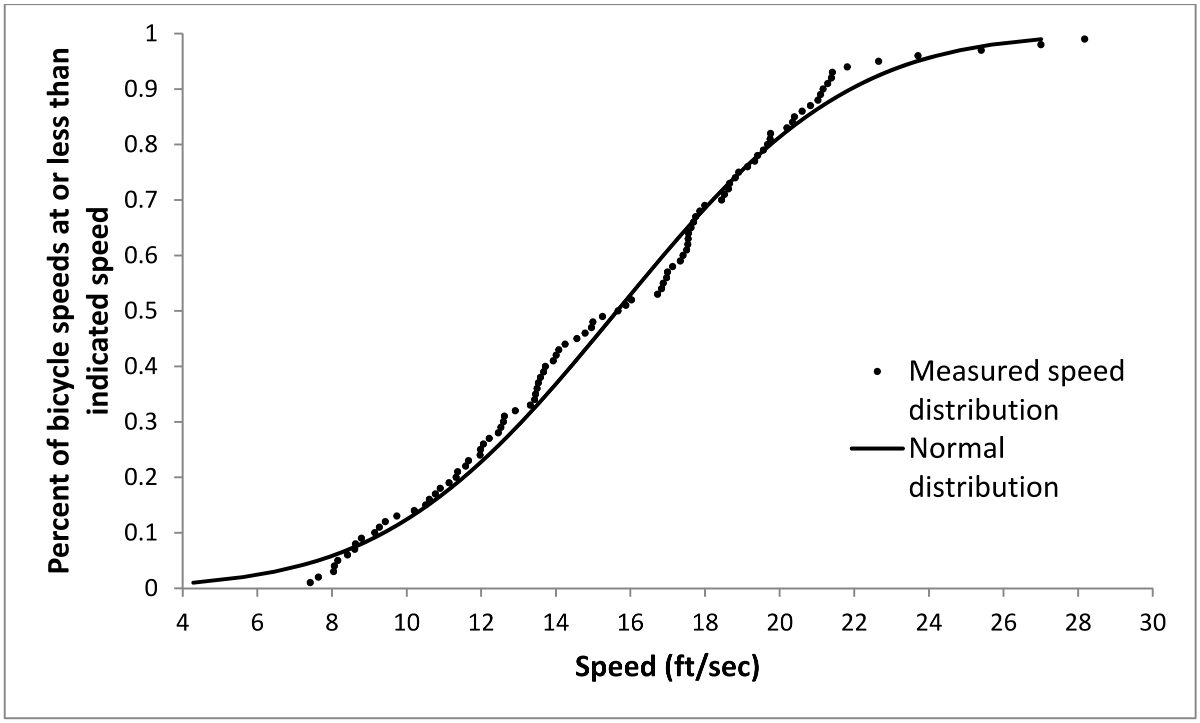

Figure 4.22. Measured speed distribution of bicyclists.

4.4 Simulations

Microscopic simulation of the pedestrian and bicycle crossing options was performed using PTV VISSIM software. The pedestrian crossings and the bicycle crossings were modeled separately. The following section will cover the setup of the VISSIM models and the simulations performed.

4.4.1 Base Model

The superstreet base model used was a modification of a currently modeled, calibrated, and validated superstreet corridor from previous research on the operation of superstreets (1). The corridor consists of five superstreets along US-17 in Leland, NC. The intersection chosen for this study is US-17 at Grandiflora/West Gate, which is situated in the middle of the corridor. The lane geometries and vehicle volumes for the modeled superstreet are shown in Table 4.16. However, the vehicle volumes inserted into this model have little to no effect on the results as the signals were pre-timed, and only the results of compliant pedestrians and bicyclists were analyzed.

Table 4.16. Superstreet lane geometry and hourly vehicle volumes.

	Approach	Left Lanes	Thru Lanes	Right Lanes	Channel Right	U-turn Lanes	Volumes (Vehicles per hour)
US-17	NB	1	2	0	1	2	1420
US-17	SB	1	2	0	1	2	1670
West Gate	WB	0	0	2	0	0	470
Grandiflora	EB	0	0	2	0	0	470

4.4.2 Pedestrian and Bicyclist Routes

The simulation models were constructed to produce three measures of effectiveness (MOEs) for both pedestrians and bicyclists. These included stopped delay per user, total number of stops per user, and total travel time per user. To compare the routes of all users among the various crossing options, 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 4.23. The lettered boxes labeled A through D represent the four quadrants, and the circled labels of A1, A2, B1, etc. represent the origin and destination points. For consistency across the models, the origin and destination points were located 800’ from the main intersection. The total number of routes produced from these origin and destination points is 48; in other words, each origin was routed to six different destinations. These destinations excluded the origin and the destination directly across the street from the origin. Table 4.17 displays all of the routes via origin and destination with the excluded paths marked in gray.

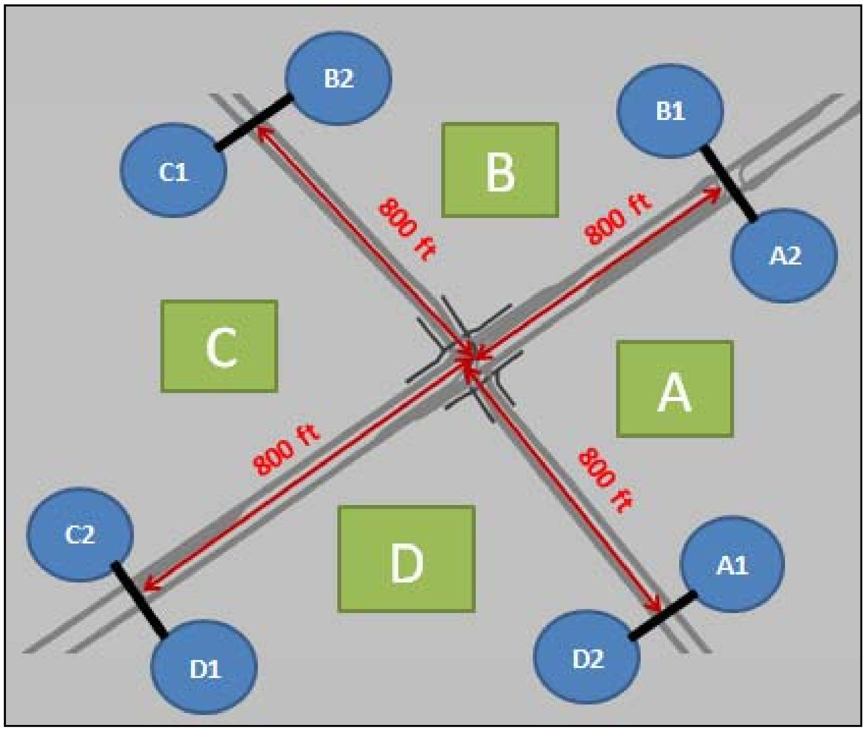

Figure 4.23. Origin and destination labels for model routes.

Table 4.17. Displaying the 48 routes with the excluded routes shown in gray.

Origin/ Destination	A1	A2	B1	B2	C1	C2	D1	D2
A1	■							■
A2		■	■					
B1		■	■					
B2				■	■			
C1				■	■			
C2						■	■	
D1						■	■	
D2	■							■

4.4.3 Pedestrian and Bicyclist Model Construction

To best model the interaction of pedestrians and bicyclists with motor vehicles, the pedestrians and bicyclists were modeled in the motor vehicle simulation portion of VISSIM rather than the pedestrian simulation. For the pedestrians, the vehicle type and vehicle model were both selected as *Pedestrian*. The vehicle type was then categorized into runners and walkers and the vehicle class within each vehicle type consisted of compliant and non-compliant.

The crosswalk geometry was constructed using links modeled as *Footpath*. This type of link allowed the pedestrians to freely overtake other pedestrians and not queue at a stop similar to vehicles. One lane in each direction was created for the crosswalks - each 6 feet wide - to allow overtaking, and the shortest allowable decision distances were selected.

For the bicyclists, the vehicle type and vehicle model were both selected as *Bicycle*. Since only compliant bicyclists traveling on the roadway were simulated, no additional categorization was needed.

4.4.3.1 User Compliance

To best mimic real conditions, the pedestrian users were modeled, as VISSIM allows, as a mix of four types: slow compliant pedestrians, fast compliant pedestrians, slow non-compliant pedestrians, and fast non-compliant pedestrians. Fast and slow pedestrians were defined in VISSIM by two different speed distributions as determined through the field data, one for walking pedestrians and another for running pedestrians. Compliant was defined in VISSIM as a pedestrian that waits for the Walk indication to cross even if a sufficient gap opens in the vehicle traffic stream; a non-compliant pedestrian does not wait for the Walk signal and uses the gap if sufficient. The non-compliance rate was determined to be 50% based on the data from a literature search shown in Table 4.18. The compliance data was not generated from the field data due to the complexity of a compliance study and time restraints for the field data portion of the research.

Table 4.18. Literature on Pedestrian Compliance.

Compliance	Location	Site Condition	Citation
70%	Beijing, China - Site 1	Unknown	(46)
57%	Beijing, China - Site 2	Unknown	(46)
85%	Columbus, Ohio	Signalized Midblock	(47)
47%	Small town in UK	Push Button Compliance	(48)
27%	London, UK	Push Button Compliance	(48)
18%	Toulouse, France	Push Button Compliance	(49)
71%	Lansing, MI	Divided boulevard bordering Michigan state and Lansing Central Business District	(7)
88%	North of France	Urban intersection – 50 km/h (31 mph)	(50)
74%	Brisbane, Australia	Central Business District	(51)
47%	Lake Buena Vista, Fl	Countdown Signal: Divided boulevard – 40 mph	(52)
59%	Lake Buena Vista, Fl	Control Site: Divided boulevard – 40 mph	(52)

4.4.3.2 Pedestrian and Bicycle Volumes and Speeds

The volumes entered were 600 pedestrians per hour and 600 bicycles per hour. The hourly volumes were divided evenly among the eight origin points shown in Figure 4.23, to produce 75 pedestrians per hour per origin and 75 bicycles per hour per origin. The volumes for pedestrians and bicyclists were chosen to ensure that each route was populated during the analysis period. Furthermore, since the signal timing was fixed in the model, the volume of pedestrians and bicyclists was an arbitrary value and would not impact the results. Additionally, the speeds for the pedestrians and bicyclists were inserted into VISSIM as a speed distribution as shown previously in Figure 4.20 through Figure 4.22.

4.4.3.3 Variables for Simulation Models

The simulation models for both the pedestrian and bicycle crossing options were set up using various input variables. The combination of these variables produced multiple scenarios that were each analyzed by the MOEs listed previously.

Two cycle lengths were considered for all the superstreets in the corridor, 90 seconds and 180 seconds. These cycle lengths were chosen as the minimum and maximum cycle lengths applied to superstreets in the field. Additionally, two signal splits were considered for the entire network, 80/20 and 60/40. Again, a minimum and maximum value was chosen for the signal splits based on the function of a superstreet in the field. Also, the progression of the vehicles in the network was adjusted to either have the vehicle platoons arrive simultaneously at the intersection being analyzed or arrive at various offset times. To accommodate the offset platoons, the northbound vehicles were given a cycle length of either 90 seconds or 180 seconds at each intersection while the southbound vehicles were given a cycle length of 81 seconds or 171 seconds at each intersection. This offset of cycle lengths produced platoons arriving sporadically at the intersection being analyzed throughout an hour of simulation. Furthermore, the U-turns which also included the midblock crossings at the intersection being analyzed were set at either 600 feet or 800 feet from the main intersection. All of the variables listed produced 16 different possible scenarios per crossing geometry, as detailed in Table 4.19.

Table 4.19. VISSIM model combinations based on variable inputs.

Variable Combination	Signal Splits	Cycle Length	U-Turn/Midblock Distance	Signal Offset Design
Scenario_1	60/40	180 sec	600 ft	Offset
Scenario_2	75/25			
Scenario_3	60/40	90 sec		
Scenario_4	75/25			
Scenario_5	60/40	180 sec	800 ft	
Scenario_6	75/25			
Scenario_7	60/40	90 sec		
Scenario_8	75/25			
Scenario_9	60/40	180 sec	600 ft	Simultaneous
Scenario_10	75/25			
Scenario_11	60/40	90 sec		
Scenario_12	75/25			
Scenario_13	60/40	180 sec	800 ft	
Scenario_14	75/25			
Scenario_15	60/40	90 sec		
Scenario_16	75/25			

4.4.4 Results Hypotheses

Prior to analysis of the results from simulation, several predictions were made about the pedestrian and bicyclist crossing geometries. First, for the pedestrians, the diagonal cross was predicted to result in the shortest travel time with least delay and stops for pedestrian movements from the southwest to northeast quadrants. However, the geometry with an overall performance of low travel time and minimal stops and delay was predicted to be the two-stage Barnes Dance cross. The median cross offers a direct cross and is symmetrical, but the conflict with the traffic signals may incur delay.

The bicycle option that was predicted to perform better than the others was the bicycle direct cross. This movement, compared to the others, has the shortest distance for crossing the two major streets, however, the signal conflicts with the major street left turn may increase the delay. The next best crossing is predicted to be the bicycle U-turn crossing as this crossing would allow for bicyclists to flow with the motor vehicles through the superstreet with the advantage of a shorter distance to the bicycle only U-turn compared to the vehicle U-turn.

4.4.5 Results Analysis with ANOVA Post Hoc Tukey

The simulation run time was 1 hour and each simulation run was carried over 10 replications. All 10 runs for each route (48 total routes), type of user (pedestrian and bicyclist), and MOE was organized before analysis. The data were analyzed using Analysis of Variance (ANOVA) with the Post Hoc Tukey test. This analysis test was chosen to examine the differences in mean values for multiple populations (53). Two-way interactions were analyzed between all the geometries and variables outlined in Table 4.19 for each MOE, this allowed for direct comparisons between two different geometries for each variable. Adjusted p-values were computed during this analysis, and the level of significance for the main effects and two-way interactions was set at an adjusted p-value < 0.05. The following section presents these findings.

5.0 RESULTS

The following sections describe the results of the VISSIM simulation runs and the ANOVA and Post Hoc Tukey analyses. Section 5.1 details the compliant pedestrian results and section 5.2 discusses the non-compliant pedestrian results.

