COMPARING THE OPERATIONAL EFFICIENCY OF SIGNALIZED INTERSECTIONS WITH EXCLUSIVE AND CONCURRENT PEDESTRIAN PHASE OPERATIONS CONSIDERING PEDESTRIAN NON-COMPLIANCE

by

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B.S. Engineering, Bangladesh University of Engineering and Technology (BUET), 2015

Submitted to the Graduate Faculty of

the Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Master of Science in Civil Engineering

University of Pittsburgh

2017

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

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COMPARING THE OPERATIONAL EFFICENCY OF SIGNALIZED INTERSECTIONS WITH EXCLUSIVE AND CONCURRENT PEDESTRIAN PHASE OPERATIONS WHEN CONSIDERING PEDESTRIAN NON-COMPLIANCE

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University of Pittsburgh, 2017

Intersections are critical locations for pedestrian safety and have a role in traffic operational efficiency. To improve pedestrian safety, the Exclusive Pedestrian Phase (EPP) was developed in the 1960s, which adds a phase entirely for pedestrian movements without any conflict with vehicles. The EPP is believed to be the safest type of pedestrian protection and has been installed in many places instead of Concurrent Pedestrian Phase (CPP). CPP allows pedestrians to cross in parallel to moving vehicles which allows conflicts between turning vehicles and pedestrians. The research hypothesis was to explore whether EPP has encouraged pedestrian non-compliance (crossing without the walk signal) and conflicting pedestrians (crossing in the direct path of a vehicle) or not and what the impact of such behavior is on vehicular intersection delay. This pedestrian behavior may lead to a less safe situation for pedestrians.

The research compared 8 pairs of intersections representing both EPP and CPP operations, which were selected based on similar area type and intersection geometry. The intersections selected were in the Pittsburgh urban area with one lane approaches and simple two-phase or three-phase traffic signal operations. Pedestrian crossings were observed and classified at those intersections, which provided the number of non-compliant and conflicting pedestrian's movements. Four of the 16 intersections with EPP, in four different land use types, were then

analyzed using the traffic simulation tool Synchro. The results of the analysis revealed the impact of non-compliant crossings on intersection vehicular delay. Analysis of the intersections was done in Synchro for different cases by modifying conflicting pedestrian volume and pedestrian phasing type, which provided a comparison of intersections delays for compliant and non-compliant crossings and the conversion of operations to CPP.

The research findings, based on the field observations, were that non-compliant crossings were significantly higher for all of the intersections with EPP when compared to similar CPP intersections. For these highly non-compliant EPP crossing intersections, changes in intersection delay was simulated under the condition of compliant behavior and delay was found to decrease slightly. Another case of total conflicting behavior of pedestrians with EPP was also simulated and intersection delay also increased. However, when the conversion of an intersection operation from EPP to CPP was modeled, delay decreased by more than 50%, even with a very high number of conflicting pedestrians.

In summary, it was found that intersections with EPP encourages pedestrian non-compliance behavior which also increases intersection delay. Even if pedestrian behavior was altered, to be more compliant, the delays would not be changed significantly. However, when an EPP intersection is converted to CPP operations, delays decreased significantly, and intersection operations improved. This could also result in improved pedestrian safety because pedestrian crossing compliance is much higher at intersections with CPP, as revealed by the research.

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PREFACE

This thesis was submitted as a part of the Master's degree requirements in Civil and Environmental Engineering with a concentration in transportation Engineering at the University of Pittsburgh. It was a result of tremendous amount of data collected from May 2017 to September 2017 and analysis afterwards. Several people have contributed during the journey.

I would first like to thank and send my gratitude to my advisor Dr. Mark J. Magalotti P.E., who was not only my advisor but also treated me like my guardian. His continuous support, specific guidelines, unlimited patience, even when I was behind my schedule, was the most important thing during this research. Without his continuous inspiration and appreciation, I may not be able to finish this on time. I would also like to thank Amanda Purcell, City of Pittsburgh Traffic Engineer, for providing the list of intersections with Exclusive pedestrian phase and her interest in the research. I would also like to thank my committee members for their guidance.

At the end, I would like to thank my fiancé Faria Amin for her continuous inspiration and bearing with me through the stressful days. I would like to thank my parents for their prayers and keeping faith in me every single day.

1.0 INTRODUCTION

This section provides an overview of the research and introduces the basic concepts of the process followed. It introduces the background, hypothesis, objectives and brief methodology of this research. The research focused on the exclusive pedestrian phase which is a special type of pedestrian phasing to prioritize pedestrians in the intersections. The focus of the research was to compare two types of pedestrian signal phasing, Concurrent Pedestrian Phasing (CPP) and Exclusive Pedestrian Phasing (EPP) from the perspective of pedestrian compliance and intersection performance.

1.1 BACKGROUND

Walking is a fundamental and sustainable mode of travel and every traveler is a pedestrian for a certain portion or the entire portion of his or her travel. But of all road users, pedestrians are among the most vulnerable in the road, particularly with increasing vehicle traffic [1]. Different measures are being taken to improve pedestrian safety but improving pedestrian safety at intersections remains a critical issue. Even after signalization of intersections the number of accidents involving pedestrians often remains high. To solve this issue, EPP has been introduced in many intersections as it prioritizes pedestrian rather than traffic. Henry Barnes, who was a strong advocate of EPP, implemented it in a few intersections of New York and Baltimore, while he was traffic commission of New York around 1962, which was considered a success. Following this success, it started being used in various parts of the world. [2]

EPP stops all vehicular movement and allows pedestrian access to cross in any direction at the intersection, including diagonally in many intersections. The purpose of an EPP for the signal operations was to clear the intersection of vehicles, allowing safe and uninterrupted movement of pedestrians in any direction and during the vehicular phase, allowing better movement of vehicles without pedestrian interference. This would improve the safety of pedestrians and reduce the potential for pedestrian-vehicle conflicts and collisions. But, the overall operational efficiency of vehicles in an intersection maybe reduced due to the introduction of an exclusive pedestrian phase. The reason is, with the exclusive pedestrian phases in place, an additional pedestrian phase is added. Length of this added phase may be between 20-24 seconds or more depending on the diagonal crossing length, pedestrian profile etc. [3]

The long waiting time due to added pedestrian phase may make a pedestrian frustrated as they try to shorten distance and reduce waiting time. In such a case, pedestrians often do not wait for the pedestrian phase, potentially resulting in unexpected interactions between pedestrians and vehicles. Also, the requested pedestrian phase may go unused if there is no pedestrian crossing in the intersection, but the drivers are delayed and have to wait for the phase to run its course.

There are benefits to the use of EPP, by reducing vehicle conflicts, however these benefits may be outweighed when the delays are significant for the vehicles and pedestrians. According to Federal Highway Administration, the safety benefit to pedestrians from this method of signal operation could be significant due to the virtual elimination of pedestrian-vehicle conflicts. But there were no details in the comparison of pedestrian crash experience between EPP and CPP [4]. On the other hand, CPP is the more predominantly used type of pedestrian accommodation at signalized intersections and therefore this comparison will assist in the selection of the appropriate accommodations at an intersection with high pedestrian volumes. The additional delays to vehicles must also be considered when evaluating the need for an EPP along with the level of pedestrian compliance to use the EPP, when compared to the CPP.

1.2 HYPOTHESIS

The author hypothesized that, EPP encourages non-compliant crossings at the intersections due to long pedestrian waiting time. These non-compliant crossings at the intersection with EPP can offset a part of the safety benefit that was supposed to be provided by eliminating pedestrian-vehicle conflicts. At the same time, EPP may also decrease vehicular operation efficiency significantly, if the traffic flow is delayed due to an increased cycle length to accommodate the additional phase for pedestrians as well as non-compliant crossings during vehicular phases.

1.3 OBJECTIVES

The objective of this thesis was to evaluate if EPP has encouraged pedestrian non-compliance, which may decline the safety benefits expected and whether the perceived safety benefits outweighs the additional vehicular delay. An additional objective was to compare the percentage of pedestrian compliance and non-compliance in intersections with EPP and CPP in different land use areas and model intersections with EPP to compare intersection delay for different pedestrian non-compliance level and signal type.

1.4 METHODOLOGY

To meet the objectives, a total of 16 intersections with EPP and CPP were selected in the City of Pittsburgh, Pennsylvania to determine the number of pedestrian compliance and non-compliance crossings. Pedestrian data was collected from the selected intersections for four hours covering morning and afternoon peak hours. The intersections were selected in areas of various land use types including residential areas, business areas and university areas. Among those 16 intersections, four intersections in different land use area were selected for analysis in traffic simulation software Synchro to compare intersection delay for different cases. The cases covered current operating conditions, ideal condition with no pedestrian-vehicle conflicts, extended condition with higher pedestrian-vehicle conflicts and an alternate condition considering the intersections having CPP instead of EPP operations. Additional vehicular volumes data and pedestrian-vehicle conflict data was collected for four selected intersections to compare intersections operational performance measured by intersection delay.

1.5 SUMMARY

This chapter provides a brief description of the topic of exclusive pedestrian phase operation and the need of comparing EPP and CPP for pedestrian compliance and vehicular delays. The author hypothesized that exclusive pedestrian phase may increase number of pedestrian non-compliance crossings, which may eventually decrease intersection’s overall operational performance by adding further delay due to non-compliance pedestrians conflicting with vehicles. To analyze the hypothesis, a methodology was developed to collect data, compare operations with and without EPP using the Synchro traffic simulation tool. The simulation results were then analyzed to determine the benefits or the EPP when compared to concurrent pedestrian phasing considering the number of non-compliant pedestrian crossings.

2.0 LITERATURE REVIEW

The following provides a summary of the literature review conducted on the research topic. Relevant reviewed literature included the definition of CPP, EPP, pedestrian compliance and non-compliance, and pedestrian-vehicle conflicts at signalized intersections. Academic research on the topic covering pedestrian compliance, pedestrian crossing behavior, pedestrian-vehicle conflicts, safety and delay was reviewed. Published field studies of pedestrian compliance and current published guidelines on the use of EPP was also reviewed which provided the basis of the hypothesis and methodology.

2.1 CONCURRENT AND EXCLUSIVE PEDESTRIAN PHASE

CPP is the most common and used all over the world, but there are so many places where EPP has also been used. A concurrent phasing operation allows pedestrian to cross parallel with the vehicle traffic on any approach having a green indication. Both pedestrians and vehicles share the same phase of traffic signal which allows concurrent flow of traffic and pedestrians (Figure 2-1). Pedestrian conflicts with the flow of traffic due to right turning and left turning movements across the pedestrian crosswalk. The conflict may be also from the vehicles of right turns on red (RTOR). Alternatively, an exclusive pedestrian phase is only for all pedestrian crossings which stops all the vehicular movement and pedestrians can cross any direction marked in the intersection (Figure 2-2). This type of phasing may be used with a RTOR prohibition also. In many places, diagonal crossing is also allowed, and diagonal crosswalk markings are provided to guide the movement.

EPP increases the overall cycle length of the signal, but ensures minimum interactions of pedestrian with the traffic. Theoretically the interaction may happen only if RTOR is allowed in the intersections with EPP.

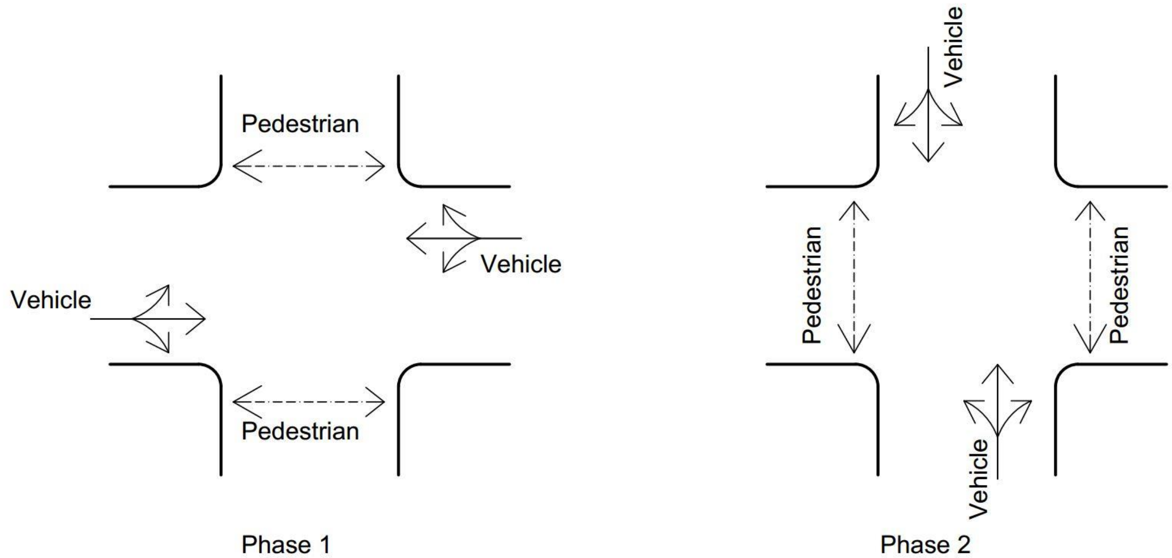

Figure 2-1 Simple two-phase intersection with Concurrent Pedestrian Phasing

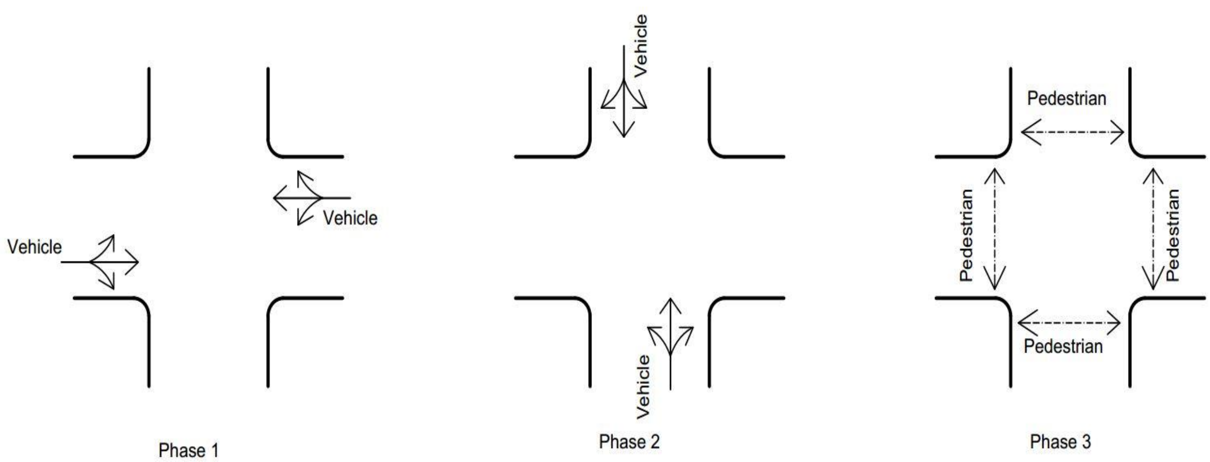

Figure 2-2 Simple three-phase intersection with Exclusive Pedestrian Phasing

2.2 PEDESTRIAN COMPLIANCE AND PEDESTRIAN-VEHICLE CONFLICT

The interaction between pedestrian and vehicle in both intersections with CPP and EPP are not always ideal. Due to non-compliance of pedestrians to intersection crossing rules, the interaction between pedestrian and vehicle may happen anytime and this may lead to various levels of pedestrian-vehicle conflicts in terms of safety.

2.2.1 Pedestrian Compliance and Non-Compliance

Pedestrian compliance in the context of this research, was based on Pennsylvania state pedestrian laws stated in section 3541, section 3542 and section 3543 of Title 75 Vehicles created by the Pennsylvania General Assembly, because this was the state where the data was collected. The laws for pedestrian crossings at signalized intersections can be summarized as follows:

- Pedestrians must obey the instructions of police officers and traffic controllers.
- No pedestrian shall suddenly leave a curb or other place of safety and walk or run into the path of a vehicle
- No pedestrian shall cross a roadway intersection diagonally unless authorized by official traffic-control devices or at the direction of a police officer. When authorized to cross diagonally, pedestrians shall cross only in accordance with the signal pertaining to the crossing movements. (Title 75: Special Vehicles and Pedestrians , 1976) [5]

For this research, in the case of an intersection with an EPP, pedestrian compliance to intersection crossing rules means, the vehicle signal indications were red in all approach and there was a walk sign for pedestrians. Pedestrian non-compliance means, the traffic lights were green in any approach and a pedestrian was crossing, even if there was very few or no vehicles entering the intersection. In the case of an interaction with CPP, if someone was crossing the road in the direction traffic had green lights and pedestrian had walk signal then it was compliance and when the pedestrian was crossing the street and walk sign was not on or flashing don’t walk sign was on and signal was green for traffic, then it was pedestrian non-compliance.

2.2.2 Pedestrian-Vehicle Conflicts

Pedestrian non-compliance to intersection crossing rules creates pedestrian-vehicle conflicts. A pedestrian-vehicle conflict can be defined as an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged [6]. As crash statistics alone are inadequate for the study of pedestrian-vehicle conflicts because of data quantity and quality issues [7], traffic conflicts can work as a reliable surrogate for traffic safety measures as conflicts are more frequently observed than crashes and a large amount of conflict data can be collected from the field [8][9]. Collecting this type of information, as compared to crash data, can provide a better indicator of the level of safety for pedestrians at the intersection. The conflicts can be categorized in the following four types: [8]

Undisturbed Passage: This means there is no possibility of any conflict and pedestrian encounter no interaction with a vehicle. This happens when pedestrian cross the intersection during pedestrian phase and there are no turning vehicles.

Potential Conflict: There is relatively low likelihood of a collision in this case because of nonverbal negotiation of who would yield, such as eye contact, hand gestures or yield law. This can occur when the driver is slowing to a stop or when a driver is waiting to make a right turn or left turn movement.

Minor Conflict: There is a small chance of a collision between the pedestrian and a motor vehicle and there was an avoidance maneuver such as slowing down or running with more than enough time before a collision would occur. For this case, the speed of the traffic has to be low and it would stop a few feet away from the pedestrian. Due to low speed, it normally does not lead to a fatal collision.

Severe Conflict: There is a high probability of fatal accident in this case in case of severe conflict. Either vehicle or pedestrian must take a sudden action to avoid the collision. Normally vehicles make a strong evasive action such as hard break or sharp turn to avoid the collision with the pedestrian, or a pedestrian must make an erratic, unplanned movement such as jumping back onto the sidewalk or springing out of the vehicle's path in order to avoid the collision with the vehicle.

Among these four types of conflict only undisturbed passages are considered as pedestrian compliance, other three categories are considered as pedestrian non-compliance for this research.

2.3 ACADEMIC RESEARCH

To address pedestrian safety a substantial amount of research has been done, but there is still much work to do and there are new issues to explore from a different and new perspective to analyze the safety measures. There are various causation factors responsible for pedestrian safety at an intersection and different studies have been done to analyze those factors and measure the importance. But, surprisingly, there have been relatively few studies performed comparing concurrent and exclusive pedestrian phase form the viewpoint of number of non-compliant crossings, and change in delay and Level of Service (LOS) of the intersections. Some researched pedestrian compliance, some observed changed crossing behavior, some evaluated interactions with traffic while some have done a safety analysis by comparing the crash history after the implementation of an EPP operation.

2.3.1 Pedestrian Compliance of EPP

After the implementation of an exclusive pedestrian phase, it is very essential to understand how users are accepting this, as any safety enhancement can be a failure if the people did not use the feature the way it should be used. A positive and accepting perspective by pedestrians is crucial for the success of an exclusive pedestrian phase as non-compliance will lead to pedestrian-vehicle conflict which will undue the goal of EPP. Some research findings revealed that, the public showed a positive attitude toward exclusive pedestrian phases and they understood the change in the way the intersection work and accepted it [10]. McKernan et al. investigated pedestrian compliance of concurrent and exclusive pedestrian crossing at 42 signalized intersections to find whether there are differences between pedestrian compliance with EPP and CPP. Using binary regression model to estimate pedestrian compliance considering pedestrian phasing type, vehicular and pedestrian volume, crossing distance and speed limit they found significantly higher pedestrian compliance with concurrent pedestrian phasing (70.33%) than exclusive pedestrian phasing (20.30%) [8]. However, they did not explore how the non-compliance impacted traffic operations, which is the subject of this research.