5.1 Compliant Pedestrian Crossing Results

As a point of reference for the results to be presented in the following section, Table 5.1 shows base values for travel time and number of stops per pedestrian for all geometries. All values shown are averaged over all routes as described in section 4.4.1. The free flow travel time was computed based on an average of all routes modeled and using one average pedestrian speed of 5.4 feet per second. This value is a weighted average speed of the walking and running pedestrians from Table 4.14. The number of stops per pedestrian is displayed as a range based on the average number of stops per the 16 simulated models from Table 4.19.

Table 5.1. Free flow travel time and minimum and maximum number of stops per pedestrian crossing geometry.

Geometry	**Free flow travel time (sec)**	**Minimum Average Number of Stops per Pedestrian**	**Maximum Average Number of Stops per Pedestrian**
Barnes Dance Cross	320	1.2	1.4
Diagonal Cross	333	1.7	2
Median Cross	327	1.7	2.1
Midblock Cross	360	1.3	1.6

The mean and standard deviation of the stopped delay time in seconds for each pedestrian crossing type is shown in Table 5.2. Box plots for the pedestrian crossing geometries on the stopped delay measure are displayed in Figure 5.1 and the results of the ANOVA with Post Hoc Tukey results are displayed in Table 5.3. In addition to the mean and standard deviation, Table 5.2 also displays the correlation value for the data. When the correlation value is near 1.0, then the data are related linearly. Alternately, if the correlation value is near zero then the data are not related linearly (54). Note that the coefficient of determination (r^2) is not used in the following tables as the data are not always linear.

On the box plots, the upper line of the box shows the upper 25% of the data, the bold center line of the box displays the 50% value, and the lower line of the box shows the lower 25% of the data. The circles in the box plots represent outlying data points (55). Additionally, the value shown in the 100% column of Table 5.2 is the largest outlier shown in Figure 5.1. In Table 5.3, the differences between the means of the geometries are shown in one column and the following columns show the minimum and maximum of all the values per geometry subtracted from the other. Also, the adjusted p-values are shown in the last column.

Table 5.2. Results for stopped delay per pedestrian crossing geometry.

Delay (sec)									
Geometry	Mean	sd	cv	0%	25%	50%	75%	100%	data:n
Two-stage Barnes Dance cross	92.1	85.0	0.9230	0	16.0	76.8	137.9	506.7	7680
Diagonal cross	119.6	111.1	0.9289	0	30.2	97.1	163.7	478.6	7680
Median cross	146.9	123.3	0.8393	0	38.8	126.9	235.5	476.0	7680
Midblock cross	110.6	101.3	0.9155	0	25.4	92.5	162.0	497.6	7680
sd: standard deviation		*cv: correlation value (R)*					*n: no. of data points (runs)*		

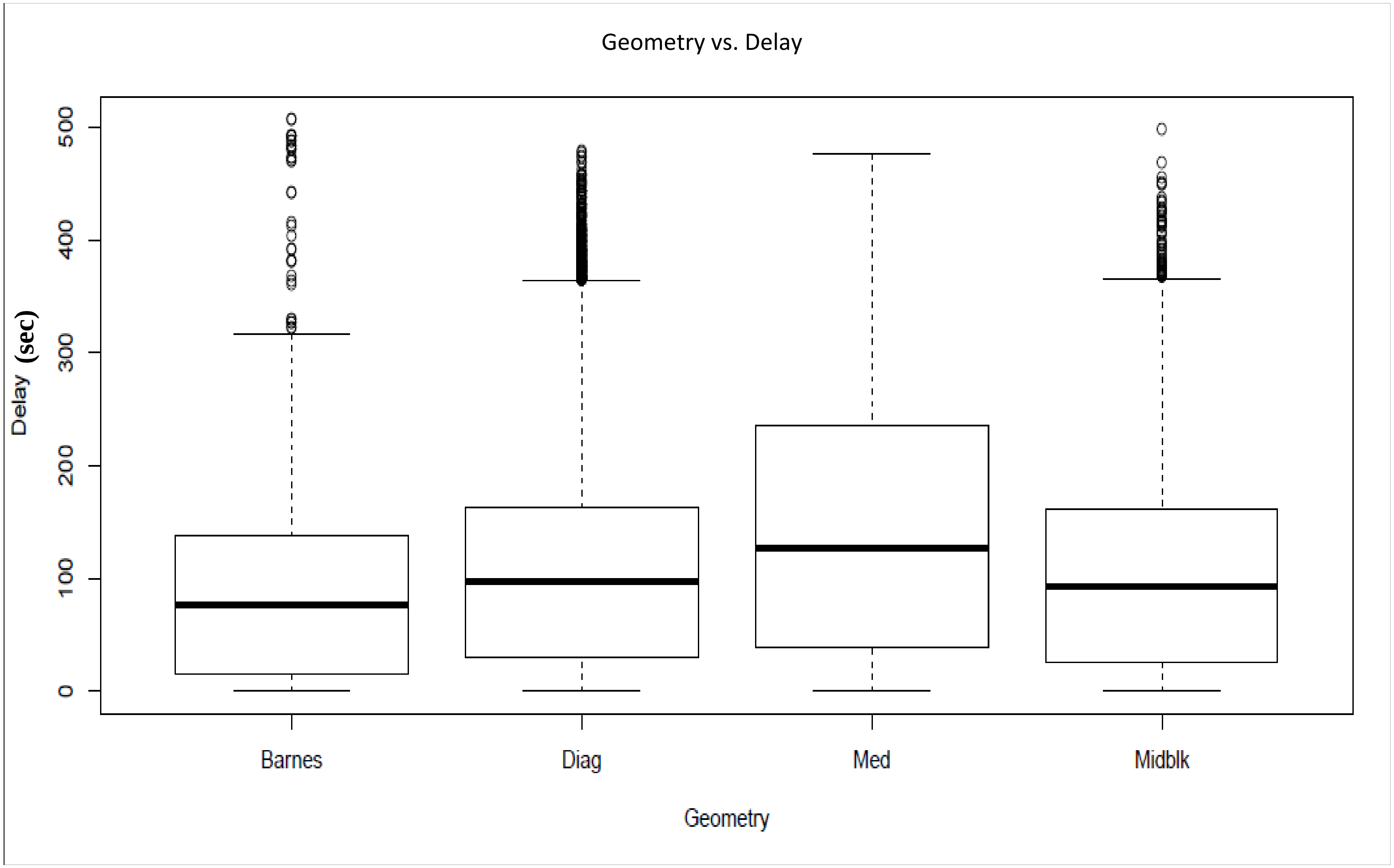

Figure 5.1. Box plots for delay per pedestrian crossing geometry.

Table 5.3. ANOVA with Post Hoc Tukey results for pedestrian stopped delay per crossing geometry.

Delay (sec)		lwr	upr	p-adj
Geometry – Geometry	diff			
Diagonal – two-stage Barnes Dance	+27.5	23.1	31.9	0.00E+00
Median – two-stage Barnes Dance	+54.8	50.4	59.2	0.00E+00
Midblock – two-stage Barnes Dance	+18.5	14.1	22.9	0.00E+00
Median – Diagonal	+27.3	22.9	31.7	0.00E+00
Midblock –Diagonal	-8.9	-13.3	-4.5	1.10E-06
Midblock –Median	-36.2	-40.6	-31.8	0.00E+00
diff: difference in mean values	*lwr: minimum difference in values*		*upr: maximum difference in values*	
	Df	Sum Sq	Mean Sq	F value
Geometry	3	11976274	3992091	354.7
Residuals	30716	345703870	11255	

The adjusted p-value indicates a significant difference between the stopped delay results for the geometries. From the mean stopped delay, the two-stage Barnes Dance cross has the lowest value with 92.1 seconds per pedestrian while the median cross produced the largest stopped delay with 146.9 seconds.

The number of stops per pedestrian geometry is shown in the following tables and figure. Table 5.4 displays the mean and standard deviation for stops per geometry and Figure 5.2 and Table 5.5 show the ANOVA with Post Hoc Tukey results for pedestrian stops.

Table 5.4. Results for total number of stops per pedestrian crossing geometry.

Stops									
Geometry	mean	sd	cv	0%	25%	50%	75%	100%	data:n
Two-stage Barnes Dance cross	1.3	0.8	0.61	0	0.8	1.8	2.0	4.6	7680
Diagonal cross	1.8	1.3	0.74	0	0.9	2.0	3.0	4.0	7680
Median cross	1.9	1.2	0.62	0	1.0	2.7	3.0	3.0	7680
Midblock cross	1.5	1.0	0.70	0	0.8	1.6	2.5	3.0	7680
sd: standard deviation		*cv: correlation value (R)*					*n: no. of data points (runs)*		

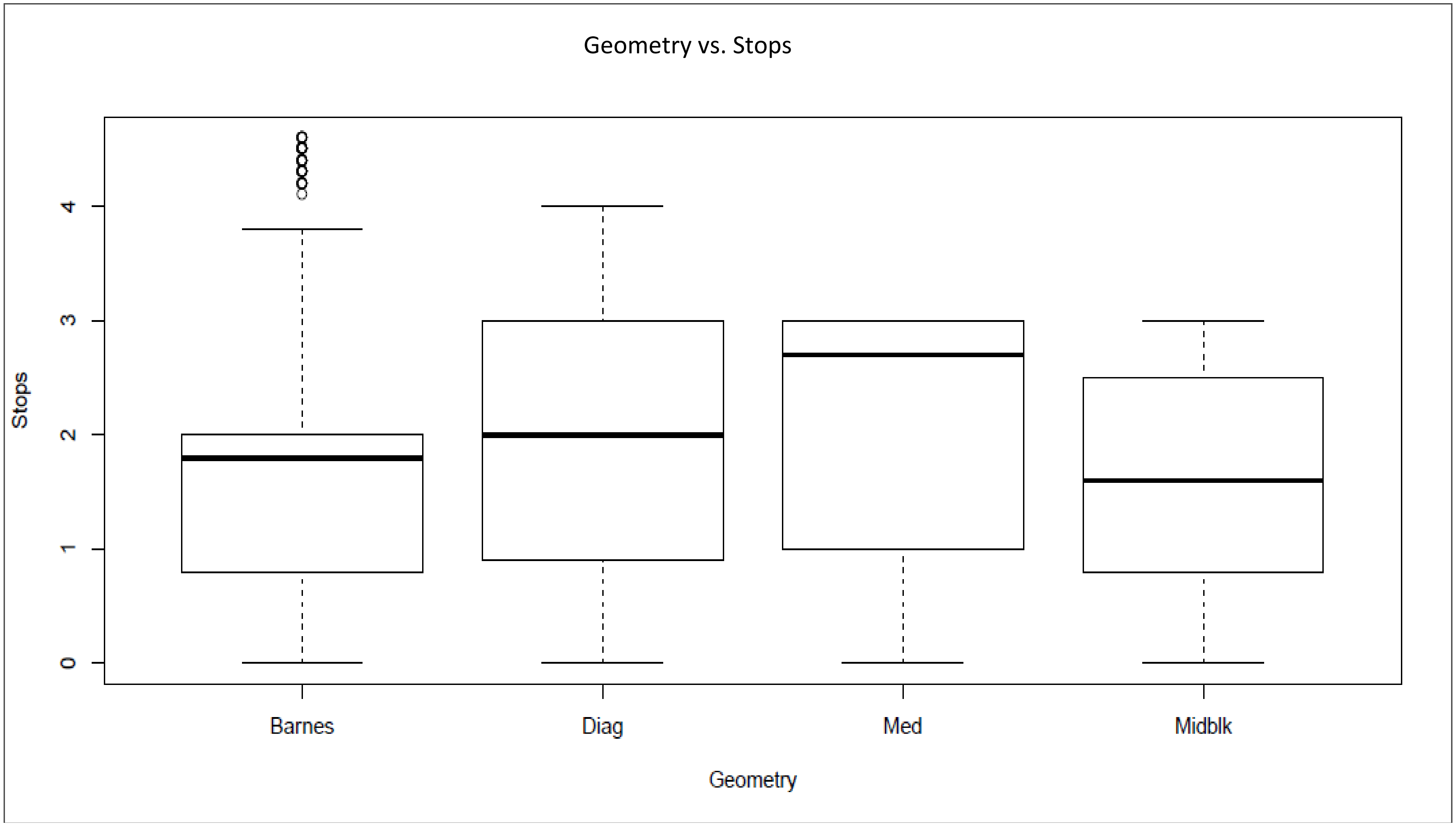

Figure 5.2. Box plots for stops per pedestrian crossing geometry.

Table 5.5. ANOVA with Post Hoc Tukey results for pedestrian stops per crossing geometry.

Stops				
Geometry – Geometry	diff	lwr	upr	p-adj
Diagonal – two-stage Barnes Dance	0.50	0.46	0.55	0.00E+00
Median –two-stage Barnes Dance	0.61	0.56	0.66	0.00E+00
Midblock – two-stage Barnes Dance	0.17	0.12	0.22	0.00E+00
Median – Diagonal	0.11	0.06	0.15	0.00E+00
Midblock –Diagonal	-0.33	-0.38	-0.29	0.00E+00
Midblock –Median	-0.44	-0.49	-0.39	0.00E+00
diff: difference in mean values	*lwr: min. difference in values*		*upr: max. difference in values*	
	Df	Sum Sq	Mean Sq	F value
Geometry	3	1863	620.9	497.2
Residuals	30716	38360	1.2	

The differences between each pair of pedestrian geometries on the total pedestrian stops measure were shown to be significant with each adjusted p-value < 0.05. The average number of stops was lowest for the two-stage Barnes Dance cross with 1.3 stops per pedestrian. The largest number of stops per pedestrian was found for the median cross with 1.9.

The results for pedestrian travel time for each crossing geometry are shown in Table 5.6, and the statistical test results are shown in Figure 5.3 and Table 5.7.

Table 5.6. Results for travel time per pedestrian crossing geometry.