2.3.2 Pedestrian Crossing Behavior at the Intersections With EPP

To measure the benefits of an EPP operation, it is also necessary to understand pedestrian crossing behavior in such an unconventional setting. Few studies investigated the changes in pedestrian crossing behavior following the implementation of an exclusive pedestrian phase. In Hediyeh et al.'s study of the changed behavior using spatiotemporal gait parameters (step length and step frequency), both average step length and walking speed was found to increase significantly for diagonal crossing compared with conventional pedestrians crossing on the crosswalks. Additionally, pedestrians seem to have the tendency to increase their step length more than their step frequency to increase walking speed. [11]

Medina et al.'s study at a busy intersection of a college campus with EPP found 15th percentile walking speeds for the diagonal and the parallel crossings were 4.37ft/s and 4.49 ft./s respectively which are higher than the 3.5 ft./s as recommended by the Manual on Uniform Traffic Control Devices (MUTCD). Though, a college campus as the location with many young people may had some effect on increased walking speeds. In addition, they observed fewer pedestrian to cross diagonally than parallelly. [12] Some other researchers also found higher pedestrian crossing speeds particularly for diagonal crossing in the intersections with EPP [13]. In the absence of a diagonal crossing, when the crossing destination is opposite diagonal corner, higher walking speed was observed through the first half of the crosswalk. [13]

2.3.3 Pedestrian-Vehicle Interactions at the Intersections with EPP

The main purpose of implementing an exclusive pedestrian phase is to reduce the interaction of pedestrian with the traffic. Zhanga et al. compared exclusive and concurrent pedestrian phasing from the perspective of severity of interaction with motor vehicles, where they observed and classified pedestrian crossing and severity of interaction. From their research, they found that, pedestrians experience lower interaction severity with motor vehicles with the exclusive pedestrian phase compared to crossing on the green light with concurrent pedestrian phase. They also found lower crash numbers in cases of exclusive pedestrian phase, but crash severity was higher than crashes of concurrent pedestrian phase. [14] Yang et al. (2005) also found exclusive pedestrian phases to be effective measures to reduce interactions between pedestrians and motor vehicles at signalized intersections [15].

2.3.4 Safety Analysis of the Intersections with EPP

Garder tested the safety benefit of exclusive pedestrian crossing at three sites in Sweden and found EPP to be beneficial in a small town and suggested that exclusive pedestrian phasing may not be effective in the urban areas due to the high numbers of non-compliant crossing behavior. He suggested that shorter waiting times will decreases the number of pedestrian non-compliance [6]. As the sample size was not very large, more detailed study is required to say whether exclusive pedestrian phase is beneficial or not form the safety enhancement perspective.

Zaidel et al. also tested the relationship between pedestrian crossing types and average number of crashes including both pedestrian and vehicle crashes. From their analyzed 5-year data from 320 signalized intersections in Israel, they concluded that, pedestrian crossing type has no effect on vehicular crashes and minor effects on pedestrian crashes. They identified vehicle volume, pedestrian activity, and intersection complexity as the reasons behind pedestrian and vehicular crashes. But they indicated that, exclusive and concurrent pedestrian phases may provide different degrees of pedestrian protection for different combinations of vehicle and pedestrian volume. [16] For exclusive pedestrian crossings, some researchers found a lower number of pedestrian crashes when pedestrian volume was moderate to high. [17]

Chen et al. described exclusive pedestrian phase as an effective countermeasure to reduce pedestrian crashes but at the same time, there was an insignificant increase in vehicle crashes [18]. Abrams et al. concluded that exclusive pedestrian phasing is capable of increasing pedestrian safety by completely separating pedestrian and vehicular movements, but the benefit is canceled if pedestrian compliance is low and they emphasized that, if violations are frequent, the use of exclusive pedestrian phase may be a safety hazard [19]. Agbelie et al. investigated crash data of seven years from 381 intersections in the State of Illinois and concluded that, a unit increase in the number of any signal phases would increase crash frequency by 0.4 [20].

Different researcher concluded differently in the matter of safety enhancement. No research was found stating the improvement of safety due to implementation on an EPP.

2.3.5 Delay at the Intersections with EPP

Nash et al. carried out a modelling work in SIDRA to assess the efficiency of exclusive pedestrian phases at traffic signals in the Melbourne Central Business District (CBD) and found a slight increase in pedestrian delay and a significant increase in vehicular delay [21]. EPP is entirely lost time from a vehicle perspective and adding an EPP increases lost time by 20-24 seconds. Abrams et al. indicated that concurrent pedestrian phasing will always minimize overall pedestrian and vehicle delay with the only exception occurring when pedestrian-vehicle conflict causes long queues of vehicles to form in a right-turning lane (or left-turning lane on a one-way street) [19].

2.4 FIELD STUDY

A review of field data collection and analysis of some relevant projects were conducted. This review was performed to understand how the data was collected and what the results indicated in order to provide guidance in the development of a methodology for the research.

2.4.1 Calgary, Alberta, Canada

Kattan et al. conducted a study to evaluate the pedestrian safety of an exclusive pedestrian phase at an intersection in Calgary, Canada. They collected pedestrian conflict data for six weeks and developed a Poisson regression model to predict the number of conflicts and non-compliance. Their findings showed decreased pedestrian-vehicle conflicts but increased pedestrian signal non-compliance. They found 13% of the non-compliance were safe as it was concurrent with the vehicle movement and 2% crossings were unsafe as it was perpendicular to the vehicle movement. [13] They continued the study to determine the longer-term effect of this operation on pedestrian safety. To do that, they collected data again one year after the implementation of exclusive pedestrian signal and developed four Poisson regression models to estimate the number of conflicts and non-compliance. They found some changes in the results from the previous study conducted at the same location. Their results illustrated that the number of pedestrian-vehicle conflicts and pedestrian non-compliance decreased significantly on weekdays but both non-compliant crossings and conflicts increased significantly on weekends. [22]

2.4.2 Oakland, California

Bechtel et al. conducted a similar study like Katta et al. in the city of Oakland, California to determine the safety impacts of an exclusive pedestrian signal. They also found a statistically significant decrease in the number of conflicts between pedestrian and vehicle but significant increase in pedestrian non-compliance. They concluded that exclusive pedestrian phase operation improved pedestrian safety despite the increased number of non-compliance as those non-compliant crossings were concurrent to traffic flow which make the crossings somehow safer. [23] [24]

2.5 GUIDELINES

The Manual on Uniform Traffic Control Devices (MUTCD) provides instructions on when installation of a traffic control signal is justified. The justification can be done by fulfilling one or more distinguished criteria such as eight-hour vehicular volumes, four-hour vehicular volumes, peak hour vehicular volumes, pedestrian volumes etc. The criteria are used to justify whether traffic signal control is needed or not, but does not provide any guidance regarding the type of pedestrian phasing that should be used. The guidelines provide guidance to adjust traffic signal operations and timing to provide sufficient crossing times for every cycle if pedestrian movement is very frequent, but again the type of pedestrian phasing is not provided. [25]

No guidelines regarding implementation of an EPP was provided in Traffic Signal Design Handbook published by PennDOT. Federal Highway Administration (FHWA) advised not to use EPP in intersections with low to moderate pedestrian volume during peak hours and not to allow

RTOR as this may confuse pedestrians, making them unclear about when or whether vehicles are allowed to turn across their path. (Federal Highway Administration , 2008)[4]

2.6 SUMMARY

The literature review concluded that there was not significant research on where and when to implement exclusive pedestrian phase operations to balance safety and efficiency. The academic research focused on the compliance issue, before and after crash analysis and safety benefits etc. But none of the studies examined the change in intersection delay and LOS for different types of pedestrian accommodations though the balance of safety benefits and vehicular delay is a critical component of the design and operations of signalized intersections. Nor does any of the research address how varying levels of compliance by pedestrians impacts operations or safety at the intersection.

To implement a new traffic signal or design the phasing there were developed guidelines to follow from MUTCD. But no specific guidelines for implementing exclusive pedestrian phase operations was found in MUTCD or similar sources.

Based on literature review it was concluded that a comparison of pedestrian compliance and non-compliance between intersections with EPP and CPP to find the whether it improves safety or not is needed. Again, the impact of non-compliant pedestrian crossings on intersection's operational performance also needs to be analyzed. Combing non-compliant crossings measurements with EPP performance may provide some guidelines regarding the implementation of an EPP.

3.0 METHODOLOGY

This chapter illustrates the process used to test the hypothesis and measure the effectivity of exclusive pedestrian phase operations for an intersection from operational perspective. The process included selection of study locations for collecting pedestrian volume, compliance and non-compliance crossing data, pedestrian-vehicle conflict data and traffic volume data. The collected data provided required information to build models in the Synchro traffic simulation tool which produced information to prove the hypothesis and develop a correlation between intersection delay and pedestrian non-compliance. Figure 3-1 shows the methodology followed.

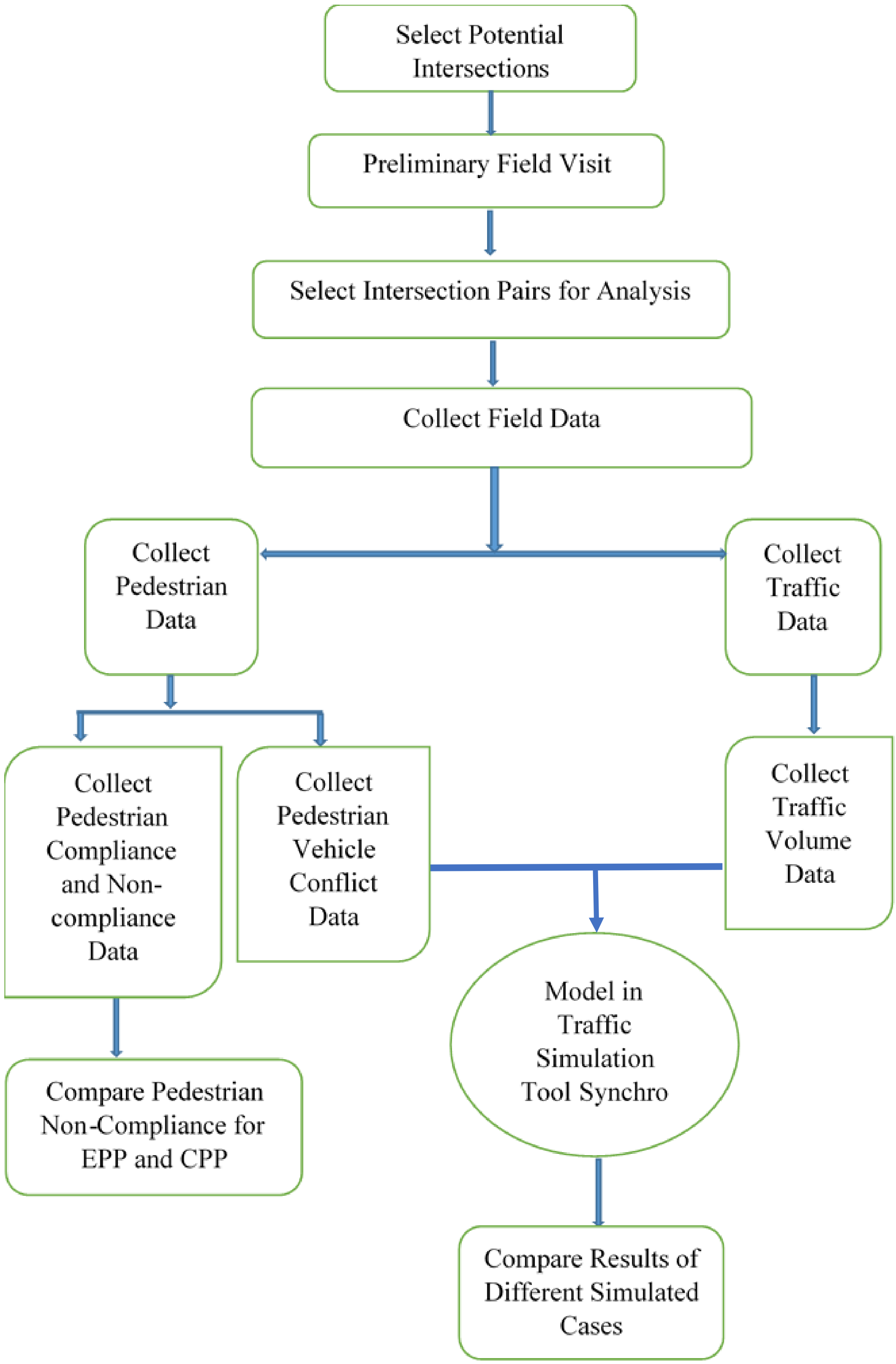

Figure 3-1. Flow chart of methodology

3.1 SELECTION OF INTERSECTIONS

To conduct the analysis of intersections with EPP, both intersections with CPP and EPP were selected. Intersections with CPP were selected matching the location and geometric type with the intersections with EPP in the same geographic area, so that they represent similar types of intersections. It is not possible to selected two intersections that were identical with exclusive and concurrent pedestrian phase because each intersection has distinctive characteristics, traffic volume, pedestrian volume and land use patterns.

Intersections were selected to serve two different analysis purposes, one was to collect pedestrian crossings data and analyze pedestrian-vehicle non-compliance and conflicts at the intersections. The second purpose was to use the simulation model to compare change in delay of each approach and the total intersection for different cases of pedestrian behavior. A list of 22 intersections with EPP was provided by the City of Pittsburgh Public Works Department. Fifty potential intersections including those 22 intersections were visited to collect intersection details, such as signal type, number of legs and number of phases. Based on the collected intersection details, one intersection with EPP was matched with another intersection with CPP that was similar in intersection's geometric characteristics and geographic location. The land use of each pair was same, or they were adjacent to each other. Eight sets of intersections, constituting two types of pedestrian phasing, were selected for four diverse types of land use patterns. Accounted land use patterns were university areas, business areas, residential areas and mixed areas. Table 3-1 shows the list of 16 intersections studied. These intersections were used for the first data collection and analysis step, which was to compare pedestrian compliance and non-compliance rates.

Table 3-1. Selected 16 intersections and their land use type

Pair No.	Pair Intersection Name	Phasing Type	No. of Phases	Land Use Type
1	Forbes Ave. -Shady Ave.	Exclusive	3	Residential
	Murray Ave.- Beacon St.	Concurrent	2	Residential
2	Fifth Ave.- N Craig St.	Exclusive	3	Residential
	Fifth Ave.- Morewood Ave.	Concurrent	2	University
3	Bigelow Blvd.-O'Hara St.	Exclusive	3	University
	Bayard St.-Bellefield Ave.	Concurrent	2	Residential
4	Bayard St. -Craig St.	Exclusive	3	Mixed
	Bayard St.-Morewood Ave.	Concurrent	2	Residential
5	Fifth Ave.-Smithfield St.	Exclusive	3	Business
	Sixth Ave.- Smithfield St.	Concurrent	2	Business
6	Fifth Ave.-Wood St.	Exclusive	3	Business
	Sixth Ave.- Wood St.	Concurrent	2	Business
7	Forbes Ave.-Murray Ave.	Exclusive	3	Mixed
	Fifth Ave.-Shady Ave.	Concurrent	2	Residential
8	Forbes Ave.-Morewood Ave.	Exclusive	3	University
	Forbes Ave.-Beeler St.	Concurrent	2	University

Among, the 8 sets of selected intersections, 4 intersections of the 8, with exclusive pedestrian phases, were selected to analyze in the simulation tool. Selection criteria was average daily traffic volume and land use pattern. These were selected for their variety of volumes and land use types to simulate the impacts of varying levels of pedestrian compliance and potential conversion to concurrent pedestrian phasing. Table 3-2 shows the selected intersections with selection criteria.

Table 3-2. Selection criteria of intersections to use in simulation tool

No.	Intersection Name	Pedestrian Phasing Type	Total peak hour traffic volume	Land use
1	Forbes Ave.-Murray Ave.	Exclusive	754	Mixed
2	Forbes Ave. -Shady Ave.	Exclusive	1,168	Residential
3	Fifth Ave.-Wood St.	Exclusive	1,628	Business
4	Bigelow Blvd.-O'Hara St.	Exclusive	1,034	Educational

3.2 DATA COLLECTION

Data collection included information on pedestrian crossings during 4 hours of a typical weekday as well as vehicular information, traffic signal operations and timings. All this information was the basis of the analysis and testing of the hypothesis.

3.2.1 Intersection Characteristics Data Collection

Intersections characteristics data was collected in two phases. Primarily intersection geometry, signal phasing and land use data was collected for 50 potential intersections which led to the selection of 8 pairs of intersections. Detailed data was then collected for the selected 4 EPP intersections of 8 pairs which included pedestrian and traffic volume data. At all 4 intersections, geometric and operational characteristics data was collected to aid pedestrian-vehicle conflict analysis and building of the simulation model. A few of the intersections with EPP included the presence of diagonal crossings though there were no pavement markings indicating that as a permitted movement. Data collected for intersections with exclusive pedestrian phases included, signal timing and phasing, pedestrian timings, number of turn lanes or turn prohibitions, provision for right-turn on red, actuation for exclusive pedestrian phase, presence of on street parking etc.

3.2.2 Pedestrian Volume and Conflict Data Collection

To collect pedestrian volume and pedestrian non-compliance data, both a video camera method and a manual data collection method were used at the selected 16 intersections. Data was collected between March 2017 and September 2017 on weekdays during the peak hours when pedestrian and traffic activity interaction was expected to be highest. For the intersections in the university area data was collected during fall of 2017 to represent normal condition of the area. Duration of data collection was 4 hours consisting of morning peaks from 7.00 AM-9.00 AM and evening peaks from 4.00 PM-6.00 PM. Manual data collection contributed to the collection of total number of pedestrian crossings at each crosswalk of the intersection at every 15-min interval. During manual data collection, the researcher also confirmed land use pattern, pedestrian signal type and number of signal phases that was recorded during the preliminary survey to select the intersection pairs.

To collect pedestrian non-compliance data, recordings of video cameras were used. A video camera was mounted on a tripod in a suitable location to cover the intersection. Video recordings provided an accurate way to categorize pedestrian non-compliance and pedestrian-vehicle conflicts. Pedestrian non-compliance data was then used to compare percent non-compliance crossings between EPP and CPP. All types of conflicts were summed together covering minor and major conflicts and data was used to simulate existing condition of the intersection. The non-compliance data was also used to simulate extended conflicting conditions considering all the non-compliant pedestrians creating a conflict with the traffic.

3.2.3 Traffic Volume Data Collection

Traffic volume data was required to analyze the 4 selected intersections in the traffic simulation tool. Traffic volume data was collected from video recordings for the same morning and evening peak hours used for pedestrian volume data collection. Volume data was collected separately for all the movements allowed in the intersection at each 15-minute interval. An electronic counting board, JAMAR counter was used to count traffic volume from the video recordings. Traffic volume data provided heavy vehicle percentage, number of turning vehicles and one peak hour for each morning and evening peak to use in traffic simulation tool. Peak hours were determined by calculating the highest consecutive traffic volumes of four consecutive 15-minute intervals. Along with the volume data, posted speed limit was also collected.

3.2.4 Selection of Simulation Tool

The researcher analyzed the available traffic simulation tools and concluded that the Trafficware software Synchro Studio 9 was best suited for the purpose. A traffic simulation tool was needed to that could incorporate exclusive pedestrian phase operations and pedestrian-vehicle conflicts to analyze the impact of pedestrian behavior on vehicle delay due to non-compliant crossings. Synchro Studio has built in functions for both. Again, Synchro allowed to input and vary conflicting pedestrian volume, even in the case of EPP operations, which was much needed for the analysis. Micro simulation software Vissim was also compatible for this research, but Synchro is used highly in the industry to design such selected intersections and it allows to optimize intersection delay and split which helped to analyze and compare different cases.

Synchro defines conflicting pedestrians as the number of pedestrians that right and left turning must yield to. These conflicting pedestrians affect the Ped-Bike factor and increasing the number of conflicting pedestrians reduces the saturated flow rate of right turns and left turns conflicting with these movement. In summary Synchro was selected to replicate the field scenarios of intersections with both concurrent and exclusive pedestrian phase and varying levels of pedestrian compliance.

3.2.5 Data Required for Model Building

The data required for building the model in Synchro for this research included intersection geometric data, traffic flow data for different approach, pedestrian volume data, pedestrian-vehicle conflict data and traffic signal phasing and timing data. Intersection geometry and traffic signal phasing data was collected from the maps acquired from Traffic Signal Asset Management System (TSAM), PennDOT website and was validated using field observation data. Pedestrian-vehicle conflict data and traffic volume data prepared from video recordings were used. For different non-compliance level, number of conflicting pedestrians were calculated and used.

3.2.6 Model Building in Simulation Tool

To compare different scenarios with different operational cases of the selected intersections, it was important to build a simulation model. To do that, each intersection geometric condition was replicated in the Synchro tool with appropriate lane and phasing arrangements. The intersection timing and phasing data collected from the field was used to create the base model for each intersection type analyzed. The simulation was done for one peak hour of operations, the maximum peak condition for both traffic and pedestrian volumes. Analysis period was 15 minutes. For each case analyzed, approach delay, approach LOS, intersection delay and intersection LOS were noted.

The analysis considered different cases to compare the change in the intersections operational efficiency measured by delay. For each intersection, the peak hour was calculated from 4 hours of collected traffic volume data taking each 15-minute interval into consideration and selecting the single highest volumes in four consecutive 15-minute intervals. For the peak hour selected, pedestrian-vehicle conflicts which actually interrupted the turning vehicles were counted from the video recordings. Availability of adjacent parking lanes, right turns on red and CBD area type were checked where applicable.

In the simulation model Synchro, after designing the intersection with collected data, simulation was done for 4 cases shown in Figure 3-2. The first 3 cases were with the EPP operating with varying levels of pedestrian compliance. In first case, current condition was modelled using counted pedestrian-vehicle-conflicts. The second case was an ideal condition with no pedestrian-vehicle conflict, because in an intersection with exclusive pedestrian phase there should not be any if pedestrians are fully compliant. This case type was selected because it represents the ideal condition.

The number of pedestrian-vehicle conflicts might change depending on time and day. So, in the third case, all non-compliant pedestrian crossings were considered as the number of conflicting pedestrians which indicated the worst possible condition from an operations impact perspective. In the fourth case, the intersection was considered having a concurrent pedestrian phase. Total number of pedestrian crossings in each leg was considered as the number of conflicting pedestrians and number of pedestrians crossing diagonally were doubled and distributed on two legs. To simulate intersections with EPP that were converted to an intersection with CPP, cycle time was modified simply by deducting the pedestrian phase time from total cycle time.

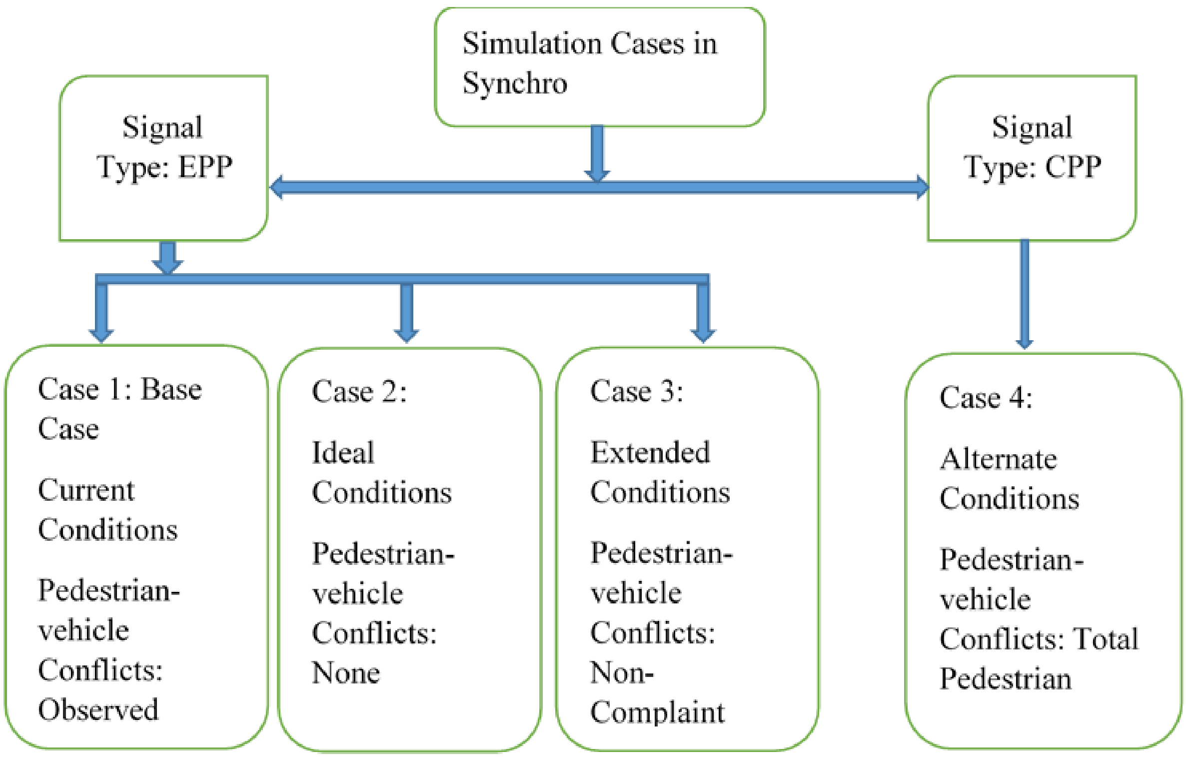

Figure 3-2. Different cases to analyze in traffic simulation tool Synchro

For each of the four-cases analyzed for the four intersections, delay was reported both for optimized and not-optimized conditions. Four intersections were then compared for different cases and change in delay was reported for varying pedestrian-vehicle conflicts and intersection signal type.

3.3 SUMMARY OF THE METHODOLOGY

The methodology was designed to best match the purpose of the study and test the hypothesis. It expanded from selection of intersection pairs to comparing intersection delay for varying pedestrian-vehicle conflicts and intersection signal types. In the interim, pedestrian and traffic data was collected which led to pedestrian-vehicle conflict analysis and comparing pedestrian compliance and non-compliance between EPP and CPP. All the collected data was then used in simulation tool Synchro for different cases which led to the testing of the hypothesis.

4.0 ANALYSIS AND MODELLING

This chapter provides the results of analysis completed to test the hypothesis. The first section provides the analysis of pedestrian crossings in intersections with EPP and CPP. Pedestrian compliance and non-compliance were compared for different intersection and land use types. The second section provides simulation results of analyzed intersections for different cases. Intersection delay obtained from the analysis was then compared for different cases and signal types.

4.1 PEDESTRIAN COMPLIANCE AND NON-COMPLIANCE

This section provides the analysis results of 16 intersections in 8 pairs to compare number of compliant and non-compliant pedestrian crossings. The intersections were in different settings covering residential areas, business areas, university areas and mixed land use areas. Every intersection pair was in similar area type or an adjacent area with a different area type. In each pair, the first intersection denoted as "intersection 1" had EPP and the second intersection denoted as "intersection 2" had CPP. Pedestrian crossing data was analyzed for four hours of the day covering morning and evening peak hours. A comparison was then made between these two types of intersection's total compliant and non-compliant crossings. Again, pedestrian crossing behavior in different land use areas was also analyzed to see if there was any relation between pedestrian non-compliance and area type.

4.1.1 Forbes Ave.-Shady Ave. and Murray Ave.- Beacon St.

These two intersections were located close to each other and both intersections had high traffic and low pedestrian volume during peak hours. From collected field data (Tables 1 and 2, Appendix A) it was observed that, in intersection 1, the non-compliance was higher than intersection 2. The number of maximum non-compliant hourly pedestrians for intersection 1 was 46 which was similar during morning and evening peak hours and for intersection 2 where the maximum number was 10. Figure 4-1 illustrates total hourly pedestrian compliance and non-compliance volume in all approach for both intersections.

For intersection 1, highest non-compliance rate was 14.37% of the total of that hour and percent non-compliance varied from 9.52% to 15.85% through the morning and evening peak hours. For intersection 2, the highest non-compliance was only 2.47% of the total pedestrians of that hour. In intersection 1, total pedestrian crossings during 4 hours of data collection was 1,049 and among them non-compliant was 132 pedestrians which was 12.58%. In intersection 2, total crossings were 889 and non-compliant crossings were 21 which was only 2.36% of the total crossings.

In intersection 1, the most non-compliant crossings occurred parallel to the traffic flow. In intersection 2, non-compliant crossings mostly occurred when there was no car on the ongoing traffic signal phase particularly during the end of vehicular phase. For both intersections, pedestrian non-compliance was high during evening peak hours. These data revealed that noncompliance activity was higher at the intersection with EPP.

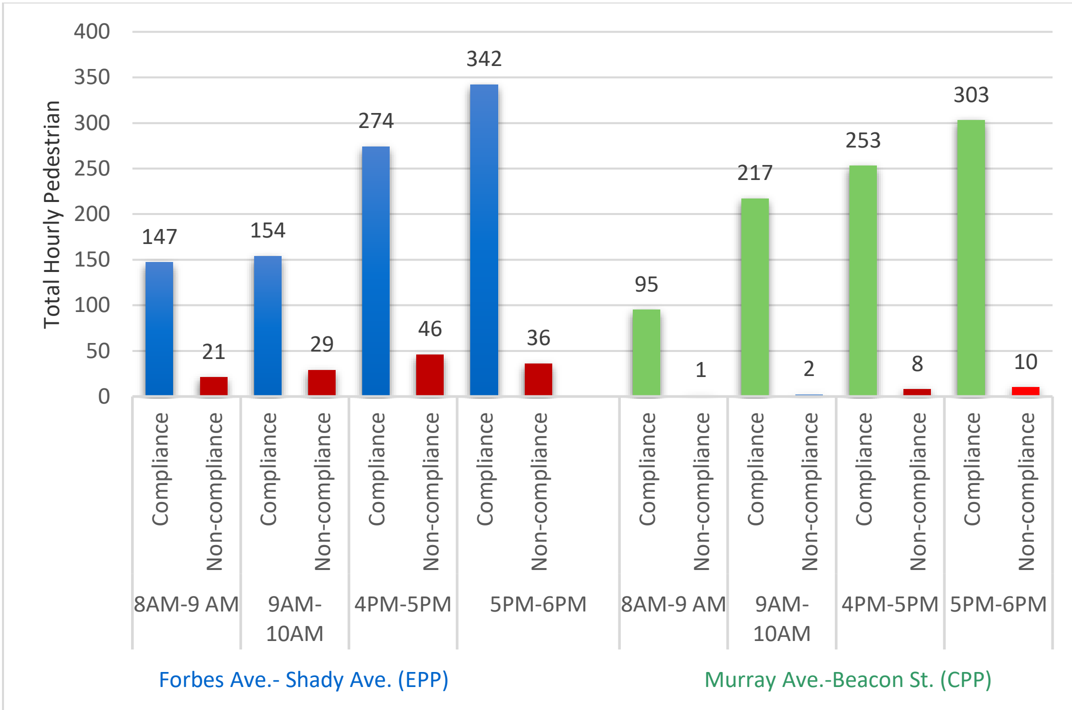

Figure 4-1. Comparison of pedestrian compliance and non-compliance in Forbes Ave.- Shady Ave. and Murray Ave.-Beacon St.

4.1.2 Fifth Ave.- N Craig St. and Fifth Ave.- Morewood Ave.

This intersection pair were in a residential area with approximately the same intersection configurations. Both intersections had high traffic volume and moderate pedestrian volume during peak hours with higher traffic flow speeds along Fifth Ave. Figure 4-2 illustrates total hourly pedestrian compliance and non-compliance volume in all approaches for both intersections. For intersection 1, highest number of non-compliance was 47 pedestrians in one hour which was 10.85% of the total of that hour and percent hourly non-compliance varied from 5.70% to 10.85% through the morning and evening peak hours. For intersection 2, the highest number of non-compliance was 14 pedestrians which was 4.03% of the total pedestrians of that hour.

For intersection 1, total number of pedestrian in all approach during 4 hours of data collection was 1,412 and 122 of them was non-compliant which was 8.64%. For intersection 2, total pedestrian for 4 hours was 1,548 and 32 of them were non-compliant which was 2.07%. So, it was evident from the data that, intersection 1 had significantly high amount of non-compliant pedestrians. Total data has been provided in Appendix A (Tables 3 and 4).Section 1.01(a)(i)Appendix A

For both intersections, most of the non-compliant crossings were found parallel to Fifth Ave. which might be due to high traffic volume and flow speed along Fifth Ave. For intersection 1 non-compliant crossing were similar during peak hours and for intersection 2 it was higher during morning peak hours. This intersection pair data supported the hypothesis that pedestrian non-compliance was higher at the intersections with the EPP.

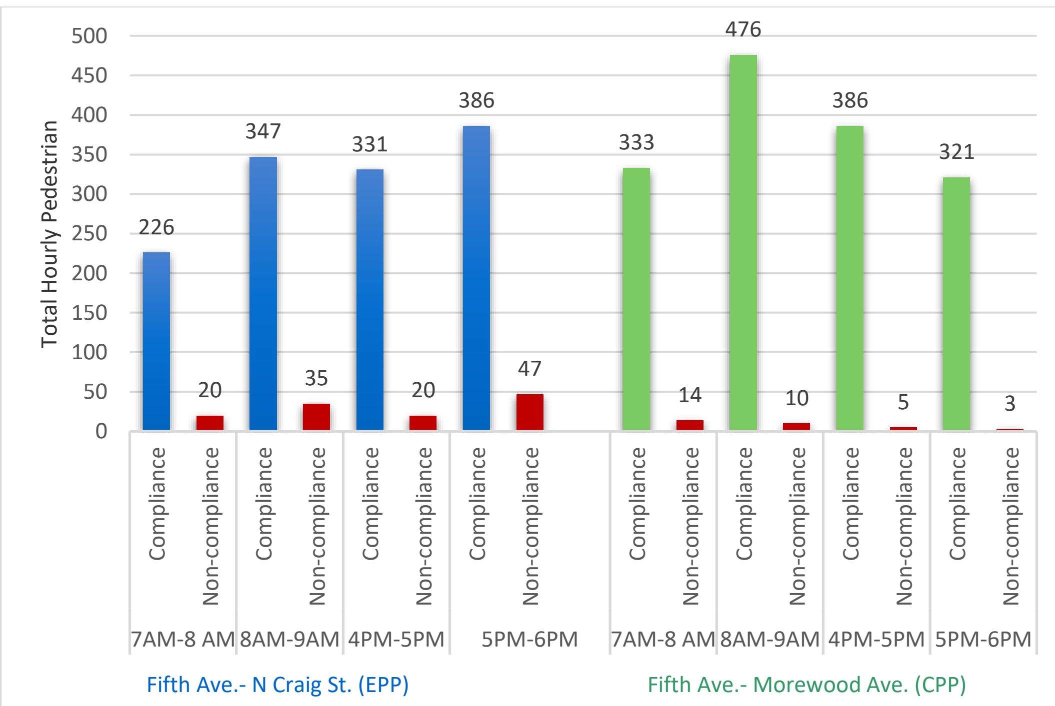

Figure 4-2. Comparison of pedestrian compliance and non-compliance in Fifth Ave.- N Craig St. and Fifth Ave. -Morewood Ave.

4.1.3 Bigelow Blvd.-Parkman Ave.-O'Hara St. and Bayard St.-Bellefield Ave.

Bigelow Blvd.-Parkman Ave.-O'Hara intersection was inside the University of Pittsburgh campus area and Bayard St.-Bellefield Ave. was just outside the campus area but mostly used by the university students. Intersection 1 had slightly different lane configurations with one extra right turning storage lane and traffic volume in intersection 1 was also higher than intersection 2. From collected field data (Tables 5 and 6, Appendix A) it was observed that, intersection 1 had very high number of non-compliance where many people were observed not to wait for the pedestrian phase but instead were crossing parallel to the traffic flow. Figure 4-3 illustrates total hourly pedestrian compliance and non-compliance volume in all approach for both intersections.

For intersection 1, highest number of non-compliance was 319 pedestrians in one hour which was 30.15% of the total of that hour and percent non-compliance varied from 26.97% to 30.15% through the morning and evening peak hours. High number of non-compliance was observed before and after class hours in adjacent buildings. Intersection 2 had insignificant number of non-compliance during observed hours. For intersection 1, total number of pedestrian in all approach during 4 hours of data collection was 2,873 and 847 of them was non-compliant which was 29.48%. For intersection 2, total pedestrian for 4 hours was 800 and 41 of them were non-compliant which was 5.13%.

In intersection 1, non-compliant crossings were observed to increase due to clan pedestrian behavior where they crossed the street while watching others cross instead of watching the pedestrian walk sign. Before and after of a class period this type of behavior was observed and sometimes pedestrians were observed to start walking during the all-red time between signal phases which led to blocking of traffic flow. High waiting times in that intersection because of the cycle length, was observed to be avoided by the students using it. High non-compliant crossings for this intersection could be related to class starting and ending times. In intersection 2, non-compliant crossings mostly occurred when there were no cars moving during the ongoing traffic signal phase.

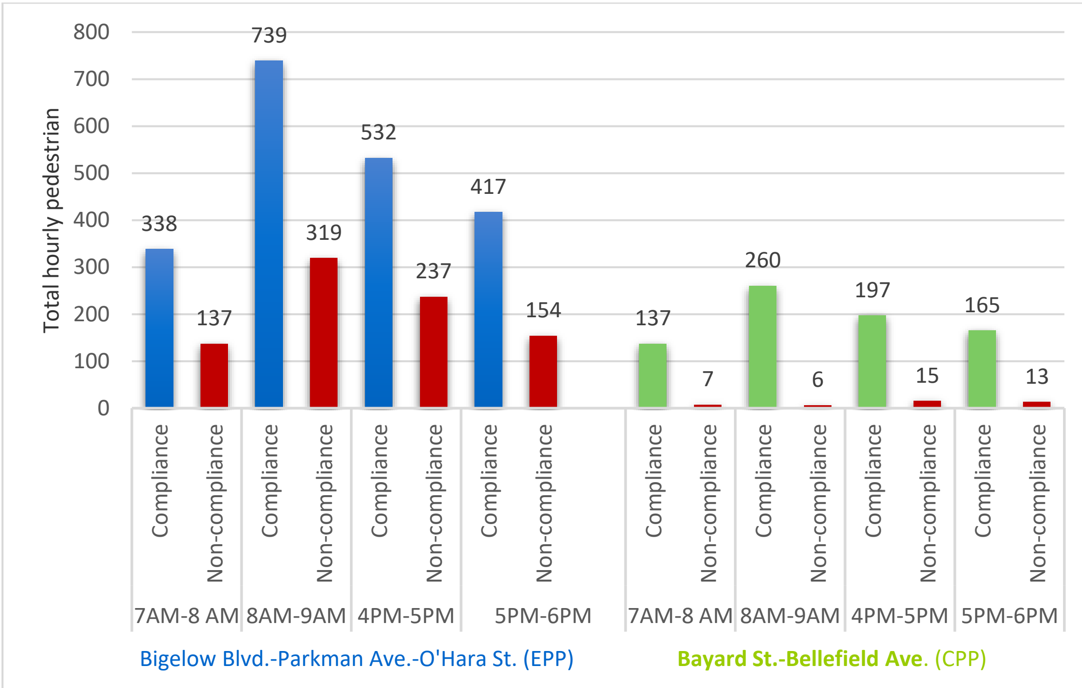

Figure 4-3. Comparison of pedestrian compliance and non-compliance in Bigelow Blvd. Parkman Ave.-O'Hara St. and Bayard St.-Bellefield Ave.

4.1.4 Bayard St. -Craig St. and Bayard St.-Morewood Ave.

Bayard St.-Craig St. was in a residential area with mixed land uses around the intersection and Bayard St.-Morewood Ave. was in residential area. Both intersections had approximately same intersection configurations and traffic volumes. From collected field data (Tables 7 and 8, Appendix A) it was observed that, intersection 1 had significantly high number of non-compliance when comparing with intersection 2.

The number of non-compliance pedestrians for intersection 1 was high with 76 pedestrian non-compliant during the 5 PM- 6PM hour, where for intersection 2, it was very few. Figure 4-4 illustrates total hourly pedestrian compliance and non-compliance volumes in all approaches. For intersection 1, percent non-compliance varied from 12.05% to 17.63% during morning and evening peak hours and for intersection 2 the highest hourly percent non-compliance was 2.54%. In intersection 2, non-compliant crossings were higher during evening peak hours. For intersection 1, total number of pedestrian in all approach during 4 hours of data collection was 1,340 and 197 of them was non-compliant which was 14.70%. For intersection 2, total pedestrian for 4 hours was 781 and 14 of them were non-compliant which was 1.79%. This also supported the hypothesis because non-compliant behavior rate has more than 5 times higher at the EPP intersection when compared to the CPP intersection.