Travel Time (sec)									
Geometry	Mean	sd	cv	0%	25%	50%	75%	100%	data:n
Two-stage Barnes Dance cross	422.1	146.5	0.3472	0	348	424.2	510.4	995.2	7680
Diagonal cross	464.9	177.6	0.3819	0	354.5	457.4	569.8	1221.2	7680
Median cross	486.9	180.9	0.3715	0	363.8	485.6	615.4	1107.3	7680
Midblock cross	478.9	217.3	0.4538	0	354.9	456.6	608.7	1357.4	7680
sd: standard deviation		*cv: correlation value (R)*				*n: no. of data points (runs)*			

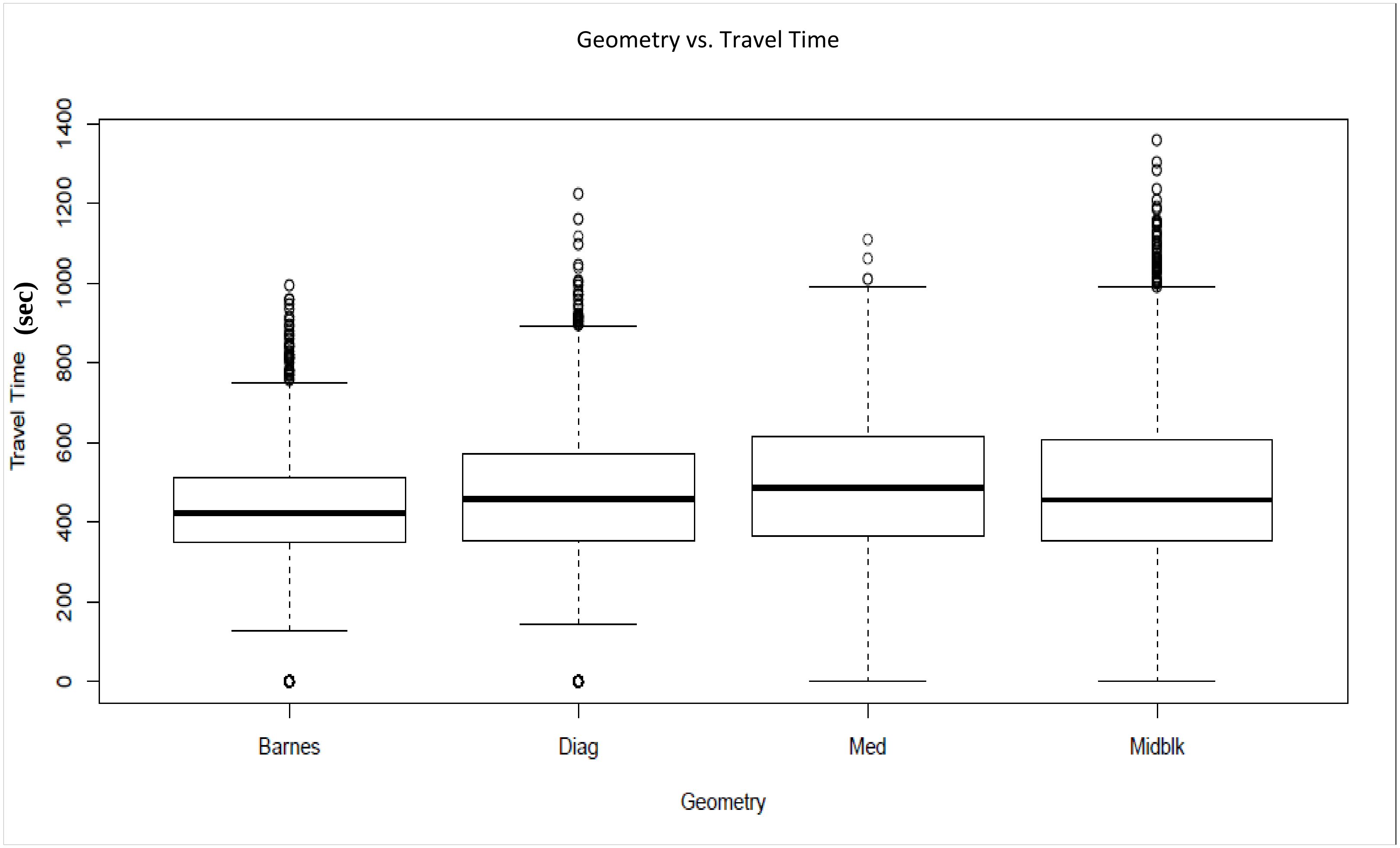

Figure 5.3. Box plots for travel time per pedestrian crossing geometry.

Table 5.7. ANOVA with Post Hoc Tukey results for pedestrian travel time per crossing geometry.

Travel Time (sec)				
Geometry vs. Geometry	diff	lwr	upr	p-adj
Diagonal – two-stage Barnes Dance	42.9	35.3	50.4	0.00E+00
Median – two-stage Barnes Dance	64.9	57.3	72.4	0.00E+00
Midblock – two-stage Barnes Dance	56.9	49.3	64.4	0.00E+00
Median – Diagonal	22.0	14.4	29.6	0.00E+00
Midblock - Diagonal	14.0	6.4	21.6	1.17E-05
Midblock - Median	-8.0	-15.6	-0.4	3.31E-02
diff: difference in mean values	*lwr: min. difference in values*		*upr: max. difference in values*	
	Df	Sum Sq	Mean Sq	F value
Geometry	3	1.92E+07	6412583	192.9
Residuals	30716	1.02E+09	33243	

All of the differences between the crossing geometries for pedestrian travel time are shown to be significant as Table 5.7 displays adjusted p-values below 0.05. The lowest average travel time occurred with the two-stage Barnes Dance cross at 422.1 seconds and the highest average travel time happened during the median cross with 486.9 seconds.

A further focus on the travel time results was done to determine the factors that affect overall travel time. As outlined in a previous section, the factors included signal design of either simultaneous or offset, cycle length of either 90 seconds or 180 seconds, signal splits of either 60/40 or 75/25, and midblock distance of either 600 feet or 800 feet. The results of the comparison between the pedestrian crossing geometries and signal design are shown in Table 5.8. The statistical test results are displayed in Figure 5.4 and Table 5.9. The average travel time per each of the geometries is shown to be less for offset signal designs, when the vehicular platoons arrive at the intersection at varying times, rather than simultaneous platoon arrivals. Offset arrivals made a greater difference with the two-stage Barnes Dance and the diagonal cross than the median or midblock cross. The statistical tests for these interactions are shown to be significant amongst each of the geometries with an adjusted p-value < 0.05.

Table 5.8. Travel time data for pedestrian crossing geometries based on signal offset design.

Geometry:Signal	mean	sd	Cv	0%	25%	50%	75%	100%	data:n
Barnes Offset	404.0	134.8	0.3337	0	343.4	411.3	483.8	957	3840
Barnes Simultaneous	440.2	155.3	0.3528	0	353.9	439.1	553.3	995.2	3840
Diag Offset	448.7	166.5	0.3711	0	351.5	446.8	546.6	1157.8	3840
Diag Simultaneous	481.2	186.6	0.3878	0	359.3	470.7	599.3	1221.2	3840
Med Offset	477.0	169.9	0.3561	0	363.4	482.1	605.2	988.8	3840
Med Simultaneous	496.9	190.8	0.3840	0	364.0	490.2	636.4	1107.3	3840
Midblk Offset	472.3	213.9	0.4529	0	354.7	447.1	596.9	1357.4	3840
Midblk Simultaneous	485.5	220.6	0.4543	0	355.5	466.5	619.1	1357.3	3840
sd: standard deviation		*cv: correlation value (R)*					*n: no. of data points (runs)*		

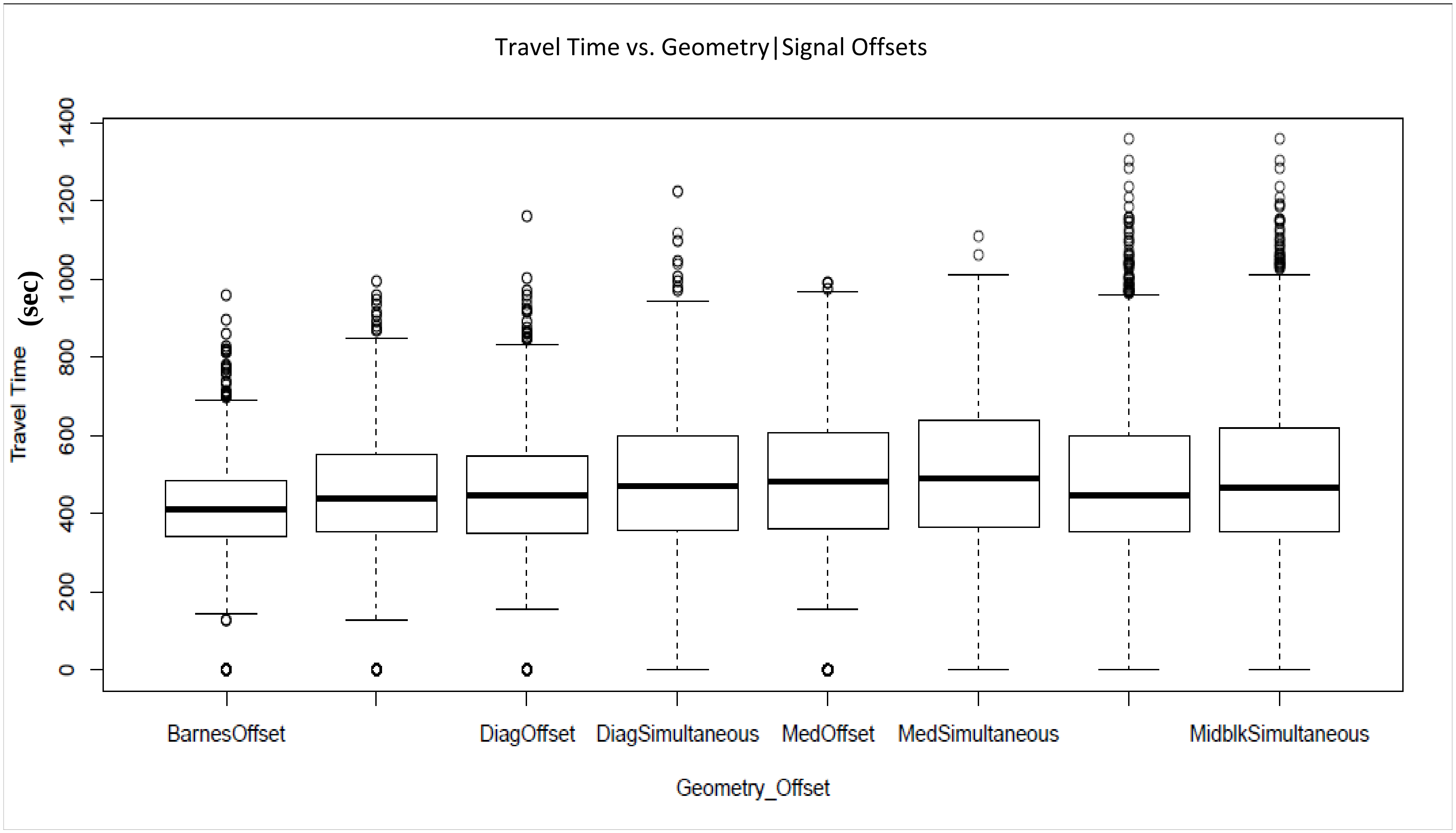

Figure 5.4. Box plots of the interaction between pedestrian crossing geometries and signal offsets for travel time.

Table 5.9. ANOVA with Post Hoc Tukey results for pedestrian travel time per crossing geometry and signal offset design.

Travel Time (sec)				
Geometry:Signal	diff	lwr	upr	p-adj
Barnes: Simultaneous-Barnes: Offset	36.2	23.7	48.8	0.00E+00
Diag: Simultaneous-Diag: Offset	32.5	19.9	45.1	0.00E+00
Med: Simultaneous-Med: Offset	19.9	7.3	32.5	4.50E-05
Midblk: Simultaneous-Midblk: Offset	13.2	0.6	25.8	3.21E-02
diff: difference in mean values	*lwr: min. difference in values*		*upr: max. difference in values*	
	Df	Sum Sq	Mean Sq	F value
geometry: signal	7	2.49E+07	3554202	107.5
Residuals	30712	1.02E+09	33064	

The results for the interactions between pedestrian crossing geometries and cycle lengths are displayed in Table 5.10, while the statistical analysis results are shown in Figure 5.5 and Table 5.11. Each of the geometries produces lower average travel time values when the cycle lengths are set at 90 seconds rather than 180 seconds; the change in cycle length made the least difference for the two-stage Barnes Dance. These results are shown to be significant as detailed in Table 5.11.

Table 5.10. Travel time data for pedestrian crossing geometries based on cycle length.

Travel Time (sec)									
Geometry: Cycle	Mean	Sd	cv	0%	25%	50%	75%	100%	data: n
Barnes180	458.3	158.7	0.3462	0	367.0	470.4	565.3	995.2	3840
Barnes90	385.9	123.1	0.3190	0	334.9	400.0	453.4	817	3840
Diag180	515.3	194.9	0.3783	0	376.7	520.5	662.2	1221.2	3840
Diag90	414.6	141.5	0.3412	0	340.8	430.5	498.8	1000.5	3840
Med180	542.6	197.6	0.3642	0	389.5	585.2	697.3	1107.3	3840
Med90	431.2	142.1	0.3296	0	354.3	455.6	521.3	934.8	3840
Midblk180	527.4	232.7	0.4413	0	378.1	523.6	681.7	1357.4	3840
Midblk90	430.5	188.8	0.4385	0	342.0	419.7	524.6	1183.4	3840

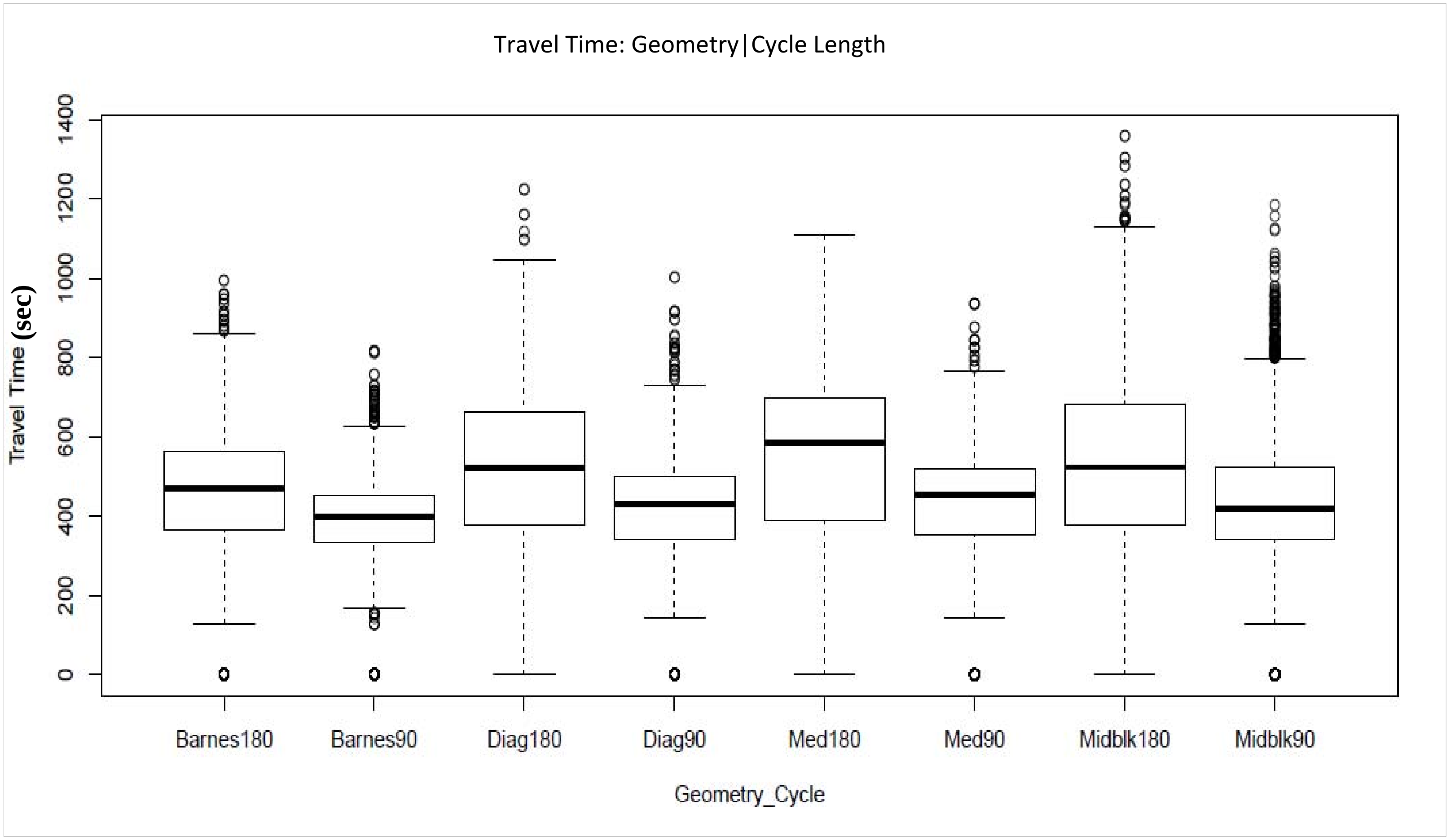

Figure 5.5. Box plots of the interaction between pedestrian crossing geometries and cycle lengths for travel time.

Table 5.11. ANOVA with Post Hoc Tukey results for pedestrian travel time per geometry and cycle length.

Travel Time (sec)				
Geometry:Cycle	diff	lwr	upr	p-adj
Barnes:180-Barnes:90	72.4	60.3	84.6	0.00E+00
Diag:180-Diag:90	100.7	88.5	112.8	0.00E+00
Med:180-Med:90	111.4	99.2	123.6	0.00E+00
Midblk:180-Midblk:90	96.8	84.7	109.0	0.00E+00
diff: difference in mean values	*lwr: min. difference in values*		*upr: max. difference in values*	
	Df	Sum Sq	Mean Sq	F value
geometry: factor(cycle)	7	90605584	12943655	418.6
Residuals	30712	949721820	30923	

The interactions between the pedestrian crossing geometries and signal splits reveal that the travel time decreases from a signal split of 75/25 to 60/40 for each of the geometries. The average travel time values are shown in Table 5.12 and the statistical analysis results are shown in Figure 5.6 and Table 5.13. Signal split made the most difference for the median cross and midblock cross.

Table 5.12. Travel time data for pedestrian crossing geometries and signal splits.

Travel Time (sec)									
Geometry: Split	Mean	sd	cv	0%	25%	50%	75%	100%	data:n
Barnes60/40	400.3	175.8	0.439	0	318	410.8	507.9	995.2	3840
Barnes75/25	443.9	105.3	0.237	190.5	368.2	433.9	513.8	766.5	3840
Diag60/40	438.2	204.4	0.466	0	322.1	439.1	566.6	1221	3840
Diag75/25	491.6	141.0	0.287	231.2	386.4	475.2	575.2	944.0	3840
Med60/40	447.3	197.2	0.441	0	327.2	453.9	575.3	1107	3840
Med75/25	526.6	153.0	0.291	231.2	411.8	515.9	647.1	900.4	3840
Midblk60/40	446.1	248.9	0.558	0	321.9	430.1	595.5	1357	3840
Midblk75/25	511.8	174.2	0.340	190	381.0	479.6	622.5	1189	3840

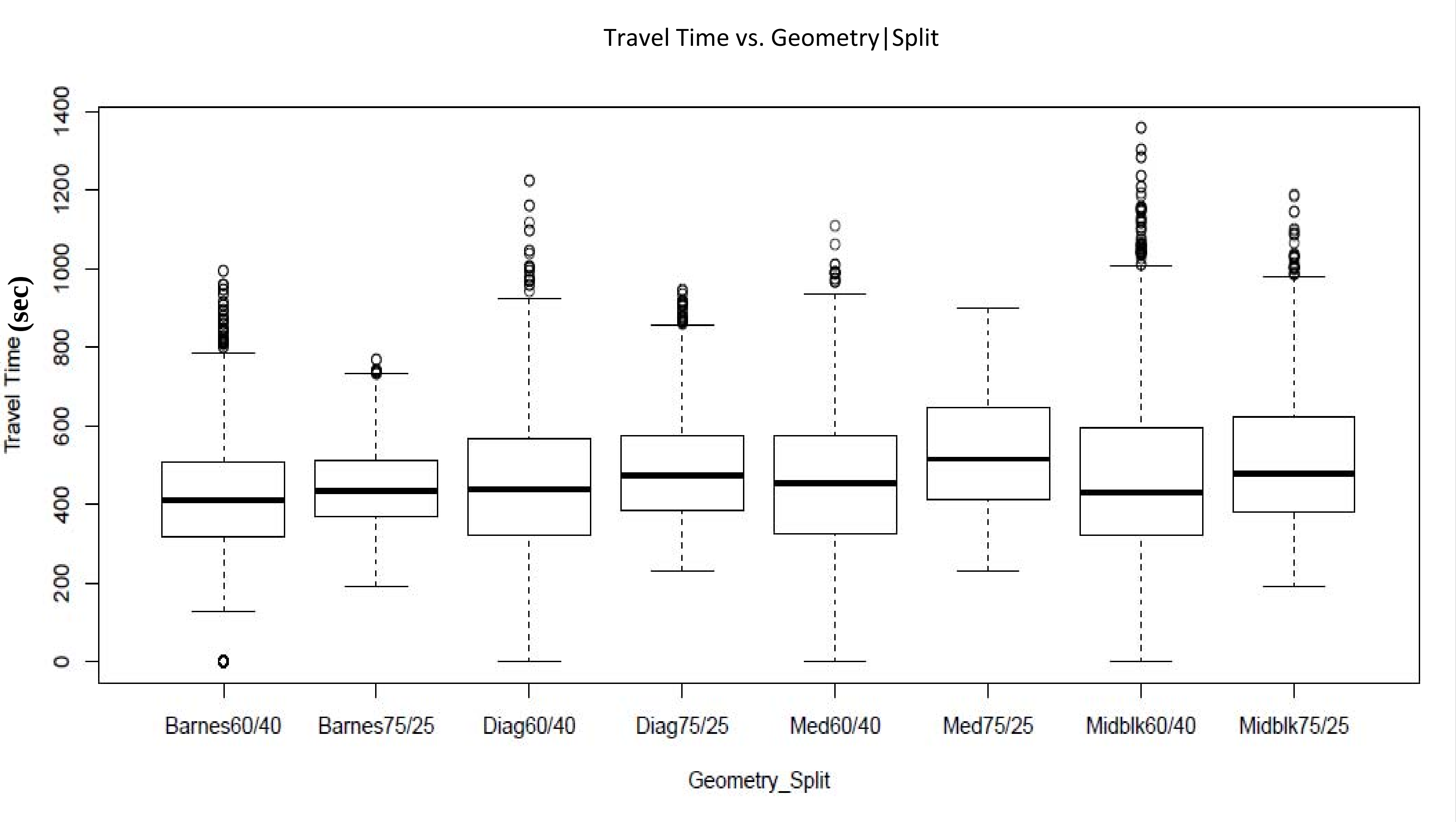

Figure 5.6. Box plots of the interaction between pedestrian crossing geometries and signal splits for travel time.

Table 5.13. ANOVA with Post Hoc Tukey results for pedestrian travel time per crossing geometry and signal splits.

Travel Time (sec)				
Geometry: Split	diff	lwr	upr	p-adj
Barnes:75/25-Barnes:60/40	43.6	31.2	56.0	0.00E+00
Diag:75/25-Diag:60/40	53.4	41.0	65.8	0.00E+00
Med:75/25-Med:60/40	79.4	66.9	91.8	0.00E+00
Midblk:75/25-Midblk:60/40	65.7	53.3	78.2	0.00E+00
diff: difference in mean values	*lwr: min. difference in values*		*upr: max. difference in values*	
	Df	Sum Sq	Mean Sq	F value
geometry: factor(split)	7	48747221	6963889	215.7
Residuals	30712	991580184	32286	

The final interaction analyzed for the pedestrian crossing geometries was for midblock distances. The mean values are shown in Table 5.14 and the statistical analysis results are shown in Figure 5.7 and Table 5.15. Of these comparisons, the only geometry with a significant difference between a midblock location of 600 ft compared to 800 ft was the median cross. The 600 ft distance produced lower average travel times at the median cross. The average travel time between the distances for the remaining three geometries was not statistically significant, as each had an adjusted p-value greater than 0.05. This result is as expected, as there was no reason to believe that distance to the crossover should make a difference for pedestrian crossing schemes focused at the central intersection.

Table 5.14. Travel time data for pedestrian crossing geometries and midblock distances.

Geometry:Midblock Distance

Travel Time (sec)	Mean	sd	cv	0%	25%	50%	75%	100%	data:n
Barnes600	422.2	146.6	0.347	0	348.3	423.9	510.6	995.2	3840
Barnes800	422.0	146.5	0.347	0	347.9	424.3	510.4	995.2	3840
Diag600	465.2	177.8	0.382	0	354.5	458.0	570.4	1221.2	3840
Diag800	464.7	177.3	0.382	0	354.5	457.2	569.5	1221.2	3840
Med600	474.0	176.2	0.372	0	358.8	474.8	591.0	988.8	3840
Med800	499.9	184.6	0.369	0	367.7	497.5	637.3	1107.3	3840
Midblk600	475.4	210.1	0.442	0	355.4	458.5	606.5	1236.5	3840
Midblk800	482.5	224.4	0.465	0	354.7	454.3	610.9	1357.4	3840

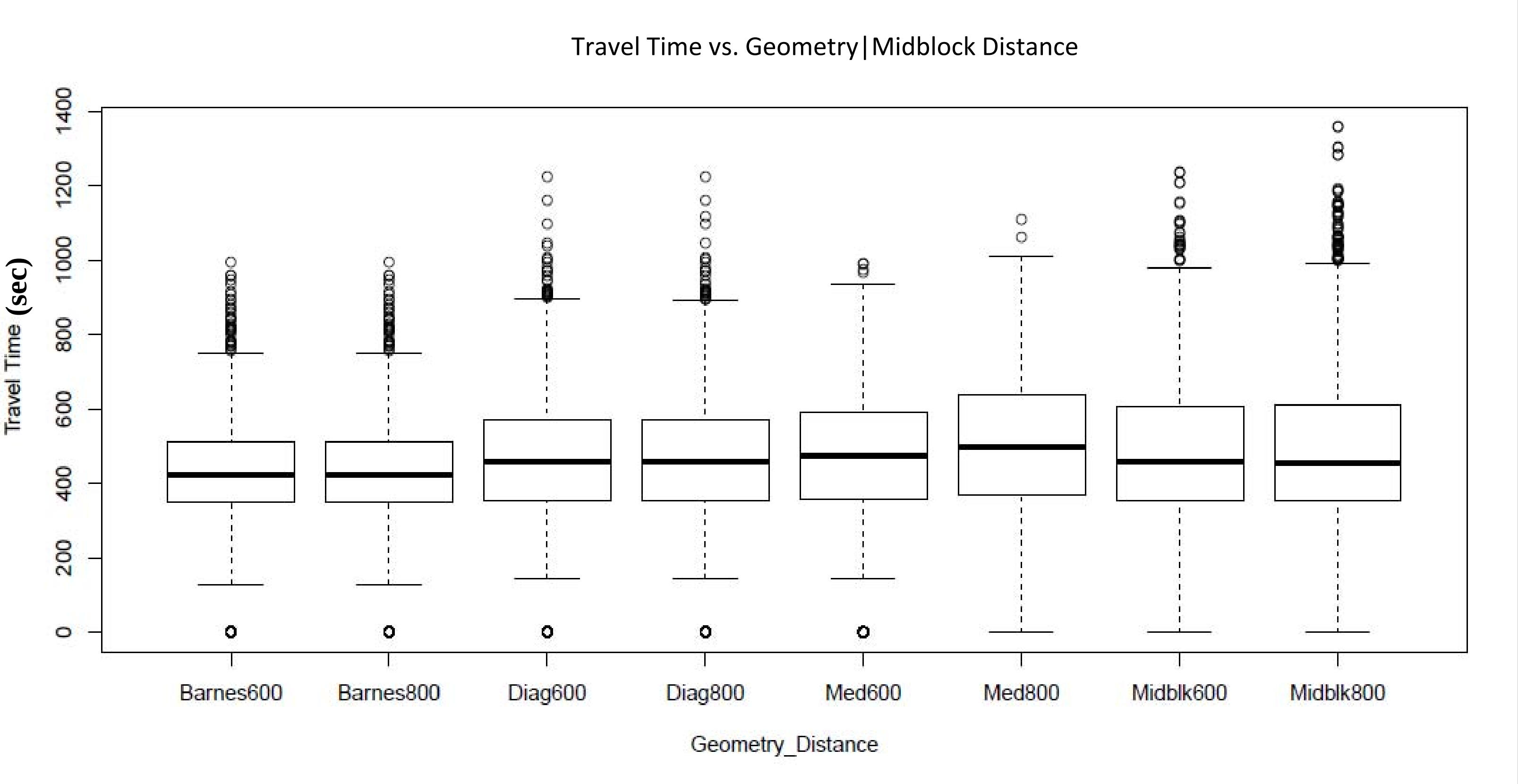

Figure 5.7. Box plots of the interaction between pedestrian crossing geometries and midblock distances for travel time.