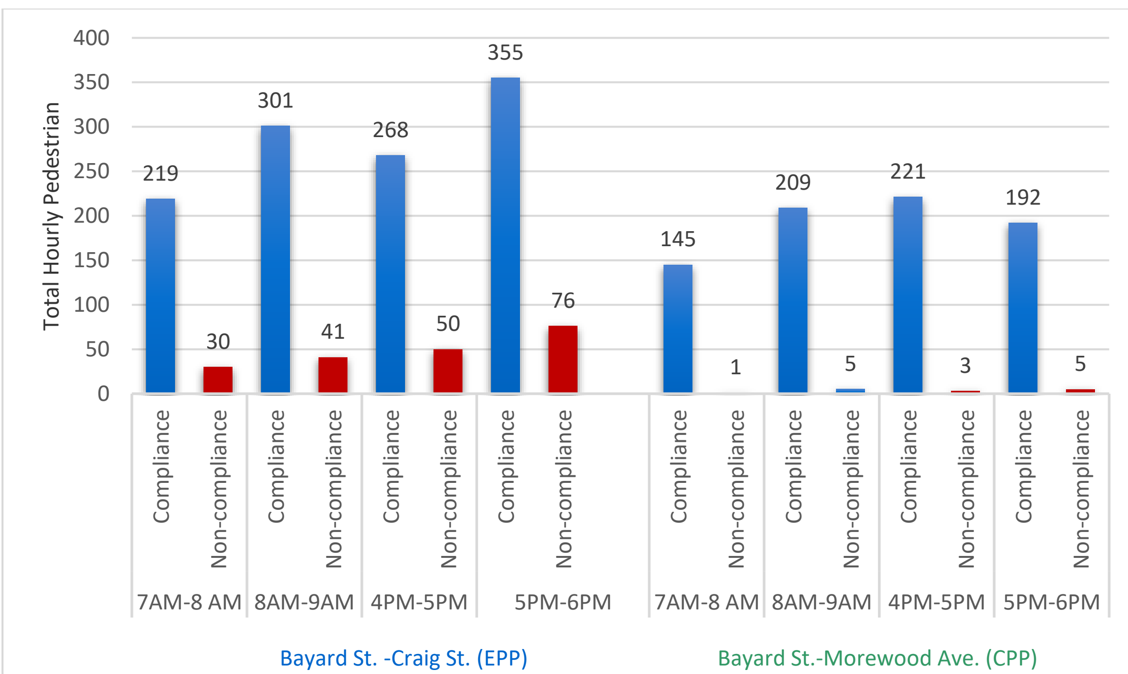

Figure 4-4. Comparison of pedestrian compliance and non-compliance in Bayard St. -Craig St. and Bayard St.-Morewood Ave.

4.1.5 Fifth Ave.-Smithfield St. and Sixth Ave.- Smithfield St.

Fifth Ave.-Smithfield St. and Sixth Ave.- Smithfield St. both were in downtown Pittsburgh with approximately the same intersection configurations, traffic and pedestrian volumes. From collected field data (Tables 9 and 10, Appendix A) it was observed that, in intersection 1, the number of non-compliance was extremely higher than intersection 2. Figure 4-5 illustrates total hourly pedestrian compliance and non-compliance volumes in all approach for both intersections. For intersection 1, the highest number of non-compliance was 464 pedestrians in one hour which was 45.40% of the total of that hour and percent non-compliance varied from 34.82% to 45.40% during morning and evening peak hours. For intersection 2, the highest number of non-compliance was 189 pedestrians which was 9.88% of the total pedestrians of that hour.

For intersection 1, total number of pedestrians in all approaches during 4 hours of data collection was 4,213 and 1,594 of them was non-compliant which was 37.84%. For intersection 2, total pedestrian for 4 hours was 3,620 and 538 of them were non-compliant which was 14.86%. In intersection 1, though the most non-compliant crossings occurred parallel to the traffic flow, the pedestrian volume perpendicular to the traffic was also high. People were found moving all the time in that intersection and pedestrians were observed to move with the flow often even when the green time was over. Again, if there weren't any vehicles in the intersection, pedestrians were often observed to cross the street and it might be due to the volumes of pedestrians in the downtown area. Pedestrians were found crossing this intersection in any direction all the time regardless of having the pedestrian phase. For intersection 2, non-compliant crossings were also in comparison to other intersections with CPP. Pedestrians were found crossing the street when the green time was over blocking the traffic flow for a few seconds and if there was no vehicle in the intersection, then many pedestrians were observed to run and cross. For this pair of intersections, pedestrian volume and non-compliant crossings were high during four hours of data collected. Although this intersection data reaffirmed the hypothesis that non-compliant behavior was higher at the intersection with EPP, it also illustrated that where pedestrian volumes are very high non-compliant behavior increases at both intersections with EPP and CPP.

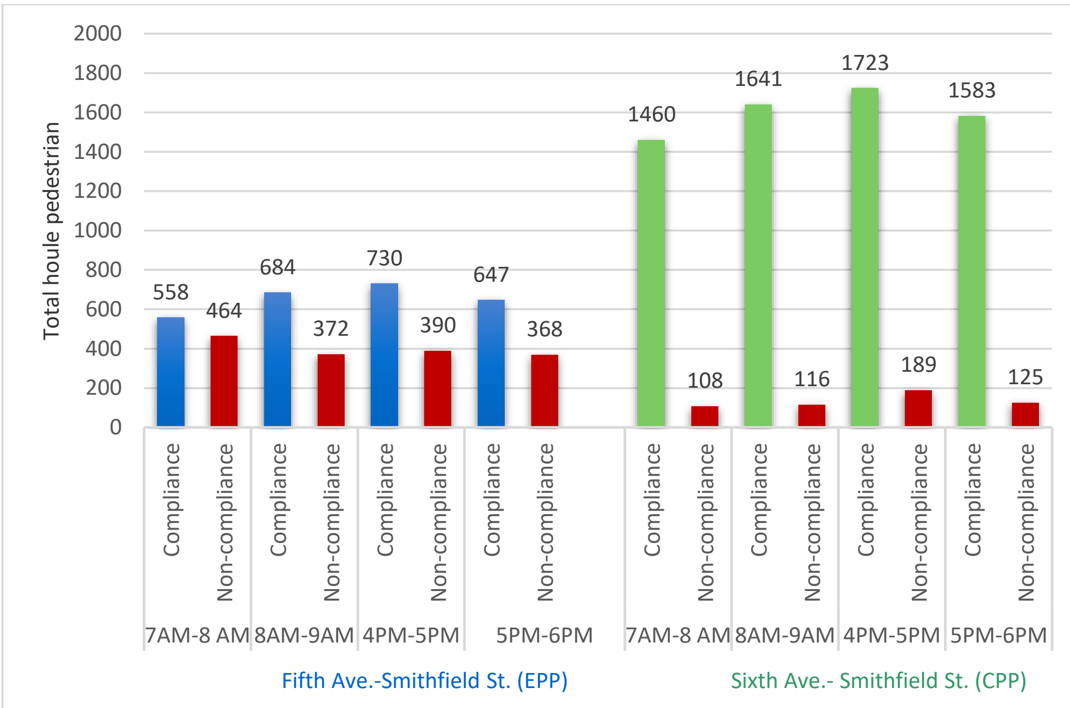

Figure 4-5. Comparison of pedestrian compliance and non-compliance in Fifth Ave.-Smithfield St. and Sixth Ave.- Smithfield St.

4.1.6 Fifth Ave.-Wood St. and Sixth Ave.- Wood St.

These two intersections were also in downtown, Pittsburgh with approximately the same intersection configurations, traffic and pedestrian volumes. From collected field data (Tables 11 and 12, Appendix A) it was observed that, in intersection 1, the rate of non-compliance for the intersection was very high. Figure 4-6 illustrates total hourly pedestrian compliance and non-compliance volume in all approaches for both intersections. For intersection 1, highest number of non-compliance was 816 pedestrians in one hour which was 45.13% of the total of that hour and percent non-compliance varied from 38.27% to 45.13% during morning and evening peak hours. For intersection 2, the highest number of non-compliance was 309 pedestrians which was 13.21% of the total pedestrians of that hour. The difference of compliance and non-compliance between two intersections was very high for all hours of data collected. For intersection 1, total number of pedestrian in all approach during 4 hours of data collection was 7,273 and 3,090 of them was non-compliant which was 42.49%. For intersection 2, total pedestrian for 4 hours was 8,123 and 753 of them were non-compliant which was 9.27%.

In intersection 1, non-compliant crossings were observed most of the time and pedestrians were found not to wait for the pedestrian signal were crossing the street anytime there was a gap. Pedestrians were observed at intersections for both concurrent and exclusive pedestrian phases that noncompliant behavior was frequently crossing perpendicular to the traffic flow. The volume of traffic crossing the intersection was not high because of low flow speed and narrow streets. Again, pedestrians were observed to move with the flow often times even when the green time was over and if there wasn't any vehicle in the intersection, pedestrians were often observed to cross the street. The high pedestrian volumes in the downtown area might be the reason behind the high number of non-compliant crossings. For intersection 2, number of non-compliant crossings were also high and though the percentage was not. The observed pedestrian behavior appeared to be similar for intersections 2 as intersection 1, but intersection 2 had concurrent flow and short waiting time, therefore non-compliance was relatively very low then the intersection 1.

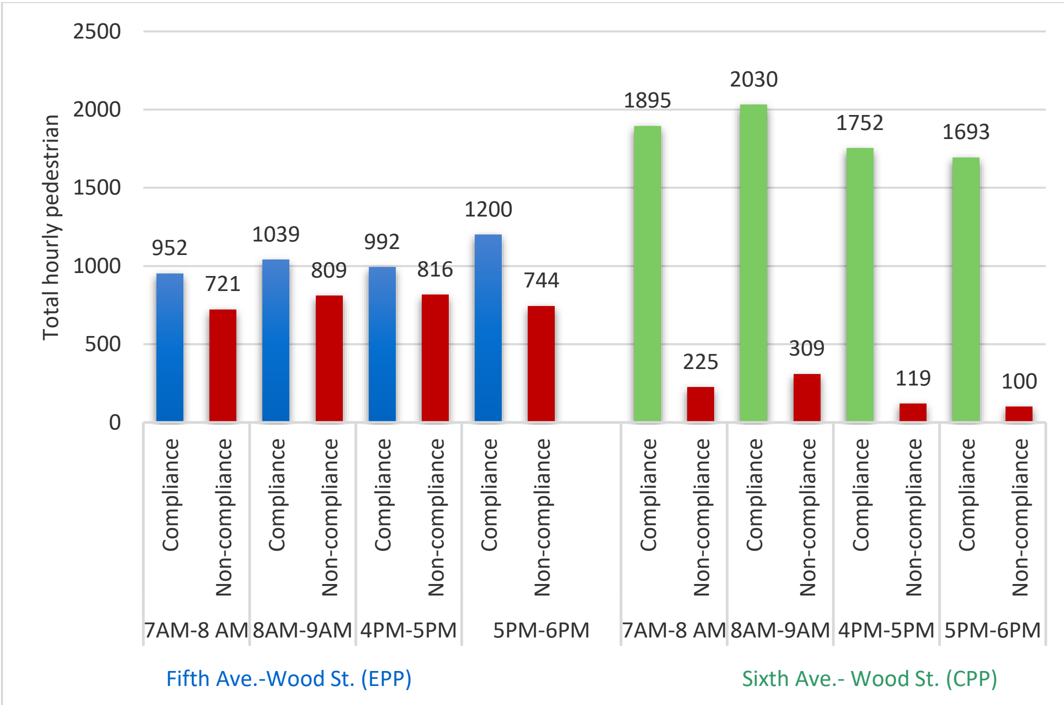

Figure 4-6. Comparison of pedestrian compliance and non-compliance in Fifth Ave.- Wood St. and Sixth Ave.-Wood St.

4.1.7 Forbes Ave.-Murray Ave. and Fifth Ave.-Shady Ave.

These two intersections were in different areas because it was difficult to find an intersection like the Forbes Ave.- Murray Ave. Intersection 1, which had high traffic and pedestrian volumes while intersection 2 had high traffic volumes but low pedestrian volumes. Turning volumes in intersection 1 were also high. These differences were kept in mind and direct comparisons between these two intersections were made (Figure 4-7). Data for these two intersections are provided in (Tables 13 and 14 of Appendix A). For intersection 1, highest number of non-compliance was 108 pedestrians, which was 15.45% of the total of that hour and hourly percent non-compliance varied from 9.30% to 15.45%. In the case of intersection 2, hourly non-compliance was very low. Total pedestrian volume for four hours in intersection 1 was 2,760 and 329 of them were non-compliant which was 11.92%. Also, in the case of intersection 2, total pedestrian volume was 857 and 3.73% of them were non-compliant.

Forbes Ave.-Murray Ave. intersection was found to perform well with EPP with low percentage of non-compliance. This may be due to the high turning volumes at the intersection. Pedestrian non-compliance was mainly parallel to the traffic and in many cases observed, it was may be due to unfamiliarity with EPP. Forbes Ave.-Murray Ave. had a very high total pedestrian volume and turning volume was also moderate with a high number of buses which may justify the use of EPP in that intersection.

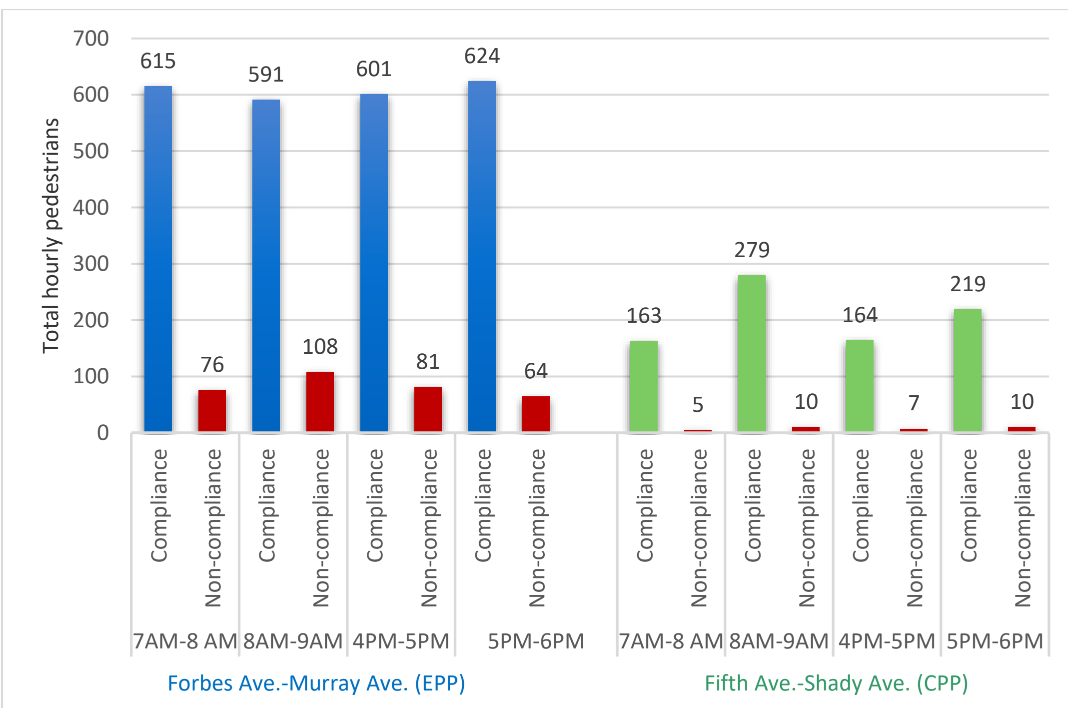

Figure 4-7. Comparison of pedestrian compliance and non-compliance in Forbes Ave.-Murray Ave. and Fifth Ave.-Shady Ave.

4.1.8 Forbes Ave.-Morewood Ave. and Forbes Ave.-Beeler St.

This pair of intersection was also not similar though both were in same area, they had similar traffic volumes and geometry but with a huge difference in the number of pedestrians. Intersection 1 was in front of Carnegie Mellon University (CMU) with many pedestrian crossings at every pedestrian phase. Complete data has been proved in (Tables 15 and 16 of Appendix A) and Figure 4-8 which shows the numbers pedestrian compliance and non-compliance for both intersections. Intersection 1 had a maximum 38 non-compliant pedestrian which was only 3.71% of hourly total. Intersection 2 was also in CMU area but had very low pedestrian volume and non-compliance rate.

Intersection 1 had 4,080 pedestrians in total four hours, 113 of them was non-compliant which was 2.77% of the total crossings. Most non-compliant crossings were perhaps due to students in rush, who were observed to run and cross the intersections. For intersection 2, total crossings in four hours was 246 and 3.25% of them was non-compliant. This pair of intersections were T-intersections, where turning volumes were very high. Forbes Ave.-Morewood Ave. intersection was found to work very well with EPP as this intersection had high traffic volume, high turning volume and high pedestrian volume.

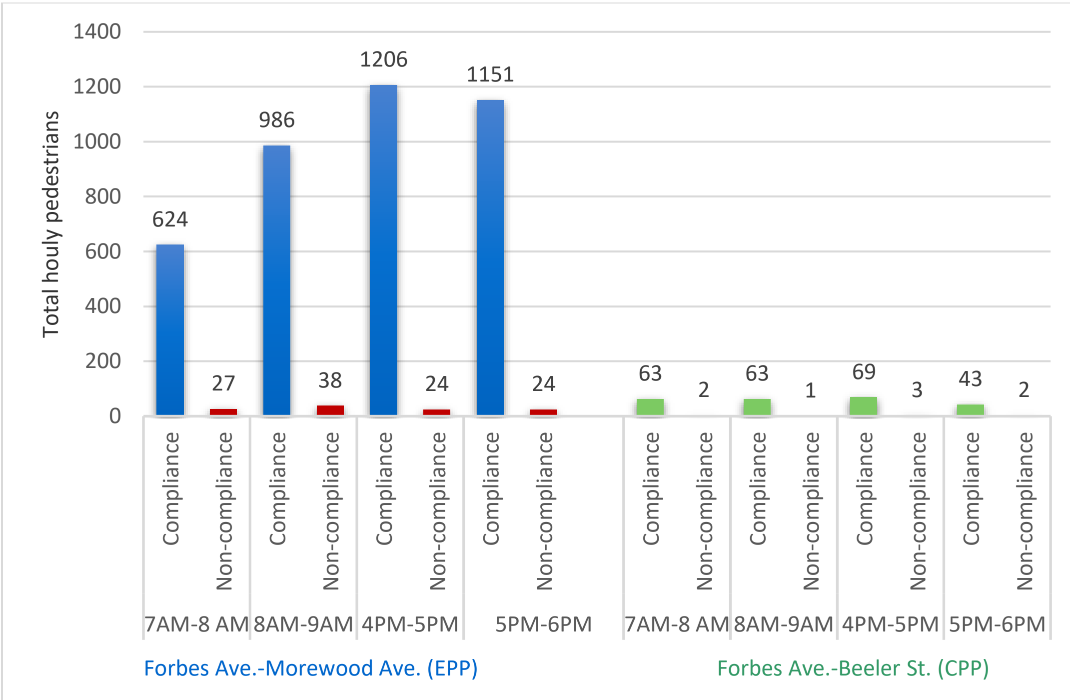

Figure 4-8. Comparison of pedestrian compliance and non-compliance in Forbes Ave.-Morewood Ave. and Forbes Ave.-Beeler St.

4.1.9 Comparison of Non-compliance Between EPP and CPP

Pedestrian non-compliance data was combined for four hours for all intersections and the result is presented in Figure 4-9. It was evident from the figure that intersection with EPP has higher non-compliance rate then intersection with CPP. Non-compliance rates for intersections varied a wide range from 2.77% to 42.49%. Forbes Ave.-Morewood Ave. was exceptional perhaps because it was a T- intersection (3-leg intersection) with very high traffic and pedestrian volumes and a reduced number of conflict points. Turning volume were also very high, which discourages non-compliant pedestrian crossings. Other than this intersection, every intersection showed high pedestrian non-compliance. When all 4-leg intersections were summed together, the difference between intersections with EPP and CPP was very clear. Pedestrian non-compliance was found to increase with the total number of pedestrians. From Figure 4-10, it was evident that intersections with higher total pedestrian showed high pedestrian non-compliance rates irrespective of intersection pedestrian phasing type. Figure 4-11 and Figure 4-12 shows the total compliance and non-compliance for EPP and CPP. Average non-compliance of seven 4-leg intersections was 23.17% for EPP and 7.94% for CPP. So, it may be concluded that intersections with EPP encourages non-compliant crossings.