Table 5.15. ANOVA with Post Hoc Tukey results for pedestrian travel time per crossing geometry and midblock distances.

Geometry:Midblock Distance

Travel Time (sec)	diff	lwr	upr	p-adj
Barnes:800-Barnes:600	-0.2	-12.8	12.4	1.00E+00
Diag:800-Diag:600	-0.5	-13.1	12.1	1.00E+00
Med:800-Med:600	25.9	13.3	38.5	0.00E+00
Midblk:800-Midblk:600	7.0	-5.6	19.6	6.92E-01
diff: difference in mean values	*lwr: min. difference in values*		*upr: max. difference in values*	
	Df	Sum Sq	Mean Sq	F value
geometry:factor(distance)	7	2.06E+07	2946366	88.74
Residuals	30712	1.02E+09	33202	

A further look into the interactions of the variables through each of the scenarios analyzed per crossing geometry can be found in Table 5.16 through Table 5.19. Among all the geometries, scenarios 3 and 7 produced the lowest values, with a few exceptions. For the two-stage Barnes dance cross in Table 5.16, scenario 8 had the lowest mean stopped delay. Scenarios 11 and 15 had the lowest mean number of stops for the diagonal cross in Table 5.17. Scenario 9 had the lowest mean stopped delay and the lowest mean travel time for the median cross in Table 5.18. Scenario 15 also had the mean number of stops for the midblock cross in Table 5.19. Scenarios 3 and 7 included an offset signal design, the 600 ft and 800 ft midblock distances, a cycle length of 90 seconds and a signal split of 60/40.

Table 5.16. Two-stage Barnes Dance crossing results per scenario (compliant pedestrians).

Signal Offset Design	U-Turn/ Midblock Distance (ft)	Cycle Length (sec)	Signal Split	Scenario	Mean of Stopped Delay (sec)	Mean of Stops	Mean of Travel Time (sec)
Offset	600	180	60/40	1	105	1.4	410
			75/25	2	103	1.3	454
		90	60/40	3	47	1.3	354
			75/25	4	47	1.3	398
	800	180	60/40	5	100	1.3	410
			75/25	6	103	1.3	454
		90	60/40	7	48	1.2	354
			75/25	8	46	1.3	398
Simultaneous	600	180	60/40	9	153	1.4	465
			75/25	10	153	1.4	505
		90	60/40	11	66	1.3	373
			75/25	12	67	1.3	419
	800	180	60/40	13	151	1.4	464
			75/25	14	153	1.4	505
		90	60/40	15	64	1.3	373
			75/25	16	67	1.3	419

Table 5.17. Diagonal crossing results per scenario (compliant pedestrians).

Signal Offset Design	U-Turn/ Midblock Distance (ft)	Cycle Length (sec)	Signal Split	Scenario	Mean of Stopped Delay (sec)	Mean of Stops	Mean of Travel Time (sec)
Offset	600	180	60/40	1	132	1.8	458
			75/25	2	155	1.9	521
		90	60/40	3	61	1.7	383
			75/25	4	67	1.9	433
	800	180	60/40	5	131	1.8	458
			75/25	6	155	1.9	521
		90	60/40	7	61	1.7	383
			75/25	8	67	1.9	433
Simultaneous	600	180	60/40	9	191	1.8	520
			75/25	10	199	2.0	564
		90	60/40	11	73	1.7	394
			75/25	12	81	1.9	448
	800	180	60/40	13	185	1.8	515
			75/25	14	199	2.0	565
		90	60/40	15	73	1.7	395
			75/25	16	81	1.9	448

Table 5.18. Median crossing results per scenario (compliant pedestrians).

Signal Offset Design	U-Turn/ Midblock Distance (ft)	Cycle Length (sec)	Signal Split	Scenario	Mean of Stopped Delay (sec)	Mean of Stops	Mean of Travel Time (sec)
Offset	600	180	60/40	1	171	1.9	496
			75/25	2	207	2.0	567
		90	60/40	3	76	1.7	391
			75/25	4	89	2.0	449
	800	180	60/40	5	179	1.9	505
			75/25	6	207	2.0	567
		90	60/40	7	76	1.7	391
			75/25	8	89	2.0	449
Simultaneous	600	180	60/40	9	70	1.8	386
			75/25	10	260	2.1	618
		90	60/40	11	97	1.8	413
			75/25	12	110	2.0	472
	800	180	60/40	13	253	2.0	584
			75/25	14	260	2.1	618
		90	60/40	15	97	1.8	413
			75/25	16	110	2.0	472

Table 5.19. Midblock crossing results per scenario (compliant pedestrians).

Signal Offset Design	U-Turn/ Midblock Distance (ft)	Cycle Length (sec)	Signal Split	Scenario	Mean of Stopped Delay (sec)	Mean of Stops	Mean of Travel Time (sec)
Offset	600	180	60/40	1	146	1.4	483
			75/25	2	158	1.6	548
		90	60/40	3	56	1.4	385
			75/25	4	64	1.6	455
	800	180	60/40	5	142	1.5	495
			75/25	6	151	1.6	553
		90	60/40	7	53	1.4	392
			75/25	8	64	1.6	466
Simultaneous	600	180	60/40	9	163	1.5	502
			75/25	10	174	1.6	563
		90	60/40	11	69	1.4	398
			75/25	12	77	1.6	468
	800	180	60/40	13	153	1.4	509
			75/25	14	165	1.6	566
		90	60/40	15	63	1.3	404
			75/25	16	72	1.5	474

5.2 Non-Compliant Pedestrian Results

As discussed in 4.4.3.1 above, the simulations were constructed with a 50% compliance rate for crossing pedestrians. The following section will display the combined simulation results for compliant and non-compliant pedestrians for all four geometries. The results per scenario are shown in Table 5.20 through Table 5.23.

Table 5.20. Two-stage Barnes Dance crossing results per scenario (compliant and non-compliant pedestrians).

Signal Offset Design	U-Turn/ Midblock Distance (ft)	Cycle Length (sec)	Signal Split	Scenario	Mean of Stopped Delay (sec)	Mean of Stops	Mean of Travel Time (sec)
Offset	600	180	60/40	1	75	1.5	385
			75/25	2	75	1.5	424
		90	60/40	3	35	1.3	347
			75/25	4	35	1.4	383
	800	180	60/40	5	72	1.5	387
			75/25	6	76	1.5	425
		90	60/40	7	34	1.3	347
			75/25	8	35	1.3	383
Simultaneous	600	180	60/40	9	92	1.4	407
			75/25	10	96	1.4	444
		90	60/40	11	45	1.3	357
			75/25	12	46	1.3	394
	800	180	60/40	13	93	1.4	409
			75/25	14	97	1.4	446
		90	60/40	15	43	1.3	356
			75/25	16	46	1.3	395

Table 5.21. Diagonal crossing results per scenario (compliant and non-compliant pedestrians).

Signal Offset Design	U-Turn/ Midblock Distance (ft)	Cycle Length (sec)	Signal Split	Scenario	Mean of Stopped Delay (sec)	Mean of Stops	Mean of Travel Time (sec)
Offset	600	180	60/40	1	88	2.0	422
			75/25	2	103	2.2	468
		90	60/40	3	43	1.7	371
			75/25	4	47	1.9	411
	800	180	60/40	5	89	2.0	422
			75/25	6	103	2.2	468
		90	60/40	7	42	1.7	371
			75/25	8	47	1.9	412
Simultaneous	600	180	60/40	9	114	1.9	447
			75/25	10	122	2.0	486
		90	60/40	11	50	1.7	379
			75/25	12	56	1.9	421
	800	180	60/40	13	112	1.9	445
			75/25	14	123	2.0	487
		90	60/40	15	50	1.7	380
			75/25	16	56	1.9	420

Table 5.22. Median crossing results per scenario (compliant and non-compliant pedestrians).

Signal Offset Design	U-Turn/ Midblock Distance (ft)	Cycle Length (sec)	Signal Split	Scenario	Mean of Stopped Delay (sec)	Mean of Stops	Mean of Travel Time (sec)
Offset	600	180	60/40	1	105	1.8	432
			75/25	2	129	2.0	488
		90	60/40	3	49	1.6	370
			75/25	4	59	1.9	417
	800	180	60/40	5	111	1.9	438
			75/25	6	129	2.0	488
		90	60/40	7	49	1.6	370
			75/25	8	59	1.9	418
Simultaneous	600	180	60/40	9	46	1.6	367
			75/25	10	149	1.9	506
		90	60/40	11	59	1.6	381
			75/25	12	68	1.8	427
	800	180	60/40	13	143	1.8	471
			75/25	14	150	1.9	507
		90	60/40	15	59	1.6	380
			75/25	16	68	1.8	427

Table 5.23. Midblock crossing results per scenario (compliant and non-compliant pedestrians).

Signal Offset Design	U-Turn/ Midblock Distance (ft)	Cycle Length (sec)	Signal Split	Scenario	Mean of Stopped Delay (sec)	Mean of Stops	Mean of Travel Time (sec)
Offset	600	180	60/40	1	96	1.5	445
			75/25	2	108	1.6	496
		90	60/40	3	39	1.4	382
			75/25	4	47	1.6	434
	800	180	60/40	5	93	1.5	455
			75/25	6	106	1.7	505
		90	60/40	7	37	1.3	392
			75/25	8	47	1.6	446
Simultaneous	600	180	60/40	9	102	1.4	452
			75/25	10	116	1.6	504
		90	60/40	11	46	1.3	386
			75/25	12	54	1.5	441
	800	180	60/40	13	99	1.5	463
			75/25	14	115	1.6	513
		90	60/40	15	44	1.3	398
			75/25	16	53	1.5	451

As expected, the stopped delay and travel time decreased for each of the geometries and at each scenario when non-compliant pedestrians were included in the results. The scenarios with the lowest overall results were the same as for the compliant-only results, namely, scenarios 3 and 7.

5.3 Bicycle Crossing Results

The bicycle crossing geometry results for average stopped delay per route, average number of stops per route and average travel time per route are shown in the following section. Prior to presenting these results, Table 5.24 establishes a standard for comparison of travel time and number of stops per bicyclists for all geometries. The values shown are averaged over all routes as described in section 4.4.2. The free flow travel time was computed based on an average of all routes modeled and using one average bicycle speed of 15.6 feet per second from Table 4.14. The number of stops per bicyclist is displayed as a range based on the average number of stops per the 16 simulated models from Table 4.19.

Table 5.24. Free flow travel time and minimum and maximum number of stops per bicycle crossing geometry.

Geometry	**Free flow travel time (sec)**	**Minimum Average Number of Stops per Bicyclist**	**Maximum Average Number of Stops per Bicyclist**
Bicycle U-Turn Cross	139	5.1	51.2
Bicycle Direct Cross	118	3.7	7.6
Bicycle Midblock Cross	146	4.5	10.1
Vehicle U-Turn	144	2.5	13.4

The mean and standard deviation for the average stopped delay in seconds per route for each of the bicycle crossing geometries are displayed in Table 5.25. The results of the ANOVA with Post Hoc Tukey results are displayed in Table 5.26. The lowest average total stop delay per route is 97.5 seconds for bicycles using the vehicle U-turn. The geometry with the greatest amount of stop delay was the bicycle U-turn with an average stopped delay of 335.7 seconds. This delay was due to the time the bicycles spent in the unsignalized bicycle U-turn waiting for a large enough gap in the vehicular traffic to be able to cross the major street to the bike lane on the right hand side. The differences between geometries for stopped delay are shown to all be significant in Table 5.26 with an adjusted p-value < 0.05 for all differences.

Table 5.25. Stopped delay results for bicycle crossing geometries.

Delay (sec)									
Geometry	mean	sd	cv	0%	25%	50%	75%	100%	data:n
Bicycle UT	335.7	848.2	2.527	0	45.5	109.3	222.5	6519	7680
Direct	133.1	115.7	0.869	0	49.1	104.7	201.4	693.2	7680
Midblk	183.0	197.6	1.080	0	49.9	116.4	269.7	3010	7680
Vehicle UT	97.5	411.3	4.217	0	0.0	0.0	70.5	6161	7680

Table 5.26. ANOVA with Post Hoc Tukey results for stopped delay per bicycle crossing geometry.

Delay (sec)				
Geometry vs. Geometry	diff	lwr	upr	p-adj
Direct-Bicycle UT	-202.5	-222.6	-182.4	0.00E+00
Midblk-Bicycle UT	-152.7	-172.8	-132.5	0.00E+00
Vehicle UT-Bicycle UT	-238.1	-258.2	-218.0	0.00E+00
Midblk-Direct	49.9	29.8	70.0	0.00E+00
Vehicle UT-Direct	-35.6	-55.7	-15.5	3.19E-05
Vehicle UT-Midblk	-85.5	-105.6	-65.4	0.00E+00
diff: difference in mean values	*lwr: minimum difference in values*		*upr: maximum difference in values*	
	Df	Sum Sq	Mean Sq	F value
geometry	3	253600000	84536910	359.3
Residuals	30716	7227000000	235283	

The results for the average total number of stops per bicycle crossing geometry are shown in Table 5.27 while Table 5.28 displays the ANOVA with Post Hoc Tukey results for average total number of stops per route per crossing geometry. The geometry with the least amount of stops on average per route was the direct cross with 4.82 stops. Furthermore, the geometry with the greatest amount of stops on average per route was the bicycle U-turn. All of the differences between geometries were shown to be significant with an adjusted p-value < 0.05 as shown in Table 5.28, with the exception of the difference between the vehicle U-turn and the direct cross.

Table 5.27. Results for total number of stops per bicycle crossing geometry.

Stops	mean	sd	cv	0%	25%	50%	75%	100%	data:n
Bicycle UT	14.1	24.7	1.76	0	3.6	7.1	13.8	236	7680
Direct	4.82	3.32	0.69	0	3.0	4.4	6.1	32.0	7680
Midblk	6.98	5.74	0.82	0	3.0	5.8	9.6	53.3	7680
Vehicle UT	5.04	11.6	2.30	0	0.0	0.0	7.8	146	7680

Table 5.28. ANOVA with Post Hoc Tukey results for total number of stops per bicycle crossing geometry.

Stops				
Geometry vs. Geometry	diff	lwr	upr	p-adj
Direct-Bicycle UT	-9.244	-9.826	-8.662	0.00E+00
Midblk-Bicycle UT	-7.090	-7.672	-6.508	0.00E+00
Vehicle UT-Bicycle UT	-9.032	-9.614	-8.450	0.00E+00
Midblk-Direct	2.153	1.572	2.735	0.00E+00
Vehicle UT-Direct	0.211	-0.371	0.793	7.87E-01
Vehicle UT-Midblk	-1.942	-2.524	-1.360	0.00E+00
diff: difference in mean values	*lwr: minimum difference in values*		*upr: maximum difference in values*	
	Df	Sum Sq	Mean Sq	F value
geometry	3	433449	144483	733.5
Residuals	30716	6050712	197	

Results for average travel time per route per bicycle crossing geometry are shown in Table 5.29 and the ANOVA and Tukey results are displayed in Table 5.30. The direct cross produced the lowest average travel time per route with 327.6 seconds and the bicycles using the vehicle U-turn had the greatest average travel times per route with 563.6 seconds. The adjusted p-values in Table 5.30 are below 0.05 and thus the differences between the geometries are significant, with the exception of the bicycles using the bicycle U-turn compared to those using the vehicle U-turn.

Table 5.29. Results for travel time per bicycle crossing geometry.

Travel Time (sec)									
Geometry	mean	sd	cv	0%	25%	50%	75%	100%	data:n
Bicycle UT	542.2	849.9	1.568	0	233.1	345.3	484.1	6852	7680
Direct	327.6	137.8	0.421	0	224.4	304.5	402.8	1030	7680
Midblk	428.5	259.0	0.605	0	236.9	376.2	555.4	3550	7680
Vehicle UT	563.6	854.8	1.517	0	233.4	374.4	530.8	6852	7680

Table 5.30. ANOVA with Post Hoc Tukey results for travel time per bicycle crossing geometry.

Travel Time (sec)				
Geometry vs. Geometry	diff	lwr	upr	p-adj
Direct-Bicycle UT	-214.6	-240.3	-188.9	0.00E+00
Midblk-Bicycle UT	-113.7	-139.4	-88.0	0.00E+00
Vehicle UT-Bicycle UT	21.4	-4.3	47.1	1.42E-01
Midblk-Direct	100.9	75.2	126.6	0.00E+00
Vehicle UT-Direct	236.0	210.3	261.7	0.00E+00
Vehicle UT-Midblk	135.1	109.4	160.8	0.00E+00
diff: difference in mean values	*lwr: minimum difference in values*		*upr: maximum difference in values*	
	Df	Sum Sq	Mean Sq	F value
geometry	3	2.76E+08	91887433	238.8
Residuals	30716	1.18E+10	384772	

As with the pedestrian crossing geometries described in the previous section, the bicycle geometries were further analyzed based on travel time and the variables of signal offset design, cycle length, signal split, and midblock distance. For the interactions between the geometries and the signal offset designs, Table 5.31 shows the mean and standard deviation of the average travel times per route. The statistical analysis results for these interactions can be found in Table 5.32. All interactions between offset and simultaneous signal design at each bicycle crossing geometry were shown to be significant with an adjusted p-value < 0.05 as shown in Table 5.32. The signal offset design for both the U-turn options produced a longer travel time than the simultaneous signal design, while the other two geometries showed a reverse effect. For the direct cross and the midblock cross, the bicycles cross both major street movements concurrently and thus an offset design was beneficial to these options. However, for the U-turn options, the bicycles are crossing one major street movement, and then traveling between the major streets before crossing the second major street movement. For these options, the simultaneous signal design produced lower travel time values.

Table 5.31. Travel time data for bicycle crossing geometries based on signal offset design .

Geometry:Signal	mean	sd	cv	0%	25%	50%	75%	100%	data:n
Bicycle UTOffset	564	890	1.58	0	243	346	473	6428	3840
Bicycle UTSimultaneous	520	808	1.55	0	220	344	495	6852	3840
DirectOffset	303	113	0.37	0	218	288	360	887.3	3840
DirectSimultaneous	352	155	0.44	0	237	324	431	1030	3840
MidblkOffset	393	214	0.54	0	231	353	509	1531	3840
MidblkSimultaneous	464	293	0.63	0	244	411	597	3550	3840
Vehicle UTOffset	586	893	1.52	0	244	375	520	6437	3840
Vehicle UTSimultaneous	541	814	1.50	0	220	374	541	6852	3840

Table 5.32. ANOVA with Post Hoc Tukey results for bicycle travel time per crossing geometry and signal offset design.

Travel Time (sec)				
Geometry:Signal	diff	lwr	Upr	p-adj
Bicycle UT:Simultaneous-Bicycle UT:Offset	-44.2	-87.0	-1.3	3.79E-02
Direct:Simultaneous-Direct:Offset	49.6	6.8	92.5	1.06E-02
Midblk:Simultaneous-Midblk:Offset	71.1	28.2	113.9	1.39E-05
Vehicle UT:Simultaneous-Vehicle UT:Offset	-45.5	-88.4	-2.6	2.84E-02

diff: difference in mean values *lwr: minimum difference in values* *upr: maximum difference in values*

	Df	Sum Sq	Mean Sq	F value
geometry:signals	7	2.98E+08	42544121	110.8
Residuals	30712	1.18E+10	384101	

Results for bicycle crossing geometries compared to cycle length for average travel time per route are shown in Table 5.33, and the ANOVA with Post Hoc Tukey results are shown in Table 5.34. The interactions between cycle lengths and each bicycle crossing geometry were shown to be significant with an adjusted p-value for each of 0.0 as found in

Table 5.34. The shorter cycle length was beneficial to all of the crossings and in particular, the U-turn crossings had significantly less travel time for the shorter cycle lengths. This was due to the amount of time the bicyclists were waiting at the U-turn; with a longer cycle length, the main street movements had longer green times and thus increased delay for the bicyclists waiting to turn.

Table 5.33. Travel time data for bicycle crossing geometries based on cycle length.

Travel Time (sec)									
Geometry:Cycle	mean	sd	cv	0%	25%	50%	75%	100%	data:n
Bicycle UT180	773.6	1149	1.485	0	253.0	444.8	605.4	6852	3840
Bicycle UT90	310.7	134.6	0.433	0	221.3	307.1	375.7	1147	3840
Direct180	382.6	158.0	0.413	0	256.1	378.6	463.8	1030	3840
Direct90	272.5	83.4	0.306	0	212.8	267.6	316.9	691.8	3840
Midblk180	532.2	303.4	0.570	0	277.0	510.9	687.2	3550	3840
Midblk90	324.8	143.5	0.442	0	214.7	303.9	419.5	958.6	3840
Vehicle UT180	801.7	1152	1.437	0	253.0	492.0	659.9	6852	3840
Vehicle UT90	325.4	143.3	0.440	0	221.3	319.9	410.8	1147	3840

Table 5.34. ANOVA with Post Hoc Tukey results for bicycle travel time per geometry and cycle length.

Travel Time (sec)				
Geometry:Cycle	diff	lwr	upr	p-adj
Bicycle UT:180-Bicycle UT:90	462.9	421.8	504.0	0.00E+00
Direct:180-Direct:90	110.0	68.9	151.2	0.00E+00
Midblk:180-Midblk:90	207.4	166.3	248.5	0.00E+00
Vehicle UT:180-Vehicle UT:90	476.3	435.1	517.4	0.00E+00
diff: difference in mean values	*lwr: minimum difference in values*		*upr: maximum difference in values*	
	Df	Sum Sq	Mean Sq	F value
geometry:factor(cycle)	7	1228000000	175493811	496
Residuals	30712	1.087E+10	353799	

Results for the interactions between the bicycle crossing geometries and signal splits are shown in Table 5.35 and the ANOVA with Post Hoc Tukey results are shown in Table 5.36. The signal splits applied to the midblock cross were shown to not have a significant difference in the travel time values. Additionally, the comparison between a 60/40 split and a 75/25 split for the direct cross had no statistical difference in the travel time data as shown with an adjusted p-value of 1.0 (Table 5.36).

Table 5.35. Travel time data for bicycle crossing geometries and signal splits.

Travel Time (sec)									
Geometry:Split	mean	sd	cv	0%	25%	50%	75%	100%	data:n
Bicycle UT60/40	670.3	1143	1.706	0	234.5	335.5	493.4	6852	3840
Bicycle UT75/25	414.1	323.4	0.781	0	232.4	358.9	475.3	2425	3840
Direct60/40	329.0	142.6	0.433	0	221.7	304.7	404.8	1030	3840
Direct75/25	326.1	132.8	0.407	120.5	228.2	304.4	400.5	944.4	3840
Midblk60/40	437.6	289.1	0.661	0	236.2	371.6	567.9	3550	3840
Midblk75/25	419.3	224.6	0.536	121.1	237.5	381.1	542.8	1596	3840
Vehicle UT60/40	692.8	1148	1.657	0	234.6	357.5	542.1	6852	3840
Vehicle UT75/25	434.3	331.9	0.764	0	232.8	388.2	522.2	2425	3840

Table 5.36. ANOVA with Post Hoc Tukey results for bicycle travel time per crossing geometry and signal splits.

Travel Time (sec)				
Geometry:Split	diff	lwr	upr	p-adj
Bicycle UT:75/25-Bicycle UT:60/40	-256.2	-298.7	-213.8	0.00E+00
Direct:75/25-Direct:60/40	-2.9	-45.3	39.6	1.00E+0
Midblk:75/25-Midblk:60/40	-18.3	-60.8	24.1	8.96E-01
Vehicle UT:75/25-Vehicle UT:60/40	-258.6	-301.0	-216.1	0.00E+00
diff: difference in mean values	*lwr: minimum difference in values*		*upr: maximum difference in values*	

	Df	Sum Sq	Mean Sq	F value
geometry:factor(split)	7	530700000	75819257	201.4
Residuals	30712	1.156E+10	376517	

The results for the interactions between the bicycle crossing geometries and the different midblock distances for travel time are shown in Table 5.37 and the ANOVA with Post Hoc Tukey results are shown in Table 5.38. The interaction with the least significance, having an adjusted p-value greater than 0.05, was with the direct cross. Additionally, there was no statistical difference between the average travel time values for the 600 ft midblock distance and the 800 ft midblock distance for the midblock cross (Table 5.38). Neither the direct cross nor the midblock cross rely on a U-turn movement, thus the midblock distances would have little to no effect on overall travel time for these two geometries.

Table 5.37. Travel time data for bicycle crossing geometries and midblock distances.

Geometry:Midblock Distance

Travel Time (sec)	mean	sd	cv	0%	25%	50%	75%	100%	data:n
Bicycle UT600	721.1	1166	1.616	0	216	355.8	542.5	6852	3840
Bicycle UT800	363.2	149.0	0.410	126.1	246.2	339.3	455.9	1077	3840
Direct600	337.4	142.0	0.421	105.6	229.7	311.6	411.0	952.1	3840
Direct800	317.7	132.7	0.418	0	218.9	298.0	392.8	1030	3840
Midblk600	427.3	270.7	0.634	0	236.4	370.8	545.8	3550	3840
Midblk800	429.6	246.8	0.574	0	237.5	384.5	564.6	1793	3840
Vehicle UT600	736.5	1171	1.590	0	215.9	379.0	568.4	6852	3840
Vehicle UT800	390.6	173.2	0.444	126.1	247.0	365.9	509.6	1203	3840

Table 5.38. ANOVA with Post Hoc Tukey results for bicycle travel time per crossing geometry and midblock distances.

Geometry:Midblock Distance				
Travel Time (sec)	diff	lwr	upr	p-adj
Bicycle UT:800-Bicycle UT:600	-357.9	-400.0	-315.9	0.00E+00
Direct:800-Direct:600	-19.6	-61.7	22.4	8.51E-01
Midblk:800-Midblk:600	2.4	-39.7	44.4	1.00E+00
Vehicle UT:800-Vehicle UT:600	-345.9	-388.0	-303.9	0.00E+00
diff: difference in mean values	*lwr: minimum difference in values*	*upr: maximum difference in values*		
	Df	Sum Sq	Mean Sq	F value
geometry:factor(distance)	7	7.52E+08	107450102	290.9
Residuals	30712	1.13E+10	369308	

The following tables compare the results of the bicycle crossing geometries with the various applied scenarios. Scenario 7 produced the lowest results for the bicycle U-turn cross in Table 5.39 and the bicycle direct cross in Table 5.40. Scenario 7 included an offset signal design, 800 ft midblock distance, 90-second cycle length and a 60/40 split. The bicycle midblock crossing in Table 5.41 had the lowest results for scenario 3, which is similar to scenario 7 with the exception of a 600 ft midblock distance. The lowest values for the vehicle U-turn cross in Table 5.42 was a combination of scenarios 3 and 7.

Furthermore, the bicycle U-turn cross and the vehicle U-turn cross had significantly larger values for scenario 1 and 2 compared to the other scenarios and other geometries. From further inspection of the simulations, it was found that at midblock distances of 600 feet, the bicyclist at both the U-turn crossings incurred large stopped delay due to the congestion of the motor vehicles on the major street and fewer and smaller allowable gaps in the vehicular traffic. The simulated bicyclists had a difficult time crossing during the gaps due to the vehicle congestion from a shorter distance between the main intersection and the vehicle U-turn and due to the lateral gap algorithm setup in VISSIM for bicycles. The MOEs of a bicycle U-turn cross at a superstreet may change depending on the motor vehicle volume applied and the distance between the bicycle U-turn and vehicle U-turn locations.

Table 5.39. Bicycle U-turn crossing results per scenario.

Signal Offset Design	U-Turn/ Midblock Distance (ft)	Cycle Length (sec)	Signal Split	Scenario	Mean of Stopped Delay (sec)	Mean of Stops	Mean of Travel Time (sec)
Offset	600	180	60/40	1	1652	51.2	1860
			75/25	2	445	17.4	648
		90	60/40	3	82	7.7	287
			75/25	4	128	10.9	338
	800	180	60/40	5	163	7.4	414
			75/25	6	156	7.0	394
		90	60/40	7	60	5.1	278
			75/25	8	73	6.3	295
Simultaneous	600	180	60/40	9	1360	43.4	1447
			75/25	10	387	14.9	521
		90	60/40	11	112	9.6	316
			75/25	12	134	10.2	352
	800	180	60/40	13	227	10.9	460
			75/25	14	215	10.1	445
		90	60/40	15	80	5.6	300
			75/25	16	96	7.3	320

Table 5.40. Bicycle direct crossing results per scenario.