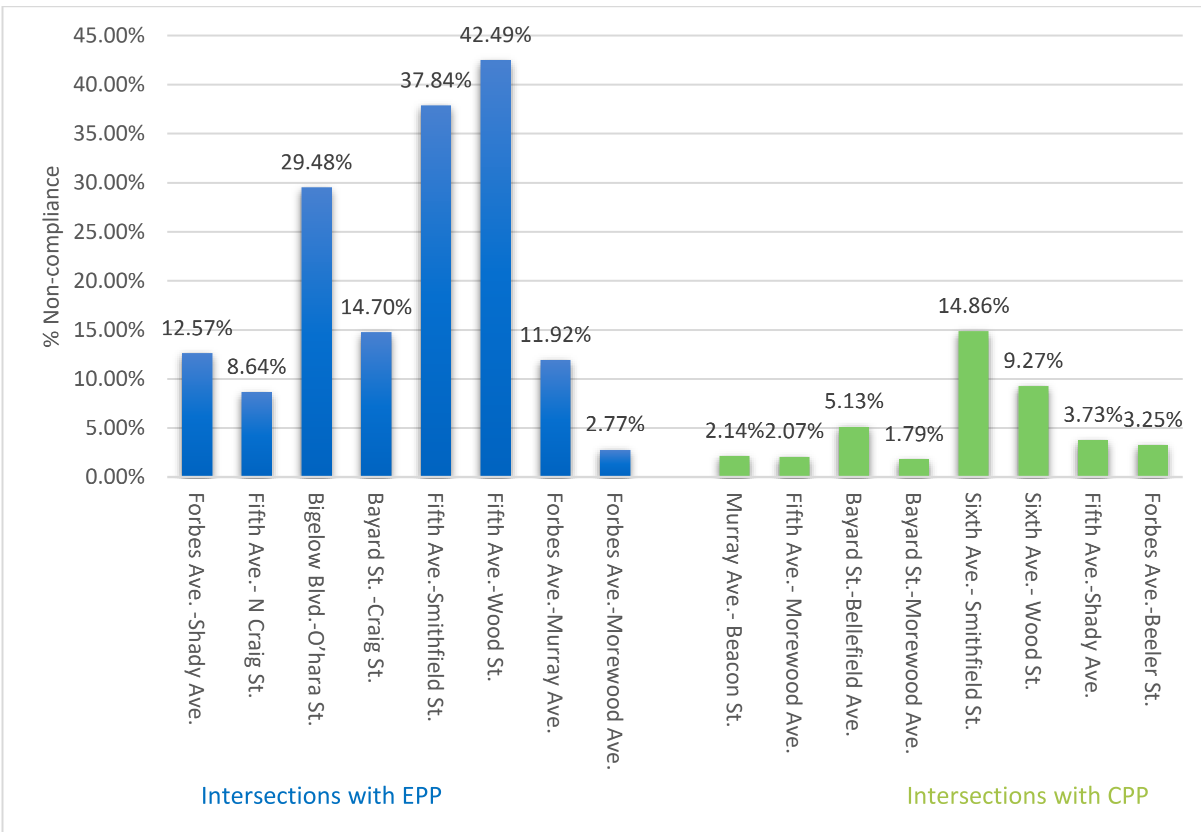

Figure 4-9. Comparison of pedestrian percent non-compliance for intersections with EPP and CPP

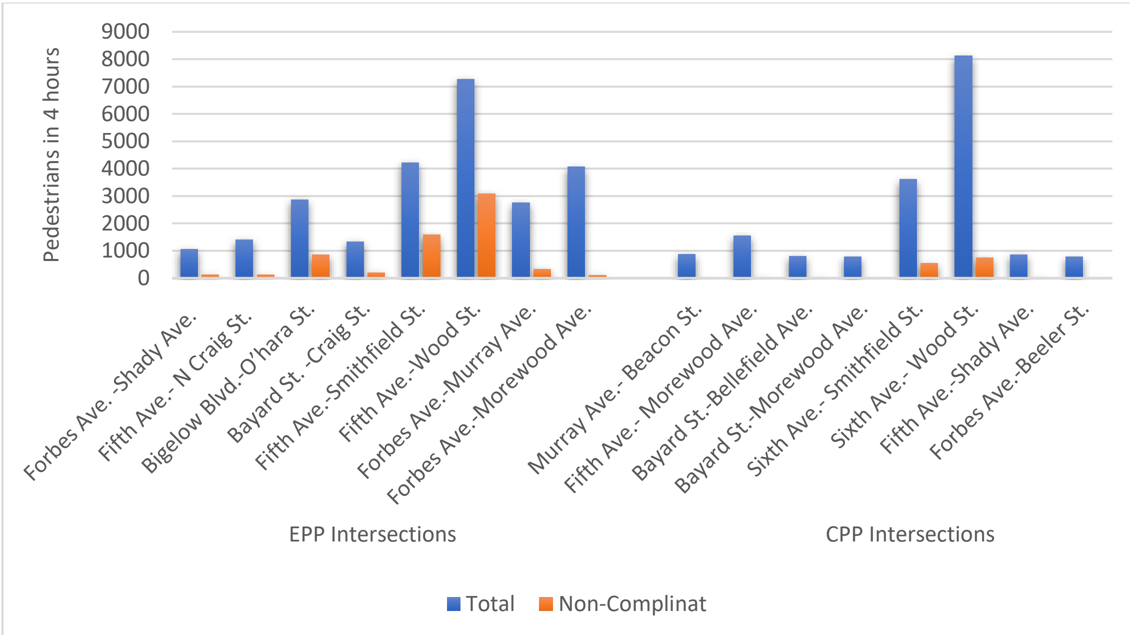

Figure 4-10. Comparison of total pedestrians and non-compliant pedestrians

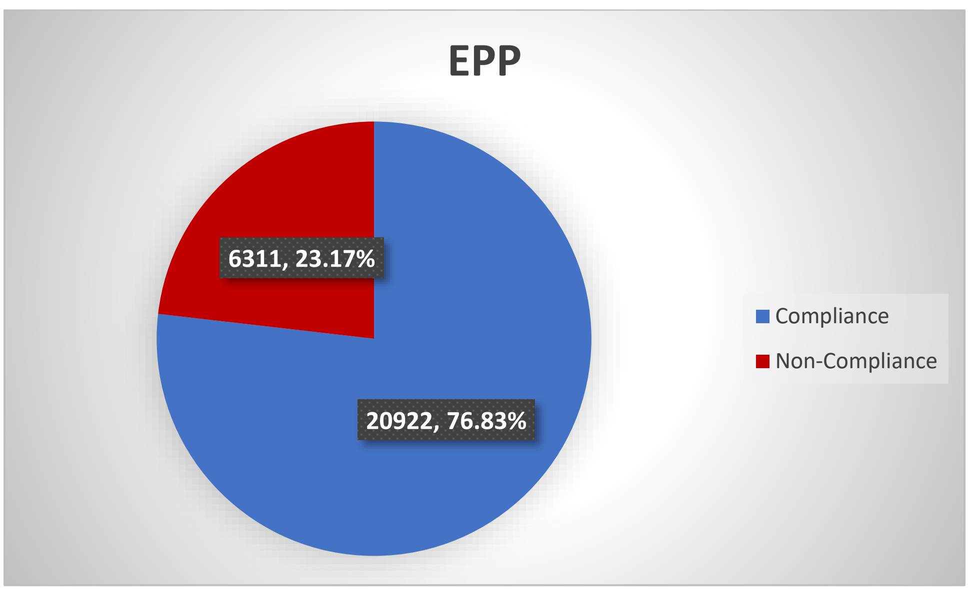

Figure 4-11. Total pedestrian crossings in seven 4-leg intersections with EPP

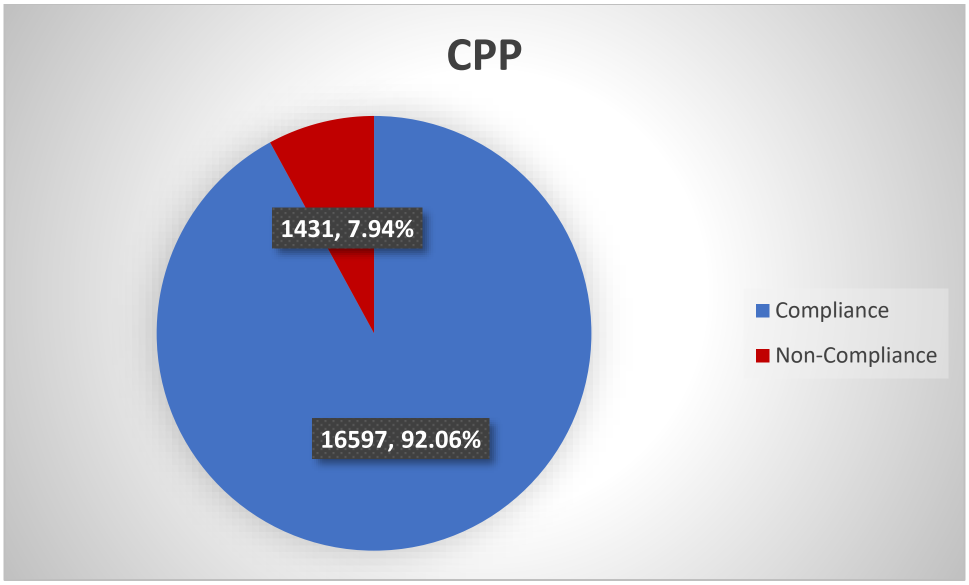

Figure 4-12. Total pedestrian crossings in seven 4-leg intersections with CPP

4.1.10 Comparison of Non-Compliance Between Different Land Use Type

Pedestrian non-compliance was compared for different land use types and the result was very different for different types. In the University areas, shown in Figure 4-13, non-compliance in intersections with CPP was low and intersections with EPP it was high. This was true except at the Forbes Ave.-Morewood Ave. intersection, which not included in the comparison because this one had different intersection geometry. More data would provide better conclusions regarding this.

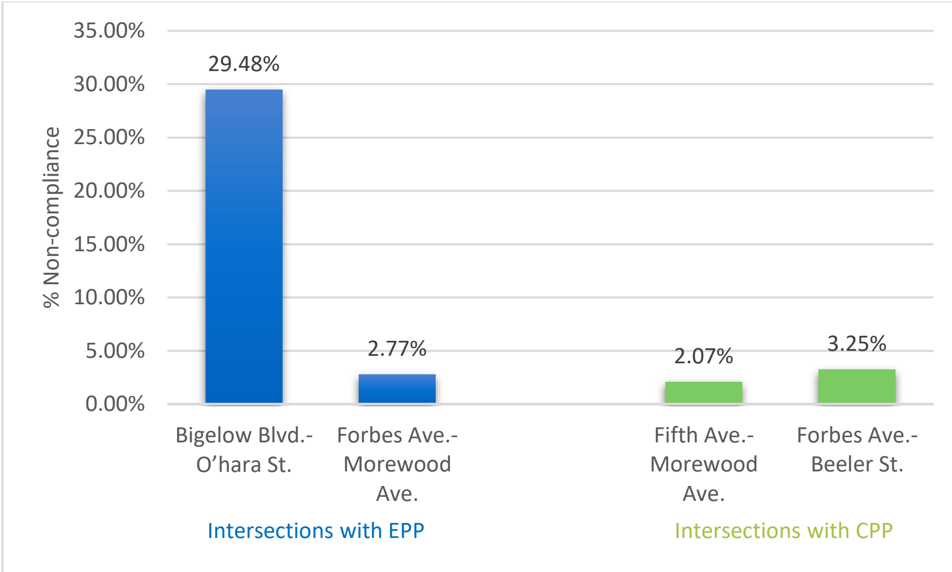

Figure 4-13. Comparison of percent non-compliance in University Areas

In case of intersections in residential areas, shown in Figure 4-14, pedestrian non-compliance was low both for CPP and EPP operations although non-compliance rates were still higher at EPP intersections. The number of pedestrian was not very high though for those intersections which may be a reason for this behavior.

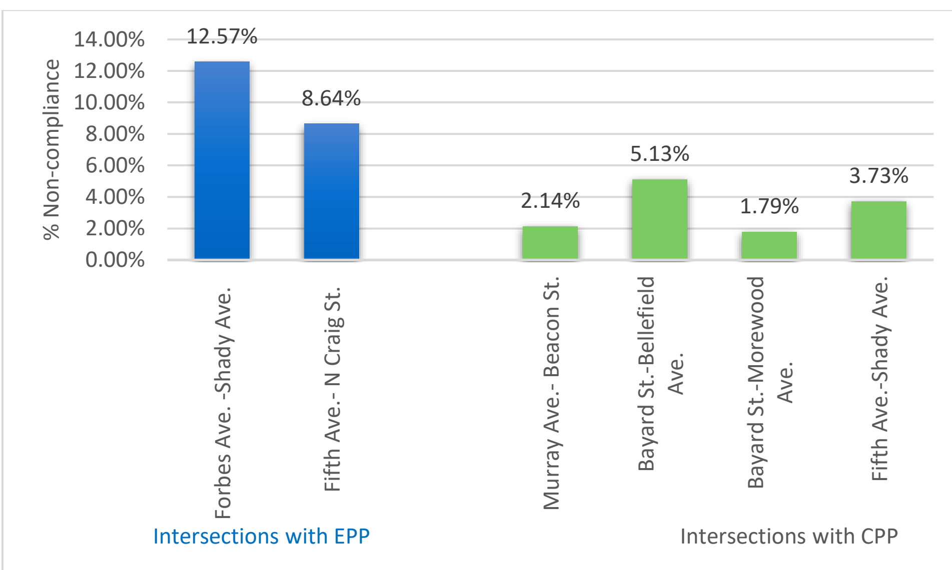

Figure 4-14. Comparison of percent non-compliance in Residential Areas

For the intersections located in business areas, pedestrian non-compliance was very high both for intersections with EPP and CPP. However, non-compliance was still a higher rate for the EPP intersections. From Figure 4-15, the difference in non-compliance for EPP and CPP seemed very high, but in reality, the impact of non-compliance on vehicular traffic was similar for both intersections. As for an intersection with CPP this high number of non-compliance means people were impacting both through traffic and turning traffic. High pedestrian volumes in a business area may be a reason behind the high number of non-compliance.

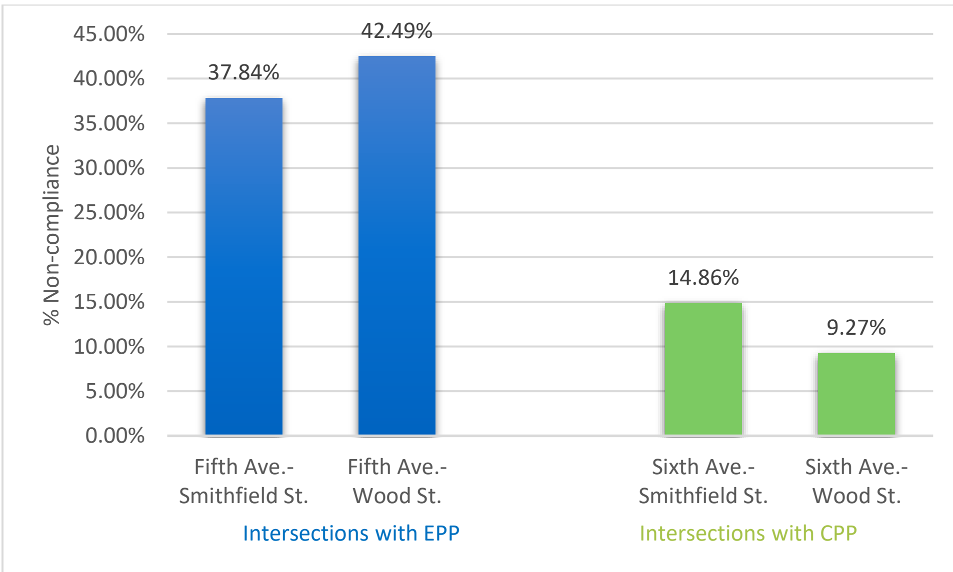

Figure 4-15. Comparison of percent non-compliance in Business area

4.1.11 Pedestrian-Vehicle Conflict Analysis

The number of conflicting pedestrian was counted for the four intersections during the selected peak hour for use in the simulation modelling. Total pedestrians, both, non-compliant and conflicting pedestrians, was summarized and the results are presented. The results showed some significant conclusions relative to this research. From Figure 4-16, the relationship among them was clear. When total pedestrian volume was high, non-compliant crossings were also high and when non-compliant crossings were high, pedestrian-vehicle conflicts were also high. This may vary, depending on the turning volume for different intersections, but for intersections with EPP this may be valid for most cases because most of these intersections had high turning traffic. This finding supports the hypothesis that, EPP doesn't necessarily increase safety at the intersections.

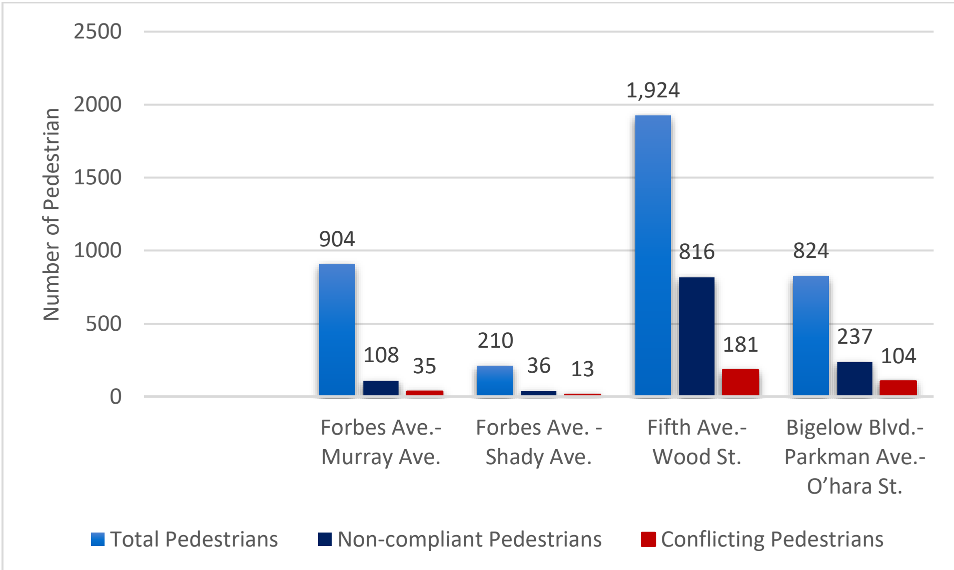

Figure 4-16. Comparison of Pedestrians Behavior at EPP Intersections

4.1.12 Summary of Pedestrian Compliance and Non-Compliance

From the analysis of the data collected, it was found that every intersection regardless of the type of land use or pedestrian operations had some non-compliant pedestrians. No intersection was found in this analysis with zero non-compliance for even an hour. Zero non-compliance may not be a realistic target, but when pedestrian non-compliance increases, the probability of pedestrian vehicle conflicts also increases and from the analysis it was found to be true. It was also found that, intersections with almost all EPP intersections had significantly higher pedestrian non-compliance rates then intersections with CPP. Again, in business areas, non-compliance rates were higher for both intersections with EPP and CPP and for residential areas it was lower. No specific relation was found between time of day and non-compliance.

4.2 MODELLING OF THE INTRESECTIONS

Four selected intersections were modeled in simulation software Synchro and analyzed for different cases in order to test the hypothesis. The cases varied based on intersection signal type, vary conflicting pedestrian volumes and types of pedestrian control. While considering exclusive pedestrian phase operations, the cases compared current operating condition with field observed pedestrian-vehicle conflicts which was the base case, ideal condition without any pedestrian-vehicle conflict, and a worst case extended condition considering field observed non-compliant pedestrians as conflicting pedestrians.

For the last case, the intersection was modeled as being converted to a concurrent pedestrian phase operation and total pedestrian volumes were considered as conflicting pedestrians. This case was selected for comparison to the base case to directly compare how an EPP operates, given the high rate of pedestrian non-compliance, to the same intersection under CPP operations which has a high rate of non-compliance.

For each intersection and case, intersection delay was measured for both current signal timings and optimized conditions. These two operations were selected for comparison because current timings cannot be assumed to reflect the optimized conditions and the cases where the operations changed optimized conditions had to be assumed. The results were then compared between intersections and cases which showed significant difference in delay between intersections with EPP and CPP.

4.2.1 Data Input and Model Development

A simulation model was developed for the four intersections using the data collected from the field. For each intersection, initially a model was built using intersection diagram and field collected data which was then modified for the different cases. In the model, traffic volumes were used for only one peak hour of the day and pedestrian volumes were calculated for different cases and used. Synchro takes pedestrian input as number of conflicting pedestrians. For ideal condition it was zero, for current condition it was field counted conflicting pedestrians, for extended condition non-compliant pedestrians were considered as conflicting pedestrians and for alternate condition all pedestrians were considered as conflicting pedestrian. These conflicting pedestrians affect the Ped-Bike factor and saturated flow rate of right turns and left turns conflicting with these movement. Area type, adjacent parking lanes, right turns on red were input, where applicable.

For the Forbes Ave.-Murray Ave. intersection there was a no turn on red regulation and there was adjacent parking lane on each approach. The pedestrian data used for different cases are tabulated in Table 4-1 and Figure 4-17 showing directional traffic volume data, approach peak hour volumes and crosswalk numbers. The intersection had a high tuning volume which includes high bus volumes between eastbound Forbes Ave. and northbound Murray Ave. For this intersection, non-compliant pedestrian volume was moderate and conflicting pedestrian volume was low.