Signal	U-Turn/	Cycle	Signal	Scenario	Mean of	Mean	Mean of

Offset Design	Midblock Distance (ft)	Length (sec)	Split		Stopped Delay (sec)	of Stops	Travel Time (sec)
Offset	600	180	60/40	1	157	5.1	362
			75/25	2	156	5.2	357
		90	60/40	3	63	4.0	265
			75/25	4	69	4.3	267
	800	180	60/40	5	161	7.6	336
			75/25	6	153	7.3	333
		90	60/40	7	60	3.7	249
			75/25	8	65	4.2	252
Simultaneous	600	180	60/40	9	226	4.8	431
			75/25	10	227	4.9	426
		90	60/40	11	92	4.1	295
			75/25	12	96	4.2	294
	800	180	60/40	13	217	4.8	414
			75/25	14	211	4.8	400
		90	60/40	15	86	4.0	278
			75/25	16	91	4.2	279

Table 5.41. Bicycle midblock crossing results per scenario.

Signal Offset Design	U-Turn/ Midblock Distance (ft)	Cycle Length (sec)	Signal Split	Scenario	Mean of Stopped Delay (sec)	Mean of Stops	Mean of Travel Time (sec)
Offset	600	180	60/40	1	232	8.5	479
			75/25	2	222	8.0	458
		90	60/40	3	67	4.5	302
			75/25	4	74	5.2	304
	800	180	60/40	5	217	8.7	482
			75/25	6	233	8.6	482
		90	60/40	7	68	4.8	319
			75/25	8	73	5.5	317
Simultaneous	600	180	60/40	9	405	10.1	655
			75/25	10	319	8.7	557
		90	60/40	11	93	5.0	331
			75/25	12	100	5.3	332
	800	180	60/40	13	322	9.5	585
			75/25	14	307	8.7	558
		90	60/40	15	95	5.0	347
			75/25	16	102	5.6	346

Table 5.42. Vehicle U-turn crossing results per scenario.

Signal	U-Turn/	Cycle	Signal	Scenario	Mean of	Mean	Mean of

Offset Design	Midblock Distance (ft)	Length (sec)	Split		Stopped Delay (sec)	of Stops	Travel Time (sec)
Offset	600	180	60/40	1	397	13.4	1885
			75/25	2	126	6.0	672
		90	60/40	3	24	2.6	298
			75/25	4	39	3.4	346
	800	180	60/40	5	85	5.8	449
			75/25	6	74	5.2	425
		90	60/40	7	24	2.5	301
			75/25	8	33	3.3	315
Simultaneous	600	180	60/40	9	336	10.3	1463
			75/25	10	107	4.1	544
		90	60/40	11	27	2.6	326
			75/25	12	39	3.4	359
	800	180	60/40	13	99	6.1	499
			75/25	14	87	5.3	477
		90	60/40	15	27	2.8	321
			75/25	16	38	3.8	337

5.4 Summary of Pedestrian and Bicycle Crossing Results

The following section summarizes the previous results section.

5.4.1 Summary of Pedestrian Crossing Results

The results of stopped delay and travel time per pedestrian crossing geometry are shown in Table 5.43, as well as the free flow travel time and computed total delay for comparison. Table 5.44 displays the results for mean number of stops per pedestrian per crossing geometry as well as the minimum and maximum average number of stops from Table 5.1. Of all the MOEs, the two-stage Barnes Dance cross produced the lowest values and the median cross resulted in the highest values.

Table 5.43. Summary of results for delay and travel time per pedestrian crossing.

Geometry	Mean Travel Time per Pedestrian (TT) (sec)	Free Flow Travel Time per Pedestrian (FFTT) (sec)	Total Delay per Pedestrian = TT - FFTT (sec)	Mean Stopped Delay per Pedestrian (sec)
Two-stage Barnes Dance cross	422	320	102	92.1
Diagonal cross	465	333	132	120
Median cross	487	327	160	147
Midblock cross	479	360	119	111

Table 5.44. Summary of results for number of stops per pedestrian crossing.

Geometry	Mean Number of Stops per Pedestrian	Minimum Number of Stops per Pedestrian	Maximum Number of Stops per Pedestrian
Two-stage Barnes Dance cross	1.3	1.2	1.4
Diagonal cross	1.8	1.7	2
Median cross	1.9	1.7	2.1
Midblock cross	1.5	1.3	1.6

The following tables summarize the difference in travel time per pedestrian crossing geometry based on offset signal design (Table 5.45), signal cycle lengths (Table 5.46), signal splits (Table 5.47), and midblock distance (Table 5.48).

Table 5.45. Summary of pedestrian crossing geometries and offset signal designs.

Geometry	Offset	Simultaneous		
Travel Time (sec):	**Mean**	**Mean**	**% Diff.**	**p-adj**
Two-stage Barnes Dance cross	404	440	9.0%	0.00E+00
Diagonal cross	449	481	7.2%	0.00E+00
Median cross	477	497	4.2%	0.00E+00
Midblock cross	472	486	2.8%	3.00E-02

Table 5.46. Summary of pedestrian crossing geometries and signal cycle lengths.

Geometry	90 second cycle	180 second cycle		
Travel Time (sec):	**Mean**	**mean**	**% Diff.**	**p-adj**
Two-stage Barnes Dance cross	386	458	18.8%	0.00E+00
Diagonal cross	415	515	24.3%	0.00E+00
Median cross	431	543	25.8%	0.00E+00
Midblock cross	431	527	22.5%	3.51E-03

Table 5.47. Summary of pedestrian crossing geometries and signal splits.

Geometry	60/40	75/25		
Travel Time (sec):	**mean**	**mean**	**% Diff.**	**p-adj**
Two-stage Barnes Dance cross	400	444	10.9%	0.00E+00
Diagonal cross	438	492	12.2%	0.00E+00
Median cross	447	527	17.7%	0.00E+00
Midblock cross	446	512	14.7%	0.00E+00

Table 5.48. Summary of pedestrian crossing geometries and midblock distances.

Geometry	600' Midblock Distance	800' Midblock Distance		
Travel Time (sec):	**Mean**	**mean**	**% Diff.**	**p-adj**
Two-stage Barnes Dance cross	422	422	0.0%	1.00E+00
Diagonal cross	465	465	-0.1%	1.00E+00
Median cross	474	500	5.5%	0.00E+00
Midblock cross	475	482	1.5%	6.92E-01

The following table (Table 5.49) summarizes the scenarios that contributed to the lowest results (mean of stopped delay, mean of stops, or mean of travel time) for the pedestrian crossing geometries. The scenarios that produced the lowest results for all four of the pedestrian crossing geometries were scenarios 3 and 7.

Table 5.49. Summary of scenarios with the lowest result values.

Geometries	Scenario	Offset Signal Design	Midblock Distance (ft)	Cycle Length (sec)	Signal Split
All	3	Offset	600	90	60/40
All	7		800		
Two-stage Barnes Dance Cross	8				75/25
Median Cross	9	Simultaneous	600	180	60/40
Diagonal Cross	11			90	
Diagonal Cross and Midblock Cross	15		800		

5.4.2 Summary of Bicycle Crossing Results

The results of stopped delay and travel time per bicycle crossing geometry are shown in Table 5.50, as well as the free flow travel time and computed total delay. Table 5.51 displays the results for mean number of stops per bicycle per crossing geometry as well as the minimum and maximum average number of stops from Table 5.24. The bicyclists using the vehicle U-turn had the lowest stopped delay and number of stops compared to the other bicycle crossing geometries. However, the bicycle direct cross had the lowest travel time.

Table 5.50. Summary of results for delay and travel time per bicycle crossing.

Geometry	Mean Travel Time (TT) (sec)	Free Flow Travel Time per Bicyclist (FFTT) (sec)	Total Delay per Bicyclist = TT - FFTT (sec)	Mean Stopped Delay per Bicyclist (sec)
Bicycle U-Turn Cross	542	139	403	336
Bicycle Direct Cross	328	118	210	133
Bicycle Midblock Cross	428	146	282	183
Vehicle U-Turn	564	144	420	98

Table 5.51. Summary of bicycle crossing geometries for the selected MOEs.

Geometry	Mean Number of Stops per Bicycle	Minimum Number of Stops per Bicycle	Maximum Number of Stops per Bicycle
Bicycle U-turn cross	14.1	5.1	51.2
Bicycle direct cross	4.8	3.7	7.6
Bicycle midblock cross	7.0	4.5	10.1
Vehicle U-turn	5.0	2.5	13.4

The following tables summarize the results for travel time compared to offset signal design (Table 5.52), signal cycle length (Table 5.53), signal split (Table 5.54), and midblock distances (Table 5.55). Table 5.55 emphasizes the differences between the median opening distances for the U-turn's. As discussed earlier, the 600 ft midblock distance produces significantly larger values than the 800 ft midblock distance.

Table 5.52. Summary of bicycle crossing geometries and offset signal designs.

Geometry	Offset	Simultaneous		
Travel Time (sec):	**mean**	**mean**	**% Diff.**	**p-adj**
Bicycle U-turn cross	564	520	-7.8%	0.04
Bicycle direct cross	303	352	16.4%	0.01
Bicycle midblock cross	393	464	18.1%	0.00
Vehicle U-turn	586	541	-7.8%	0.03

Table 5.53. Summary of bicycle crossing geometries and signal cycle lengths.

Geometry	90 second cycle	180 second cycle		
Travel Time (sec):	**mean**	**mean**	**% Diff.**	**p-adj**
Bicycle U-turn cross	311	774	149%	0.00
Bicycle direct cross	273	383	40.4%	0.00
Bicycle midblock cross	325	532	63.9%	0.00
Vehicle U-turn	325	802	146%	0.00

Table 5.54. Summary of bicycle crossing geometry and signal splits.

Geometry	60/40	75/25		
Travel Time (sec):	**mean**	**mean**	**% Diff.**	**p-adj**
Bicycle U-turn cross	670	414	-38.2%	0.00
Bicycle direct cross	329	326	-0.9%	0.00
Bicycle midblock cross	438	419	-4.2%	0.00
Vehicle U-turn	693	434	-37.3%	0.00

Table 5.55. Summary of bicycle crossing geometry and midblock distances.

Geometry	600' Midblock Distance	800' Midblock Distance		
Travel Time (sec):	**mean**	**mean**	**% Diff.**	**p-adj**
Bicycle U-turn cross	721	363	-49.6%	0.00E+00
Bicycle direct cross	337	318	-5.8%	8.51E-01
Bicycle midblock cross	427	430	0.6%	1.00E+00
Vehicle U-turn	737	391	-47.0%	0.00E+00

The following table summarizes the scenarios that produced the lowest results among the bicycle crossing geometries. Each of the geometries had the lowest results at either scenario 3 or 7. The signal split of 60/40 for these two scenarios produced the lowest results, however when all 16 scenarios were averaged as shown in Table 5.54, the 75/25 split had the lowest travel time.

Table 5.56. Summary of scenarios with the lowest result values.

Geometries	Scenario	Offset Signal Design	Midblock Distance (ft)	Cycle Length (sec)	Signal Split
Bicycle midblock cross and Vehicle U-turn	3	Offset	600	90	60/40
Bicycle U-turn cross, Bicycle direct cross and Vehicle U-turn	7		800		

5.5 Simulated Pedestrian and Bicycle Crossing Results Compared to HCM Results

A travel time comparison was made between the results of the simulations and the results of the HCM calculations displayed earlier. The HCM calculations were made for one path through the intersection (south to north) and the simulation results were an average of all routes through the intersection. Furthermore, to display the travel time for one complete path from the HCM results, the free flow travel times along the 800 ft portions to and from the intersection were added to the travel time values shown in Table 4.11 and Table 4.12. These differences likely explain why the HCM travel time results are consistently lower than the simulation results. The pedestrian comparison is shown in Table 5.57 and the bicycle comparison is shown in Table 5.58.

Table 5.57. Pedestrian travel time comparison between simulated results and HCM calculations.

Pedestrian Geometries	Simulated Mean Travel Time per pedestrian (sec)	HCM Travel Time (south to north) per pedestrian (sec)
Two-stage Barnes Dance cross	422	363
Diagonal cross	465	395
Median cross	487	370
Midblock cross	479	695

Table 5.58. Bicycle travel time comparison between simulated results and HCM calculations.

Bicycle Geometries	Simulated Mean Travel Time per bicyclist (sec)	HCM Travel Time (south to north) per bicyclist (sec)
Bicycle U-turn cross	542	167
Bicycle direct cross	328	152
Bicycle midblock cross	428	275
Vehicle U-turn	564	N/A

The HCM calculations are a quick method to estimate travel times for pedestrians and bicyclists through an intersection. However, since microsimulation is a more extensive and thorough analysis, and produced significantly different values than the HCM in the above tables, it is then the current preferred method for analyzing pedestrian and bicycling activities at unconventional intersections.

6.0 CONCLUSIONS

The objective of this research was to consider the unique challenges for pedestrians and bicyclists at signalized superstreet intersections and recommend crossing alternatives for both users. After thorough searches for common practices that could be applied to the superstreet intersection, the research team, with the advice of a panel of pedestrian and bicycling advocates and professionals, developed several crossing options. These options were analyzed through microsimulation in PTV VISSIM and were analyzed based on average stopped delay per route, average number of stops per route, and average travel time per route.

The following sections describe the conclusions of this project including the current state of practice, invention of new crossing geometries, and conclusions of the simulations for the pedestrian and bicycle crossing geometries. Again, all of the simulations have the following similarities: 1) the origin-destination demands or volumes on each of the routes are identical, 2) the motor vehicle delays and demands were ignored in the research, and 3) all of the simulated pedestrians and bicyclists were compliant with the traffic signals.

6.1 New Crossings and Current Practice

This project conceived and tested several new crossing geometries for both pedestrians and bicyclists. The newly conceived geometries included:

- Pedestrian median cross
- Bicycle direct cross
- Bicycle U-turn cross

These new options were tested along with more conventional options such as the z-crossing, Barnes Dance, and midblock crossings.

Additionally, a thorough search of current practices throughout the country was performed. This search produced several key points.