Figure 4-17. Forbes Ave. and Murray Ave. intersection diagram

Table 4-1. Number of conflicting pedestrians in Forbes Ave.-Murray Ave. for different cases

Case	Pedestrian type	1-2	2-3	3-4	4-1[1]
Current condition	Conflicting pedestrians	10	7	12	6
Extended condition	Non-compliant pedestrians	39	19	30	20
Alternate condition	Total pedestrians	218	218	263	205

Forbes Ave.-Shady Ave. intersection had high traffic volume during peak hours and right turns on red are allowed. The intersection had long storage lane for right turning and through movement along Shady Ave. There was adjacent parking at eastbound Forbes Ave. Figure 4-18 shows the intersection diagram, approach volumes and crosswalk number and Table 4-2 shows the

[1] Crosswalk directions

conflicting pedestrian volume for different cases. The intersection had a very small number of non-compliant and conflicting pedestrians and the total pedestrian volume was also low during the peak vehicle hour.

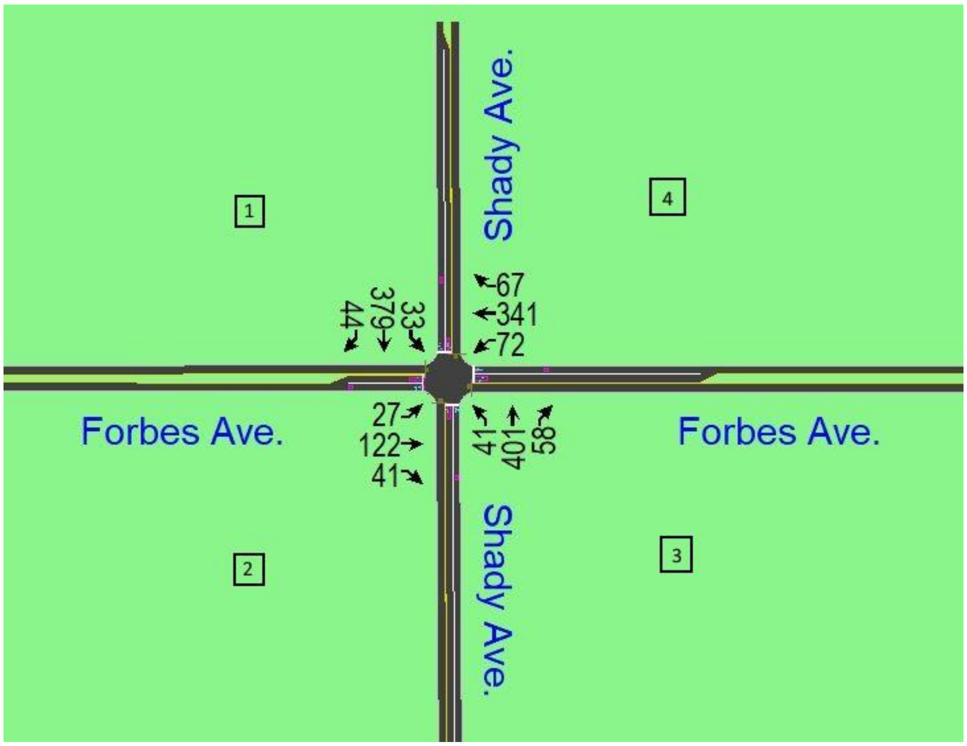

Figure 4-18. Forbes Ave. and Shady Ave. intersection diagram

Table 4-2. Number of conflicting pedestrians in Forbes Ave.-Shady Ave. for different cases

Case	Pedestrian type	1-2	2-3	3-4	4-1
Current condition	Conflicting pedestrians	4	2	1	6
Extended condition	Non-compliant pedestrians	8	9	12	7
Alternate condition	Total pedestrians	45	51	64	50

The Fifth Ave.- Wood St. intersection had a very high number of pedestrian volumes and pedestrian non-compliance was also very high. Traffic volumes crossing the intersection and turning volumes were low. Right turns on red were allowed in this intersection and the area type was a CBD. Figure 4-19 shows the intersection diagram and approach volumes and Table 4-3 shows the conflicting pedestrian volume for the different cases.

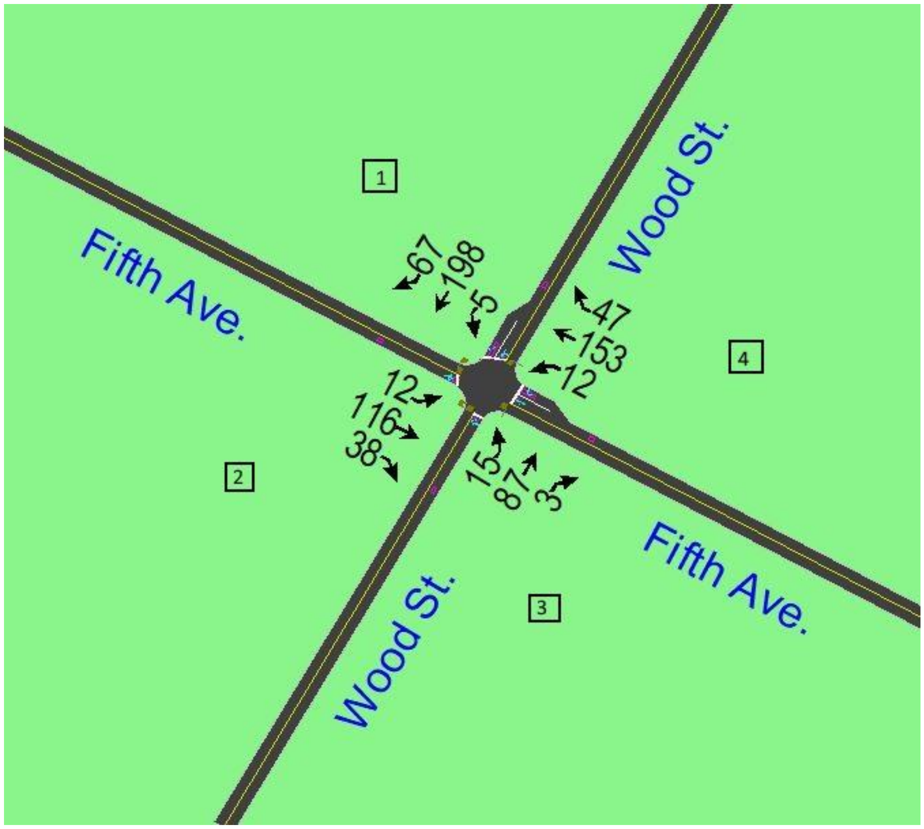

Figure 4-19. Fifth Ave. and Wood St. intersection diagram

Table 4-3. Number of conflicting pedestrians in Fifth Ave. and Wood St. for different cases

Case	Pedestrian type	1-2	2-3	3-4	4-1
Current condition	Conflicting pedestrians	45	68	26	42
Extended condition	Non-compliant pedestrians	212	264	152	188
Alternate condition	Total pedestrians	604	572	432	316

The Bigelow Blvd.-Parkman Ave.-O'Hara St. intersection had moderate traffic volume with high turning volumes between the two approaches of Bigelow Blvd. The intersection had a very high number of pedestrians and pedestrian non-compliance was also very high. Right turns on red was allowed in this intersection and there was an adjacent bike lane which was not included in the simulation, considering the relevance to the purpose of this study. Figure 4-20 shows the intersection diagram and Table 4-4 shows conflicting pedestrian volumes used for different cases.

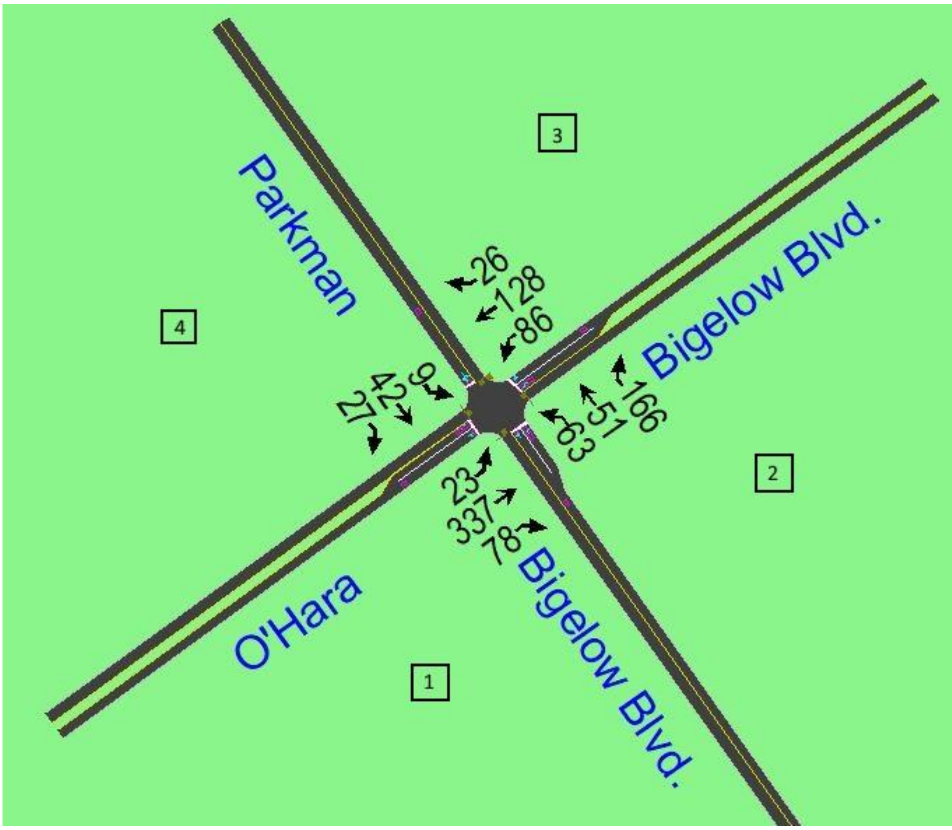

Figure 4-20. Bigelow Blvd.-Parkman Ave.-O'Hara St. intersection diagram

Table 4-4. Number of conflicting pedestrians in Bigelow Blvd.-Parkman Ave.-O'Hara St. for different cases

Case	Pedestrian type	1-2	2-3	3-4	4-1
Current condition	Conflicting pedestrians	20	6	32	46
Extended condition	Non-compliant pedestrians	32	9	52	144
Alternate condition	Total pedestrians	232	84	122	386

4.2.2 Case 1: Current Condition with EPP

Intersections were first simulated for current condition with field observed pedestrian vehicle conflicts and the current timings and then optimized timings for the base condition to compare different cases. Cycle length and split was optimized for each intersection to improve the current operating condition. Table 4-5 shows current operating condition and both current and optimized delays and cycle lengths for the four intersections. Forbes Ave.-Murray Ave. and Fifth Ave.-Wood St. intersections showed no difference in cycle length when optimized but there were reductions in intersection delay. The difference in delay may not be critical because there will always be some difference between software optimized delay and field operating delay however for comparison purpose to other cases optimized is important.

In the case of Forbes Ave.-Shady Ave., cycle length was increased to 90 seconds from 80 seconds and delay was reduced to 47.2 seconds from 70.7 seconds when optimized. The 23.5 seconds decrease in delay was very significant considering the fact that the intersection currently had an inefficient cycle length which led to formation of long queues. The reason behind 80 seconds of cycle length for this intersection may be due to adjacent intersection Forbes Ave.-Murray Ave. which had the same cycle length and is operating well. But traffic and pedestrian volumes for these two intersections were very different. In the case of Bigelow Blvd.-Parkman Ave.-O'Hara St., the cycle length was decreased form 90 seconds to 80 seconds and delay was improved to 27.8 seconds from 32.7 seconds. The change in cycle length was very relevant considering the high non-compliant pedestrian crossings and moderate traffic volume in that intersection.

Table 4-5. Intersection analysis results comparison, Base Case-Current Condition

	Forbes Ave.- Murray Ave.	**Forbes Ave. - Shady Ave.**	**Fifth Ave.- Wood St.**	**Bigelow Blvd.- Parkman Ave.- O'Hara St.**
Total hourly traffic volume	1,168	1,626	753	1,036
Total conflicting pedestrian volume	35	13	181	104
Total conflicting traffic volume	453	383	199	478
Cycle length (seconds)	80	80	70	90
Total intersection average vehicular delay (seconds)	**39.3**	**70.7**	**24.3**	**32.7**
Cycle length (optimized)	80	90	70	80
Total intersection average vehicular delay (optimized) (seconds)	**36.8**	**47.2**	**23.3**	**27.8**

4.2.3 Case 2: Ideal Condition with EPP

In ideal condition, in the case of an EPP would be no pedestrian-vehicle conflicts during vehicular phases. To test that case, current condition of each intersection was modified, and number of conflicting pedestrians were made zero. The result has been shown in Table 4-6. The results for this case, considering field condition and optimized condition were analogous to base condition discussed in the previous section. The difference in delay between ideal condition and current condition will be discussed later in this chapter.

Table 4-6. Intersection analysis results comparison, Ideal Condition

	Forbes Ave.- Murray Ave.	**Forbes Ave. - Shady Ave.**	**Fifth Ave.- Wood St.**	**Bigelow Blvd.- Parkman Ave.- O'Hara St.**
Total hourly traffic volume	1,168	1,626	753	1,036
Total conflicting pedestrian volume	0	0	0	0
Total conflicting traffic volume	453	383	199	478
Cycle length (seconds)	80	80	70	90
Total intersection average vehicular delay (seconds)	**38.8**	**70**	**24**	**32**
Cycle length (optimized)	80	90	70	80
Total intersection average vehicular delay (optimized) (seconds)	**36.3**	**46.6**	**23.1**	**27.3**

4.2.4 Case 3: Extended Condition with EPP

In the extended condition, the intersections were again modified changing the volume of pedestrian-vehicle conflicts. In this case, the worst case possible by the existing pedestrian volume was analyzed and to do that all the non-compliant crossings were considered as conflicting pedestrians. This is because Synchro only considers increases in delay due to pedestrian activity results for direct pedestrian conflicts not non-compliant behavior. The results of the analysis have been shown in Table 4-7. The results are similar to the base condition and current condition and will be compared later in this chapter.

Table 4-7. Intersection analysis results comparison, Extended Condition

	Forbes Ave.-Murray Ave.	**Forbes Ave. - Shady Ave.**	**Fifth Ave.-Wood St.**	**Bigelow Blvd.-Parkman Ave.-O'Hara St.**
Total hourly traffic volume	1,168	1,626	753	1,036
Total conflicting pedestrian volume	108	36	816	237
Total conflicting traffic volume	453	383	199	478
Cycle length (seconds)	80	80	70	90
Total intersection average vehicular delay (seconds)	**40**	**71.3**	**25.3**	**33**
Cycle length (optimized)	80	90	70	80
Total intersection average vehicular delay (optimized) (seconds)	**37.3**	**47.3**	**24.2**	**28.1**

4.2.5 Case 4: Alternate Condition with CPP

EPP at the four intersections was then simulated for conversion to CPP to compare the change in operational efficiency due to change in pedestrian signal type accommodations. To do that, the pedestrian phase was removed from total phasing and results were noted for each intersection. The cycle length and split were than optimized for each intersection to compare with other cases. For this signal type, the volume of conflicting pedestrian was assumed to be the total pedestrians crossing the intersection. This tests the worst-case pedestrian behavior and most likely would not occur, however this was selected to compare the conversion to CPP to the other cases to determine if the worst case still resulted in better intersection operations. Pedestrians crossing diagonally was also considered by adding the number in the two affected approaches for each diagonal crossing. The results have been shown in Table 4-8. The difference in delay between the normal condition and optimized condition were not as different as found earlier in Case 1: Base condition. The change in delay was because of rounding the cycle length to desired level except for Bigelow Blvd.-Parkman Ave.-O'Hara St. intersection where the cycle length was reduced to 55 seconds from 66 seconds.

Table 4-8. Intersection analysis results comparison, Alternate condition

	Forbes Ave.-Murray Ave.	**Forbes Ave. -Shady Ave.**	**Fifth Ave.-Wood St.**	**Bigelow Blvd.-Parkman Ave.-O'Hara St.**
Total hourly traffic volume	1,168	1,626	753	1,036
Total conflicting pedestrian volume	904	210	1,924	824
Total conflicting traffic volume	453	383	199	478
Cycle length (seconds)	56	56	46	66
Total intersection average vehicular delay (seconds)	**17.6**	**21.1**	**11.4**	**14.8**
Cycle length (optimized)	50	60	50	55
Total intersection average vehicular delay (optimized) (seconds)	**17.3**	**20.3**	**11.9**	**13**

4.2.6 Comparison Between Different Cases Of EPP

The three cases of the four intersections with EPP were compared to find the impact of pedestrian non-compliance on intersection delay. When the current condition (Case 1), was compared to the ideal condition, (Case 2), the delay was found to decrease slightly for all four intersections because in the ideal condition there was no conflicting pedestrians. Figure 4-21 shows the comparison of optimized and not-optimized delay of four intersections between ideal and current condition. Table 4-9 shows the seconds of delay increase and percent increase in intersection delay for both optimized and not-optimized conditions. The % increase in delay varied between 1.00% to 2.19%. For the Forbes Ave.-Murray Ave. intersections the number of hourly conflicting pedestrians was 35 and for the Forbes Ave. -Shady Ave. intersections it was only 13. As the non-conflicting volume was low, it does not decrease the delay significantly. For the Fifth Ave.-Wood St. intersection, hourly non-compliant pedestrian was 181 but hourly turning volume was only 199 vehicles. For the Bigelow Blvd.-Parkman Ave.-O'Hara St. intersection, % increase in delay was 2.19% for the current condition compared to the ideal condition, which was the highest and was due to moderate turning vehicle volume and non-compliant pedestrian volume. The results were almost same when optimized delay was compared.

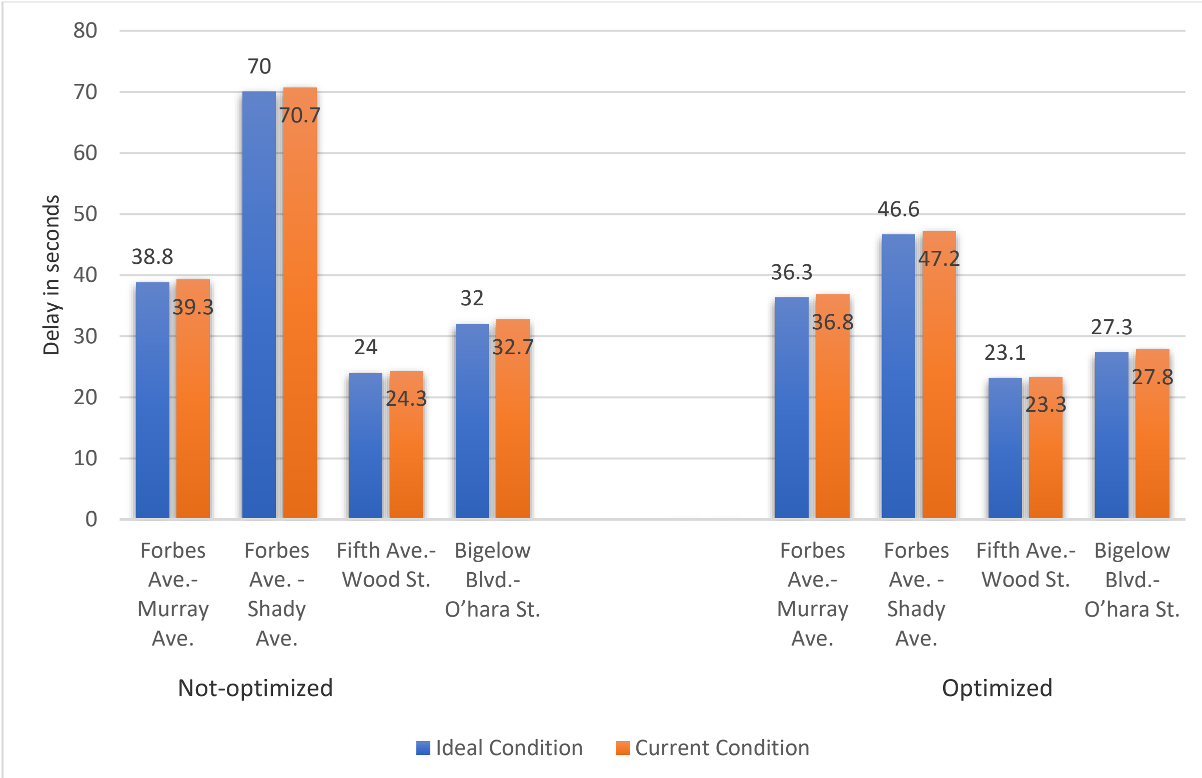

Figure 4-21. Comparisons of intersections operation between ideal condition and current condition

Table 4-9. Change in intersection delay between current condition and ideal condition

	Forbes Ave.- Murray Ave.	**Forbes Ave. - Shady Ave.**	**Fifth Ave.- Wood St.**	**Bigelow Blvd.- O'Hara St.**
Increased delay (seconds)	**0.5**	**0.7**	**0.3**	**0.7**
% Increased delay	1.29%	1.00%	1.25%	2.19%
Increased delay (seconds) (optimized)	**0.5**	**0.6**	**0.2**	**0.5**
% Increased delay (optimized)	1.38%	1.29%	0.87%	1.83%

When extended conditions (Case 3) were compared with current conditions (Case 1) (Figure 4-22), the delay was more as the number of conflicting pedestrian increased. Table 4-10 shows the increase and percent increase in delay for all the intersections. The Fifth Ave.-Wood St. intersection was found be impacted highly as non-compliant pedestrian was highest for that intersection and at the other intersection of Forbes Ave.- Shady Ave. was least impacted due to having less pedestrian non-compliance. The increase in delay was similar for optimized condition. When ideal conditions (Case 2) was compared with extended conditions (Case 3), the increase in delay was clearer. For, the Forbes Ave.-Murray Ave. intersection, the increase was 3.09% and for the Fifth Ave.-Wood St. intersection delay increase was 5.42%.

None of the intersections analyzed had high turning volumes and when the non-compliant pedestrian volume was high, turning volume was very low. So, the intersections selected did not highly change the delay due to pedestrian non-compliance. This raised a question, if EPP was necessary for all these intersections except Forbes Ave.-Murray Ave. because they had low to moderate turning vehicles which causes greater delay due to pedestrian conflicts?

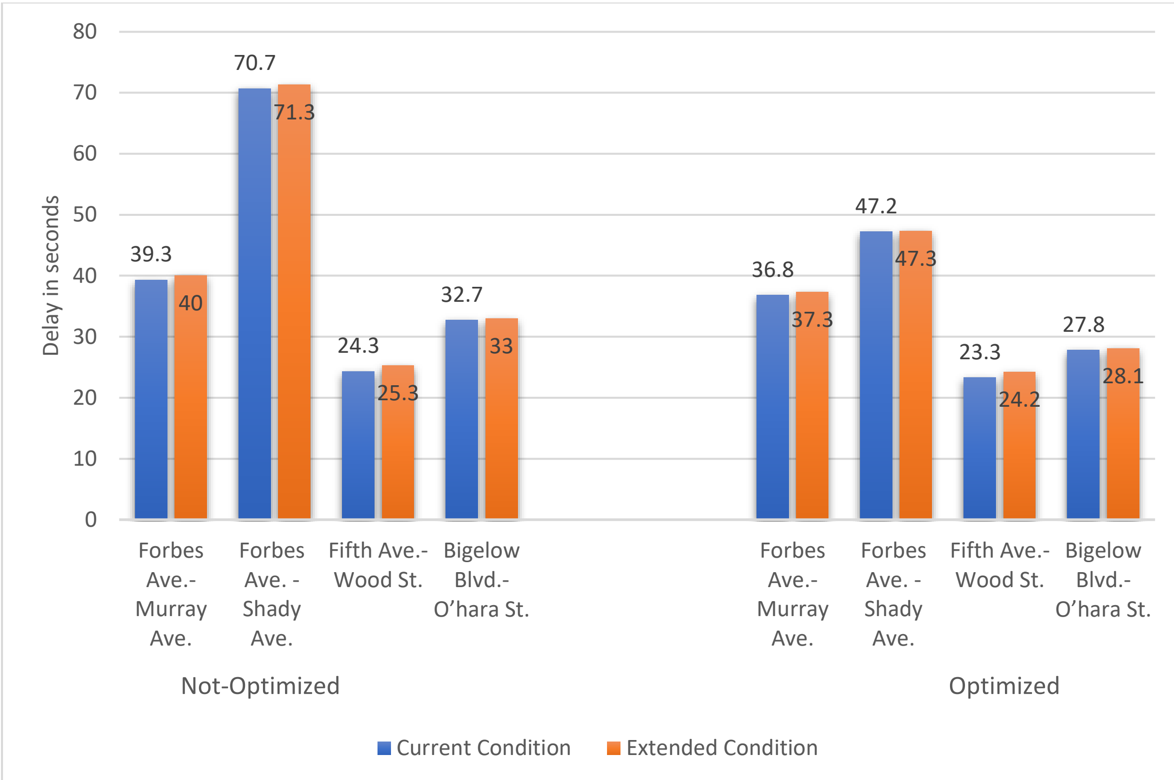

Figure 4-22. Comparisons of intersections operation between current condition and extended condition

Table 4-10. Change in intersection delay between current condition and extended condition

	Forbes Ave.- Murray Ave.	**Forbes Ave. - Shady Ave.**	**Fifth Ave.- Wood St.**	**Bigelow Blvd.- O'Hara St.**
Increased delay (seconds)	**0.7**	**0.6**	**1**	**0.3**
% Increased delay	1.78%	0.85%	4.12%	0.92%
Increased delay (seconds) (optimized)	**0.5**	**0.1**	**0.9**	**0.3**
% Increased delay (optimized)	1.36%	0.21%	3.86%	1.08%

4.2.7 Comparison Between EPP and CPP

When intersections with EPP were considered as converting to CPP the change in delay was very significant. Figure 4-23 shows the delay of current condition (with EPP Case 1) and alternate condition (with CPP Case 4). It was evident from the figure that, delay was different for optimized conditions. But, the difference in delay between EPP and CPP was very high both for optimized and not-optimized conditions. The drastic change in delay was logical, when converting the intersection to CPP the pedestrian phase was removed which essentially decreased the cycle time and intersection delay. Table 4-11 shows the decrease and percent decrease in delay due to the elimination of the pedestrian crossing phase. The improvement was very high for all four intersections. Forbes Ave.-Murray Ave. had a decrease of 55.22% in delay while Forbes Ave.-Shady Ave. had a decrease of 70.16% in delay as both of these intersections had a very high volume of traffic particularly the later one. Even with 1,924 hourly pedestrian volumes, Fifth Ave.-Wood St. showed a 53.09% decrease in intersection delay. The results were similar when optimized delay was compared except for Forbes Ave.-Shady Ave. as this intersection had changed delay for both cases when optimized.

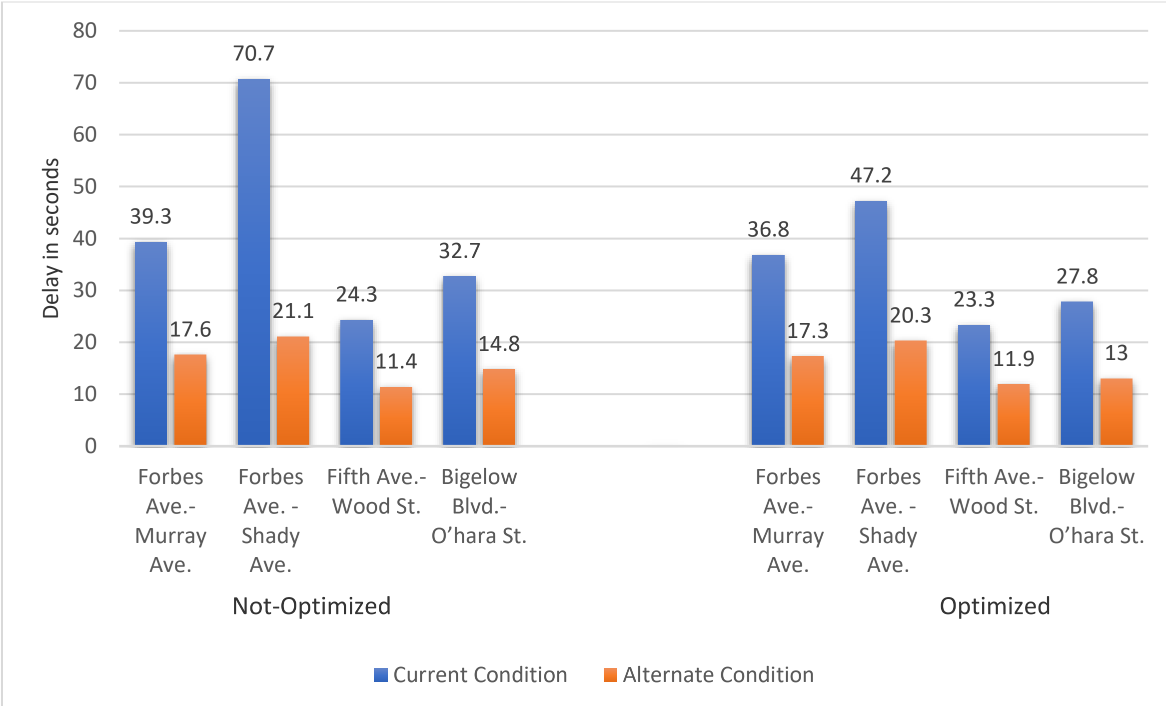

Figure 4-23. Comparison of intersections operation between current condition and alternate condition

Table 4-11. Change in intersection delay between current condition and alternate condition

	Forbes Ave.- Murray Ave.	**Forbes Ave. - Shady Ave.**	**Fifth Ave.- Wood St.**	**Bigelow Blvd.- O'Hara St.**
Decreased delay (seconds)	**21.7**	**49.6**	**12.9**	**17.9**
% Decreased delay	55.22%	70.16%	53.09%	54.74%
Decreased delay (seconds) (optimized)	**19.5**	**26.9**	**11.4**	**14.8**
% Decreased delay (optimized)	52.99%	56.99%	48.93%	53.24%

4.2.8 Summary of Simulation Modelling Results

Current intersection signal timing was found to be not optimized for two intersections; Forbes Ave.-Shady Ave. and Bigelow Blvd.-Parkman Ave.-O'Hara St. Both intersections were found having severe intersection delay. Forbes Ave.-Shady Ave. had very high traffic volume with a cycle length of 80 seconds while the optimized cycle length was 90 seconds. The number of pedestrians was not very high in that intersection while long vehicle queues were observed during peak hours of the day. Bigelow Blvd.-Parkman Ave.-O'Hara St. intersection had a cycle length of 90 seconds when optimized it was 80 seconds. Traffic volumes at this intersection were not very high during peak hours of the day, and turning volume was high only between the two approaches of Bigelow Blvd. This intersection had a high pedestrian with high non-compliance rate.

Delay due to pedestrian non-compliance was found increasing for every intersection though the increase was not very high. Around 1 second increase was observed for both optimized and not-optimized conditions. The increase was not significant due to low pedestrian vehicle conflicts observed in those intersections, which was due to low turning volume, and the resulting low conflicting pedestrian volume. Delay decreased significantly while considering intersections as having CPP, even with very high conflicting pedestrian volume. For both optimized and not-optimized conditions the decrease in delay was around 50% or more.

5.0 SUMMARY AND CONCLUSIONS

The following provides a summary of the analysis results, conclusions and recommendations for future research. While this research has identified high non-compliance rates for intersections with EPP, the criteria for conversion to CPP is governed by many factors. This research has identified several of those factors.

5.1 FINDINGS OF PEDESTRIAN CROSSING BEHAVIOR

From the analysis of 16 intersections in different land use areas and signal operation types, the hypothesis was tested and proved. The analyzed intersections were in an urban area with one approach lane in each direction. The findings are summarized below:

Intersections with EPP were found to encourage non-compliant pedestrian crossings. For four-leg intersections, the percent non-compliance varied from 8.64% to 42.49%.

Average non-compliance in four hours for 4-leg intersection with EPP was found 23.17% and for intersection with CPP it was 7.94%.

Pedestrian non-compliance for both EPP and CPP was higher in intersections in Business area and lower in residential area.

For urban intersections, non-compliant crossings were not dependent on time of the day, highest pedestrian non-compliance was observed during both morning and evening peak hours. Here, only 4 peak hours data was considered, collection of the entire day data may provide different conclusions.

Pedestrian non-compliance was related to pedestrian-vehicle conflicts, higher the number of pedestrian non-compliance, higher was pedestrian-vehicle conflicts.

When pedestrian volume was high, pedestrian non-compliance was also found to be high irrespective of intersection's pedestrian phasing type. Higher non-compliant pedestrians were found even with lower cycle lengths but higher total pedestrian intersections.

When turning volume was high, pedestrian non-compliance was found to be low. In 3-leg intersections, pedestrian non-compliance was lower than the four-leg intersections due to high volumes of turning vehicle.

Pedestrian non-compliance was also observed to be low in the intersections with high vehicle speed.

Higher pedestrian-vehicle conflicts were observed in intersections with EPP. As, in the intersections with CPP, non-compliant crossings were mostly when there was no traffic on that approach. Though in downtown area, in the intersections with very high pedestrian volume, pedestrian-vehicle conflicts were high both for EPP and CPP intersections.

When intersection's cycle length was high, pedestrians were observed to be more driven to cross without pedestrian phase and if there was no turning vehicle, then in many cases they were observed to execute non-compliant crossings.

Intersection's total pedestrian, area type, cycle length, vehicle speed, turning vehicle volume were found to impact pedestrian non-compliance.

5.1.1 Findings of Simulation Modelling

From the analysis done in Synchro for intersections considering different cases there were some findings relating intersection's present operational condition, impact of non-compliant pedestrian crossings, and impact of changing pedestrian signal type. The findings are based on analysis of 4 intersections in urban area with one lane in each direction. The findings are summarized as follows.

The intersections considered for this research were evaluated in both existing timing and optimized timing conditions. All the intersections were found not to be optimized in the field. Few had 10 seconds of difference in optimized and operating cycle length. That is why, the use of optimized signal timings was essential, to compare among different cases.

Existing non-compliant pedestrian crossings didn't significantly increase intersection delay when modeled as conflicting pedestrians. The increase in intersection delay was between 0.87% to 1.87%. Additional 0.21% to 3.86% increase in delay may occur due to increased non-compliance. The reason behind lower increase in intersection delay was, low number of pedestrian vehicle conflicts due to low turning vehicle volumes on analyzed intersections. Intersection with higher turning volumes and conflicting pedestrians showed a more significant increase in intersection delay.

When EPP intersections were modeled converting to CPP, they were found to be significantly more efficient for the vehicular movement at all the intersections. Delays in the converted intersections were found to be more than 50% less than EPP intersections.

Intersections with high vehicle volume and low pedestrian volume were found not to perform well with EPP. These types of intersections show drastically different delays for EPP and CPP.

Intersections with low turning volume and even with very high pedestrian volumes were also found not to be efficient with EPP. Even for high pedestrian volumes, adding a pedestrian phase was found to increase delays significantly.

If the turning volumes and pedestrian volumes both are not high, conversion to CPP will be effective and should be considered when possible because of the benefits of overall intersection performance.

5.2 CONCLUSIONS

The hypothesis that, EPP encourages non-compliant pedestrian crossings was proved form the collected pedestrian crossings data which showed an average of 30.16% non-compliance in intersection with EPP where for CPP operations it was 8.62%. As pedestrian-vehicle conflicts increased due to increase in pedestrian non-compliance, it may be said that, intersections with EPP may not necessarily improve pedestrian safety. Again, non-compliant crossings by pedestrians impacts intersection operational performance. Pedestrian non-compliance was found to increase intersection delay slightly even if the turning volumes and number of conflicting pedestrians were not significant at the intersection. However, when these intersections were modeled as converted to CPP operations, delays reduced significantly, and it was more than 50%. It was found that, if CPP is used instead of EPP, on average 65.73% decrease in pedestrian non-compliance and 53.04% decrease in total intersection delay may be found. It may be concluded that, in an intersection with EPP, delay is increased due to the additional pedestrian phase and pedestrian non-compliance.

5.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The research attempted to suggest boundary values of pedestrian volumes and vehicular turning volumes for the implementation of EPP or the conversion of current EPP operations to CPP. A more extensive evaluation of conditions at various intersection conditions is needed to create more specific guidelines or boundary conditions to create guidance for transportation engineers. This could be done with the help of simulation software by varying the number of conflicting pedestrians and traffic volumes and comparing intersection delay results. If the intersection delay increases with CPP operations beyond a set limit due to pedestrian-vehicle conflicts, then EPP may be considered.

The other area of future research to be explored could be the quantification of the safety benefits of converting EPP to CPP or the reverse. While this research has shown that pedestrian compliance is higher with CPP, the severity and number of crashes could be explored under the two conditions. It is inferred that less conflicts between pedestrians and vehicles should lead to safer conditions, but this should be verified by a crash analysis. Also, a Crash Modification Factor (CMF) could be developed for converting an intersection with EPP to an intersection with CPP.

APPENDIX A

PEDESTRIAN VOLUME DATA

Appendix A provides hourly pedestrian data collected from the field. The following is the field data collected for all of the study intersections.

Figure 1: Forbes Ave. and Shady Ave.

Table 1. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Forbes Ave. and Shady Ave. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	1-3	2-4	Total	Percentage
7AM-8 AM	Compliance	37	42	18	21	14	15	147	87.50%
	Non-compliance	8	7	10	6	0	0	21	12.50%
8AM-9 AM	Compliance	33	21	36	27	21	16	154	84.15%
	Non-compliance	1	9	12	7	0	0	29	15.85%
4PM-5PM	Compliance	35	37	54	86	50	12	274	85.63%
	Non-compliance	5	15	16	10	0	0	46	14.37%
5PM-6PM	Compliance	16	38	79	126	25	58	342	90.48%
	Non-compliance	1	9	14	12	0	0	36	9.52%

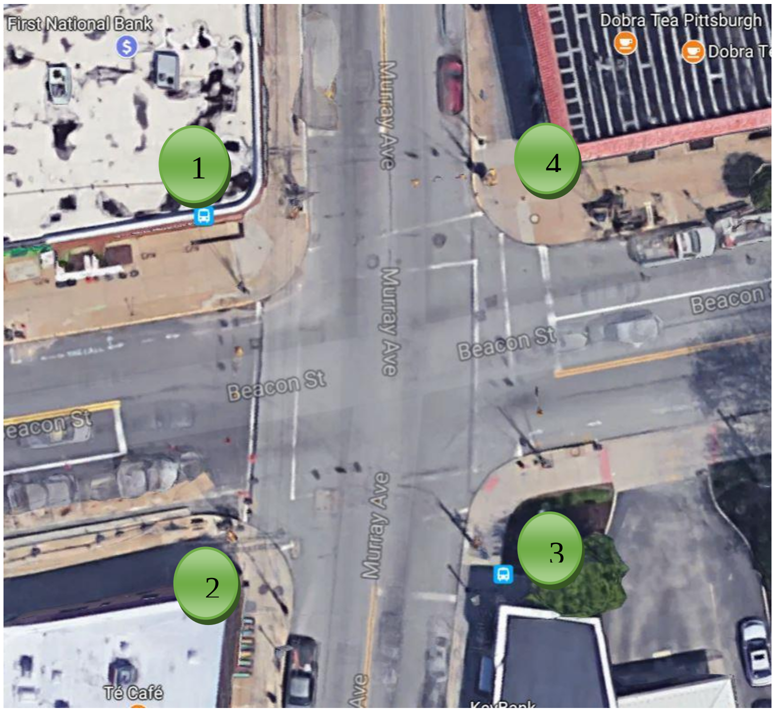

Figure 2: Murray Ave. and Beacon St.

Table 2. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Murray Ave. and Beacon St. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	Total	Percentage
7AM-8 AM	Compliance	20	24	37	14	95	98.96%
	Non-compliance	0	1	0	0	1	1.04%
8AM-9AM	Compliance	46	45	89	37	217	99.09%
	Non-compliance	0	0	2	0	2	0.91%
4PM-5PM	Compliance	68	15	108	62	253	96.94%
	Non-compliance	4	0	0	4	8	3.06%
5PM-6PM	Compliance	102	38	168	87	395	97.53%
	Non-compliance	7	0	3	0	10	2.47%

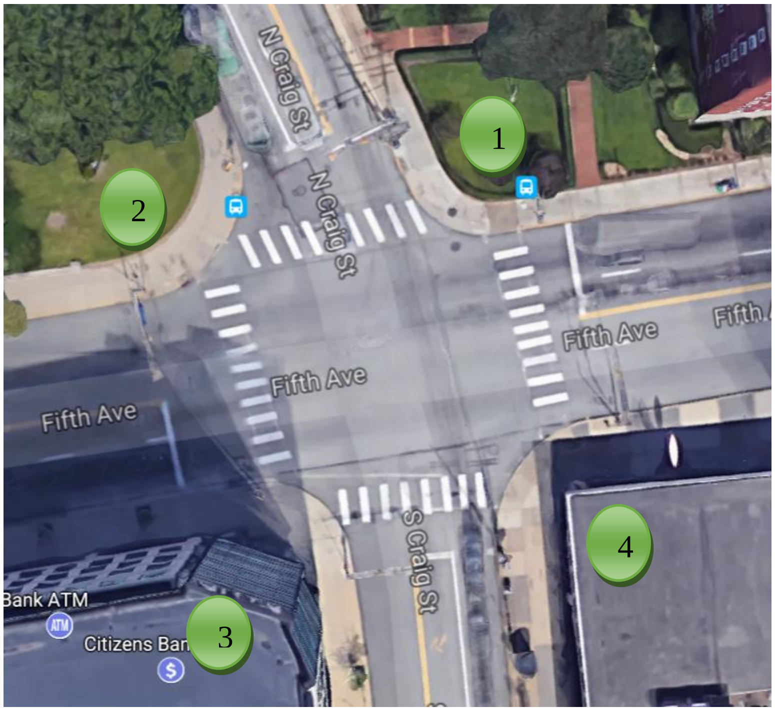

Figure 3: Fifth Ave. and Craig St.