- Engagement of the unconventional intersection community allowed professionals to discuss current tasks on unconventional projects and to offer suggestions for the superstreet project as well as increased national interest in the results of this project.
- The Bike Spot, though not applicable for this project, may benefit other intersections, as it is a unique way-finding measure for bicyclists.
- Pictures of a superstreet in Texas showing an application of the pedestrian diagonal cross aid in the visualization of a constructed pedestrian crossing here in North Carolina.
- From Utah, the diagram of the transit stop in the median is a rare look at transit locations and has potential for benefiting arterials and other locations with wide medians.

6.2 Simulated Pedestrian Crossing Geometries

As predicted, the two-stage Barnes Dance cross had the lowest average stopped delay per route, lowest average total stops per route, and lowest average travel time per route. Conversely, the median cross produced the greatest value for each of these MOEs. The diagonal cross and the midblock cross had values between the two-stage Barnes Dance cross and the median cross. The midblock cross had slightly better stopped delay times and total number of stops than the diagonal cross, however, the diagonal cross had a slightly better travel time than the midblock cross.

As for the variables that were shown to influence travel time values for the pedestrian, signal design, cycle length, and signal split all had an influence on each of the crossing geometries.

- Using travel time as the performance measure, each of the crossing geometries had an increased performance for signals that were programmed to have vehicular platoons arrive at an offset between the northbound direction and the southbound direction compared to a simultaneous arrival. These results may change based on the size of the superstreet that is being crossed.

- A shorter cycle length of 90 seconds compared to 180 seconds produced shorter travel times for all crossing geometries.
- A signal split of 60/40 compared to 75/25 resulted in a decrease in travel time for each of the pedestrian crossing geometries.

The distance of the midblock from the main intersection had the least significance on travel time among all of the geometries for the factors tested. For the two-stage Barnes Dance cross and the diagonal cross there was no significant difference between a midblock located 600 feet from the main intersection to a midblock located 800 feet from the main intersection. Additionally, the midblock cross did not produce a significant difference between the 600 feet midblock distance and the 800 feet midblock distance. However, for the median cross, a midblock located 600 feet from the intersection performed relatively better than a midblock located 800 feet from the intersection.

6.3 Simulated Bicycle Crossing Geometries

Of all the bicycle crossing geometries, the bicycle direct cross had the lowest average number of stops per route and the lowest average travel time per route, thus making the hypothesis partly true about the bicycle direct cross producing low result values. Bicyclists using the vehicle U-turn had the lowest average stopped delay per route but also had the greatest average travel time per route compared to the other three bicycle crossing geometries. The bicycle U-turn cross had the greatest average stopped delay per route and the most stops per route, opposite of the hypothesis. Lastly, when examining the midblock distances for the bicycle U-turn, the results for the 800 ft midblock distance were more comparable to the bicycle direct cross.

The major conclusions on the variables that influenced travel time for the bicycle crossing geometries are listed below:

- Vehicle platoons that arrived offset from the northbound and southbound directions had an impact on the travel times for the bicycle direct cross and the bicycle midblock cross. The offset platoon arrival resulted in shorter travel times for bicyclists traveling on these geometries.

- A cycle length of 90 seconds rather than 180 seconds produced lower travel times for each of the bicycle crossing geometries. The largest decrease in travel time between the two cycle lengths happened at the bicycle U-turn option.
- Each of the bicycle crossing geometries performed better in regards to travel time when the signals were set at a 75/25 split rather than a 60/40 split. The biggest decrease in travel time between the two splits occurred for the bicyclists using the U-turn options. However, when examining the two scenarios (3 and 7) that produced the lowest results, the 60/40 split was lower than the 75/25 split.
- The bicycle U-turn and bicyclists using the vehicle U-turn displayed significant decreases in travel time when the vehicle U-turn was located 800 feet from the intersection compared to 600 feet. The direct cross did not produce a significant difference between the two distances and the midblock cross showed no difference in the travel time values for the different midblock distances.
- The bicycle U-turn results for the 800 ft midblock location were comparable to the results of the direct cross.

6.4 Recommendations

The following sections outline the recommended pedestrian and bicycle crossing geometries to be implemented at a newly constructed signalized superstreet intersection where there is meaningful pedestrian or bicycle crossing demand. Additionally, these recommended geometries may be applied to an existing superstreet intersection to address current pedestrian and bicycle needs as well as to prepare for future pedestrian and bicycle usage.

6.4.1 Recommended Pedestrian Crossing Geometry

The two-stage Barnes Dance cross performed better than the other geometries for all three MOEs. However, the Barnes Dance is an application only considered for significantly high volumes of pedestrians, as in a busy Central Business District intersection, due to the significant time taken from the cycle for the exclusive pedestrian phases. The pedestrian geometry recommended for a more typical superstreet intersection is the diagonal cross in combination with the midblock cross. The combination of these crossings will allow pedestrians several options to cross the superstreet. The addition of the midblock cross will allow many pedestrians the option of crossing to their desired destination without even entering the main superstreet intersection, which should help ease pedestrians into this unconventional design. The extra signal needed to implement the midblock cross design should add only negligible delay and travel time to superstreet side street turning vehicles, particularly in a corridor with several superstreets where there is perfect progression. The midblock crossing will serve adjacent land uses well, and will even provide transit agencies a safe and convenient place to locate a bus stop.

Additionally, to decrease the travel time for pedestrians and ultimately increase the pedestrian performance at a superstreet, several variables should be considered. First, the superstreet can accommodate short cycle lengths, and a cycle length closer to 90 seconds would improve pedestrian travel times. Second, the arrival of the vehicle platoons can improve pedestrian performance when the platoons do not arrive simultaneously on both sides of the mainline. Fortunately, this will be the case at most superstreet intersections. Lastly, a signal split closer to 60/40 will improve pedestrian crossing travel times; however, from the motorist's perspective the superstreet performs better with a wider range in the signal split.

Ultimately the level of comfort for pedestrians crossing a superstreet lies in the design details. The crossings must be accessible, so care should be taken to ensure that the design helps pedestrians find the crossings, properly align themselves to cross, and can maintain a correct heading as they cross. Due to the complexity of the intersection, pedestrian signals are recommended for all crossings, and push buttons may not be necessary given that a typical superstreet will utilized fixed times. If an accessible pedestrian signal is not used, care should be taken to provide an audible message that tells users when it is safe to cross.

6.4.2 *Recommended Bicycle Crossing Geometry*

The bicycle crossing geometry recommended for the superstreet is the bicycle direct cross along with the shared use path at the midblock cross. Providing these two crossings allows options for bicyclists of varying skills to choose the crossing route and path with which they are most comfortable. The bicycle direct cross would allow for efficient crossing of the superstreet with minimal exposure to the major street vehicles. Detail will need to be applied in the signing and marking of the bicycle median cut when used in combination with the pedestrian diagonal cross so as to not cause confusion with the crossing pedestrians. Figure 6.1 shows a pedestrian diagonal cross in combination with the bicycle direct cross.

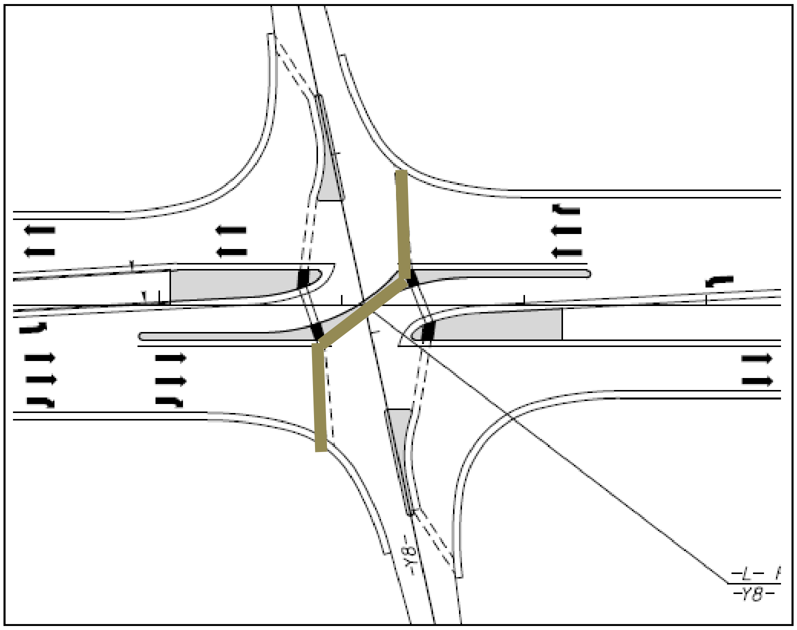

Figure 6.1. Pedestrian diagonal cross combined with a bicycle direct cross (pedestrian crossing is highlighted for effect).

Other design details will be crucial to the effectiveness of the bicycle direct cross. Bicycle detection is necessary if fixed times are not utilized so that bicyclists waiting to cross the major street can call for service. This can be achieved through thoughtfully placed and sensitized loop detectors. One should not assume that bicyclists must use the bicycle direct cross where it is applied for two reasons. First, some bicyclists may not be comfortable executing the lateral position changes necessary to move from the right side to the center of the minor street in order to be properly positioned to utilize the bicycle direct cross. These bicyclists may prefer to turn right onto the major street and stay to the right to utilize the midblock crossing. Secondly, it is also important to note that in locations where group rides frequently traverse a superstreet, storage needs in the median may be insufficient for them to use the bicycle direct cross. Group rides will likely utilize the vehicle U-turn, and therefore, the consideration of bicycle detection needs in right turn lanes from the minor street should not be dismissed just because a bicycle direct cross is provided. Furthermore, the bicycle direct cross would benefit from additional design measures taken at the superstreet. First, as with the pedestrian crossings, the bicycles would benefit from a shorter cycle length, with better performance during this test at a 90-second cycle. Second, similar to the pedestrian performance, the bicycles at a direct cross should experience shorter travel times when the vehicle platoons arrive offset as described in this report.

The bicycle U-turn crossing may be a fair competitor to the bicycle direct cross after further examination into the site characteristics, mainly vehicle volume and distance between the bicycle and vehicle U-turn locations. The performance of the bicycle U-turn crossing varied widely depending on distance to the vehicle U-turn crossing, and probably would vary greatly with vehicle volume as well, but at its best it was a good design option. While this study did not simulate signalization at the bicycle U-turn, this may be a feasible option at some sites. Also, when considering the bicycle U-turn crossing, design considerations need to be made for storage capacity of multiple bicyclists queued in the median cut.

The researchers recommend that NCDOT designers always consider that some bicyclists will use the vehicle facilities to make their movements even when off-roadway treatments have been provided. Signal detectors that sense bicycles, sharrows, and other considerations should be provided as defaults at the appropriate places in the vehicle lanes even where a bicycle direct cross or bicycle U-turn cross has been provided.

6.5 Need for Further Research

6.5.1 Bicyclists and Pedestrians

Further research into bicyclists and pedestrians at superstreets should include:

- Modifications to the Highway Capacity Manual to determine level of service for pedestrians and bicyclists at unconventional intersections, quantitative as well as qualitative (ease of crossing, comfort, etc.).
- A look into the most effective way-finding signs to be added to the MUTCD for pedestrians and bicyclists at unconventional intersections.
- A look into the operational benefits to bicyclists at superstreets and other unconventional intersections when bicycle detection is used.

6.5.2 Superstreets

Additional research for superstreets should include ways in which to better accommodate large vehicles, particularly emergency vehicles at both urban and rural locations, and large farm equipment in rural applications. Possible modifications may be to use signal pre-emption for emergency vehicles and mountable curbs as opposed to maneuvering the U-turn with large equipment.

7.0 PUBLIC OUTREACH MATERIALS AND FOCUS GROUP

To help demonstrate the recommended crossing routes for pedestrians and bicyclists at a superstreet, outreach materials were developed for public use. The following section discusses the public outreach materials that were developed and the outcomes of a focus group on these materials.

7.1 Public Outreach Materials

Three forms of content for outreach materials were developed to detail pedestrian and bicyclists’ activities at a superstreet including a brochure, presentation slides and a video simulation. The presentation and the video were developed in full by the research team, while the brochure was developed in coordination with the communication office of NCDOT for consultation on the graphics. The presentation slides and the brochure can be found in Appendix D, Figure D1 and Figure D2, respectfully. These materials have been revised to reflect the comments and suggestions from the focus group.

The brochure and presentation cover a brief overview of the operation of a superstreet from the vehicle perspective as well as detail the recommended ways to cross a superstreet as a pedestrian and as a bicyclist. The simulation video shows a bird’s eye view of the entire intersection and also follows the recommended crossings from the ground level.

7.2 Focus Group

Drafts of the outreach materials were constructed and presented to a focus group. The individuals at the focus group were given the opportunity to discuss and comment on the materials. The main suggestion was that the materials should have a clear and concise message; less detail and brief descriptions were favored. For example, the brochure depicted the same base image showing the pedestrian and the bicycle crossing facilities. The focus group suggested that displaying the bicycle crossing facilities on the same graphic used to explain pedestrian movements was confusing. Also, while possible movements for the pedestrian were depicted from one approach, the focus group requested that the image focus on only one path through the intersection. The crossing should be further broken down into three separate pictures, zoomed in to the critical features, instead of one large diagram. The three images should show: 1) an aerial view close-up of the diagonal crossing, indicating only the pedestrian path through the intersection from the southeast corner to the northwest corner; 2) an aerial view close-up of the mid-block crossing with the pedestrian path indicated; and 3) a ground-level view from one of the corners of the superstreet intersection. Also, where feasible, bulleted text was preferred over detailed paragraphs. The group further mentioned that the benefits of the pedestrian crossing should be highlighted; such as only crossing one direction of traffic at one time, and that the islands or refuges aid the crossing pedestrian. The group also wanted to see the intersection in relation to the surrounding land use.

For the bicyclists, the group suggested that the brochure should more clearly state that bicyclists also have the option of taking the lane and using the motor vehicle paths. The group wanted to see where the signals would be located on the diagram and specifically the location of any bicycle signals, if used. The group noted that motorists may be confused by the location of bicyclists on the left side of a lane and that additional signage may be needed to clarify this unexpected bicycle behavior.

The focus group indicated that they better understood the pedestrian or bicyclist movements when the crossing facilities were overlaid on a photographic aerial of a real intersection, as was shown during the presentation slides. As with the brochure, though, the group felt that focusing on only one crossing for one path for one mode per slide was easiest to understand.

For the videos, the group favored the flyover of the intersection and suggested that this portion be longer to see how all the pedestrians, bicyclists, and motorists interact. Furthermore, the group thought that the video helped to clarify the crossings and should be considered at public forums in addition to the brochure and presentation.

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