Table 3. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Fifth Ave.-N Craig St. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	1-3	2-4	Total	Percentage
7AM-8 AM	Compliance	38	21	95	22	25	25	226	91.87%
	Non-compliance	3	5	4	8	0	0	20	8.13%
8AM-9AM	Compliance	52	55	103	54	38	45	347	90.84%
	Non-compliance	2	15	8	10	0	0	35	9.16%
4PM-5PM	Compliance	77	34	121	30	30	39	331	94.30%
	Non-compliance	2	8	3	7	0	0	20	5.70%
5PM-6PM	Compliance	64	57	112	45	51	57	386	89.15%
	Non-compliance	0	20	1	26	0	0	47	10.85%

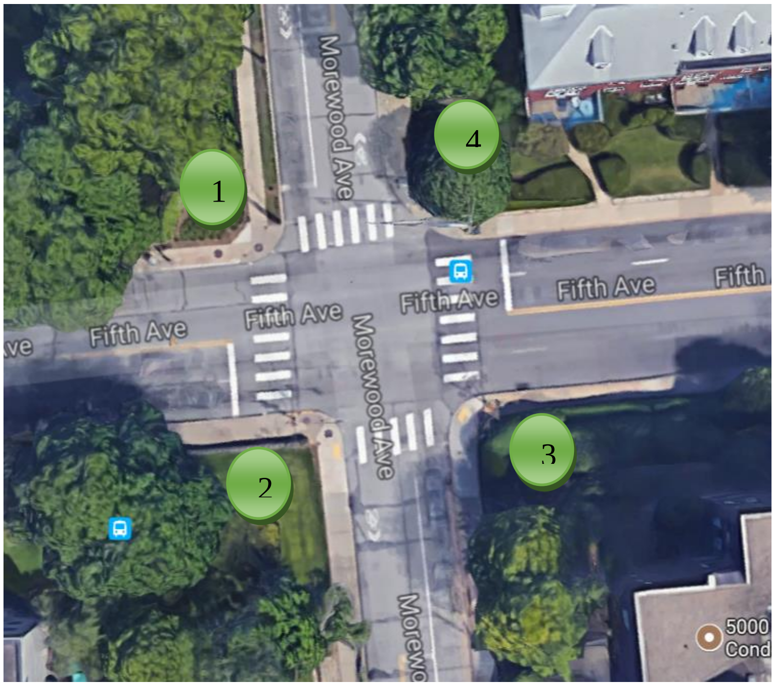

Figure 4: Fifth Ave. and Morewood Ave.

Table 4. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Fifth Ave.- Morewood Ave. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	Total	Percentage
7AM- 8 AM	Compliance	11	222	8	92	333	95.97%
	Non-compliance	5	2	3	4	14	4.03%
8AM- 9AM	Compliance	38	284	30	124	476	97.94%
	Non-compliance	0	5	2	3	10	2.06%
4PM- 5PM	Compliance	58	171	25	132	386	98.72%
	Non-compliance	0	2	2	1	5	1.28%
5PM- 6PM	Compliance	49	129	36	107	321	99.07%
	Non-compliance	0	0	1	2	3	0.93%

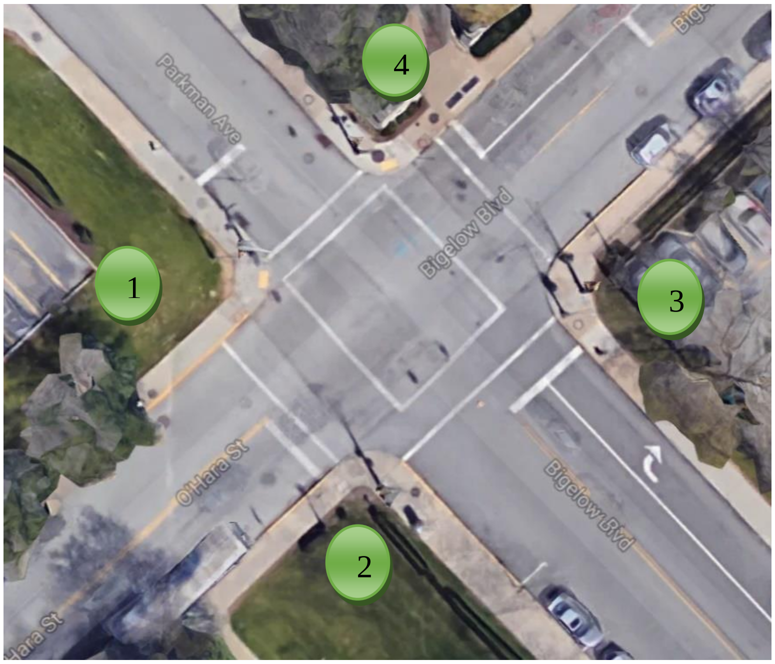

Figure 5: Bigelow Blvd. Parkman Ave.-O'Hara St.

Table 5. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Bigelow Blvd.-O'Hara St. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	1-3	2-4	Total	Percentage
7 AM-8 AM	Compliance	172	84	7	61	8	6	338	71.16%
	Non-compliance	73	19	1	44	0	0	137	28.84%
8 AM-9 AM	Compliance	362	247	5	86	32	7	739	69.85%
	Non-compliance	254	34	0	31	0	0	319	30.15%
4PM-5PM	Compliance	159	34	56	228	41	14	532	69.18%
	Non-compliance	32	9	52	144	0	0	237	30.82%
5PM-6PM	Compliance	136	22	40	186	25	8	417	73.03%
	Non-compliance	76	5	28	45	0	0	154	26.97%

Figure 6: Beyard St. and Bellefield Ave.

Table 6. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Beyard St. and Bellefield Ave. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	Total	Percentage
7AM-8 AM	Compliance	48	22	52	15	137	95.14%
	Non-compliance	3	0	4	0	7	4.86%
8AM-9AM	Compliance	112	40	85	23	260	97.74%
	Non-compliance	4	0	2	0	6	2.26%
4PM-5PM	Compliance	74	34	70	19	197	92.92%
	Non-compliance	8	0	6	1	15	7.08%
5PM-6PM	Compliance	62	36	45	22	165	92.70%
	Non-compliance	8	1	4	0	13	7.30%

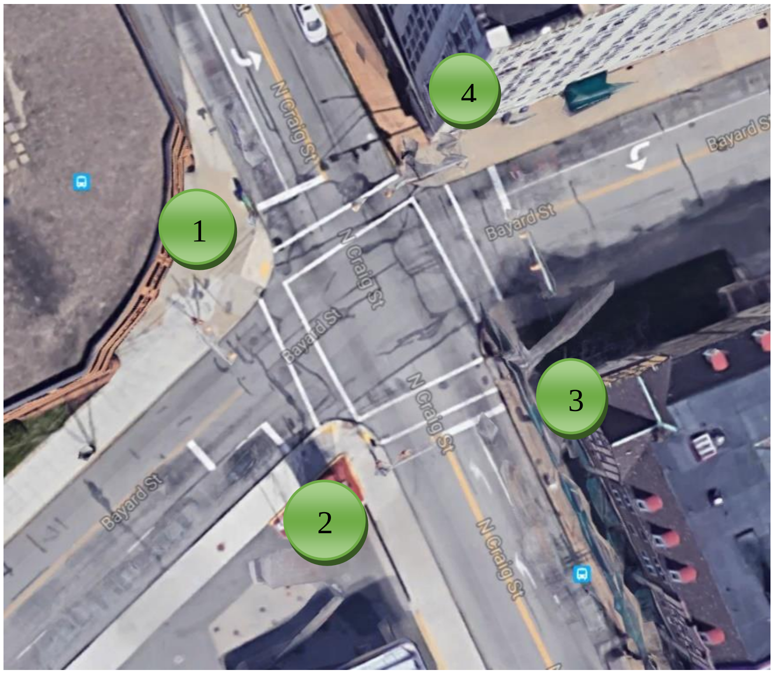

Figure 7: Bayard St. -Craig St.

Table 7. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Bayard St. -Craig St. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	1-3	2-4	Total	Percentage
7AM-8 AM	Compliance	25	30	78	52	12	22	219	87.95%
	Non-compliance	7	4	6	13	0	0	30	12.05%
8AM-9AM	Compliance	42	56	87	48	16	52	301	88.01%
	Non-compliance	10	2	7	22	0	0	41	11.99%
4PM-5PM	Compliance	32	36	89	59	18	34	268	84.28%
	Non-compliance	8	4	9	29	0	0	50	15.72%
5PM-6PM	Compliance	36	50	98	78	6	87	355	82.37%
	Non-compliance	6	15	18	37	0	0	76	17.63%

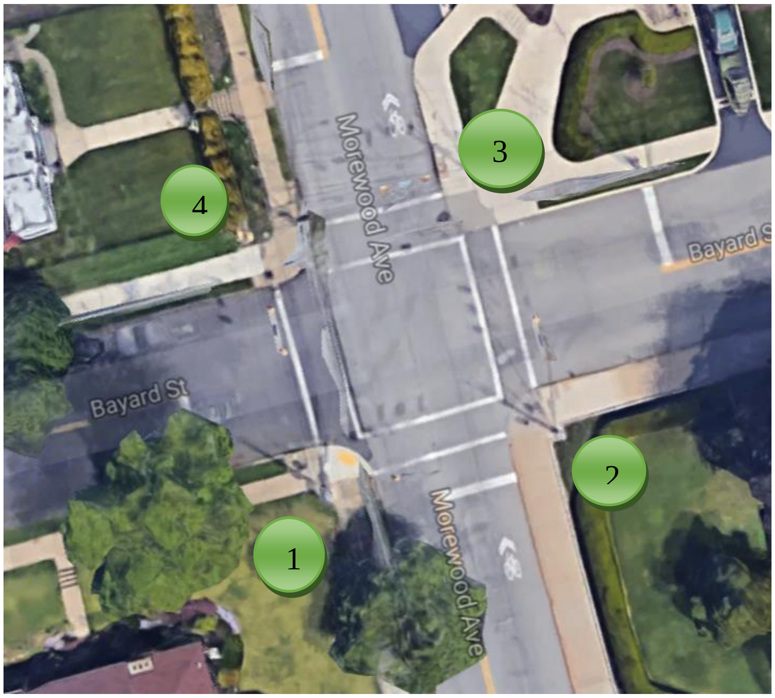

Figure 8: Bayard St. -Morewood Ave.

Table 8. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Bayard St.-Morewood Ave. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	Total	Percentage
7AM-8 AM	Compliance	32	65	28	20	145	99.32%
	Non-compliance	0	0	0	1	1	0.68%
8AM-9AM	Compliance	60	84	40	25	209	97.66%
	Non-compliance	2	0	2	1	5	2.34%
4PM-5PM	Compliance	52	94	35	40	221	98.66%
	Non-compliance	1	0	2	0	3	1.34%
5PM-6PM	Compliance	48	76	36	32	192	97.46%
	Non-compliance	0	0	4	1	5	2.54%

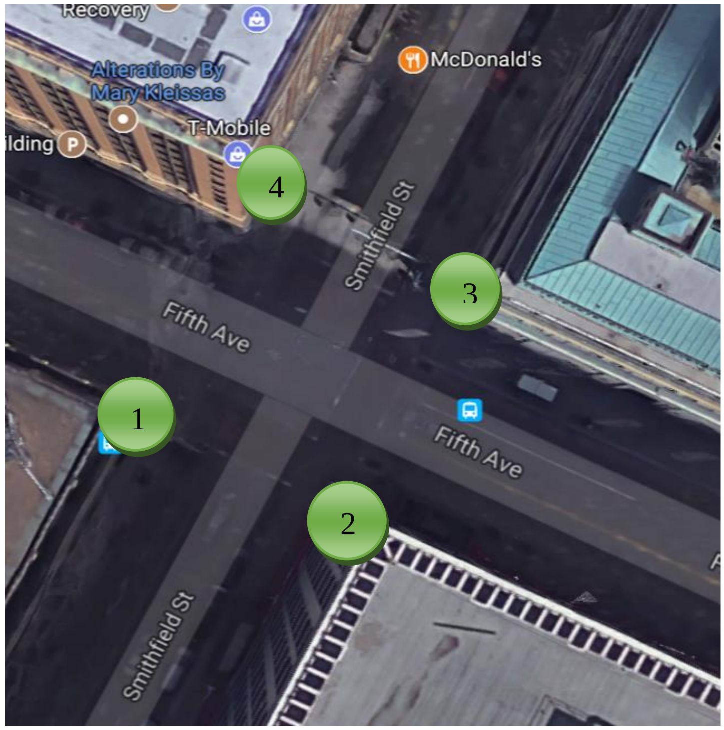

Figure 9: Fifth Ave.-Smithfield St.

Table 9. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Fifth Ave.-Smithfield St. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	1-3	2-4	Total	Percentage
7AM-8 AM	Compliance	136	79	122	186	24	11	558	54.60%
	Non-compliance	157	66	109	132	0	0	464	45.40%
8AM-9AM	Compliance	192	101	136	202	45	8	684	64.77%
	Non-compliance	76	47	114	135	0	0	372	35.23%
4PM-5PM	Compliance	210	85	150	221	52	12	730	65.18%
	Non-compliance	115	67	71	137	0	0	390	34.82%
5PM-6PM	Compliance	168	74	180	194	23	8	647	63.74%
	Non-compliance	100	54	72	142	0	0	368	36.26%

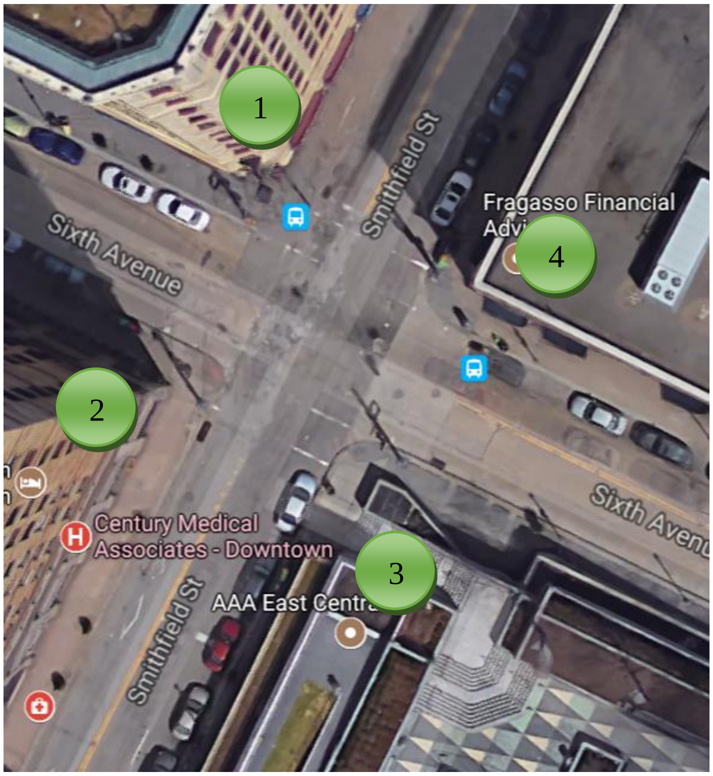

Figure 10: Sixth Ave.-Smithfield St.

Table 4.10 Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Sixth Ave.- Smithfield St. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	Total	Percentage
7AM-8 AM	Compliance	396	382	396	286	1460	93.11%
	Non-compliance	21	26	20	41	108	6.89%
8AM-9AM	Compliance	465	402	482	292	1641	93.40%
	Non-compliance	18	42	32	24	116	6.60%
4PM-5PM	Compliance	424	455	504	340	1,723	90.12%
	Non-compliance	12	48	54	75	189	9.88%
5PM-6PM	Compliance	390	440	464	289	1,583	92.68%
	Non-compliance	13	40	35	37	125	7.32%

Figure 11: Fifth Ave.- Wood St.

Table 11. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Fifth Ave. -Wood St. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	1-3	2-4	Total	Percentage
7AM-8 AM	Compliance	218	146	328	122	86	52	952	56.90%
	Non-compliance	142	203	194	182	0	0	721	43.10%
8AM-9AM	Compliance	235	170	342	136	110	46	1039	56.22%
	Non-compliance	98	338	220	153	0	0	809	43.78%
4PM-5PM	Compliance	276	192	248	128	116	32	992	54.87%
	Non-compliance	212	264	152	188	0	0	816	45.13%
5PM-6PM	Compliance	300	216	372	144	120	48	1200	61.73%
	Non-compliance	116	324	132	172	0	0	744	38.27%

Figure 12: Sixth Ave.- Wood St.

Table 12. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Sixth Ave. and Wood St. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	Total	Percentage
7AM-8 AM	Compliance	485	372	502	536	1895	89.39%
	Non-compliance	52	41	62	70	225	10.61%
8AM-9AM	Compliance	512	418	552	548	2030	86.79%
	Non-compliance	45	56	122	86	309	13.21%
4PM-5PM	Compliance	440	368	402	541	1752	93.64%
	Non-compliance	21	17	28	53	119	6.36%
5PM-6PM	Compliance	446	346	394	507	1693	94.42%
	Non-compliance	17	25	16	42	100	5.58%

Figure 13: Forbes Ave.-Murray Ave.

Table 13. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Forbes Ave. and Murray Ave. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	1-3	2-4	Total	Percentage
7AM-8 AM	Compliance	75	201	109	51	59	120	615	89.00%
	Non-compliance	19	16	28	13	0	0	76	11.00%
8AM-9AM	Compliance	102	139	97	42	60	151	591	84.55%
	Non-compliance	39	19	30	20	0	0	108	15.45%
4PM-5PM	Compliance	94	165	88	65	54	135	601	88.12%
	Non-compliance	35	10	24	12	0	0	81	11.88%
5PM-6PM	Compliance	124	140	96	48	68	148	624	90.70%
	Non-compliance	26	10	19	9	0	0	64	9.30%

Figure 14: Fifth Ave.- Shady Ave.

Table 14. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Fifth Ave. and Shady Ave. intersection

Hours	Crossing behavior	1-2	2-3	3-4	4-1	Total	Percentage
7AM-8 AM	Compliance	35	38	37	53	163	97.02%
	Non-compliance	0	1	2	2	5	2.98%
8AM-9AM	Compliance	48	53	91	87	279	96.54%
	Non-compliance	2	3	3	2	10	3.46%
4PM-5PM	Compliance	32	18	49	65	164	95.91%
	Non-compliance	1	2	1	3	7	4.09%
5PM-6PM	Compliance	84	35	58	42	219	95.63%
	Non-compliance	1	2	4	3	10	4.37%

Figure 15: Fifth Ave.- Morewood Ave.

Table 15. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Forbes and Morewood intersection

Hours	**Crossing behavior**	**1-2**	**2-3**	**3-1**	**Total**	**Percentage**
7AM-8 AM	Compliance	510	108	6	624	95.85%
	Non-compliance	25	2	0	27	4.15%
8AM-9AM	Compliance	725	253	8	986	96.29%
	Non-compliance	31	4	3	38	3.71%
4PM-5PM	Compliance	825	370	11	1206	98.05%
	Non-compliance	17	3	4	24	1.95%
5PM-6PM	Compliance	743	388	20	1151	97.96%
	Non-compliance	12	4	8	24	2.04%

Figure 16: Forbes Ave.-Beeler St.

Table 16. Comparison between pedestrian compliance and non-compliance to intersection traffic signal at Forbes Ave. and Beeler St. intersection

Hours	Crossing behavior	1-2	2-3	Total	Percentage
7AM-8 AM	Compliance	25	38	63	96.92%
	Non-compliance	0	2	2	3.08%
8AM-9AM	Compliance	32	31	63	98.44%
	Non-compliance	0	1	1	1.56%
4PM-5PM	Compliance	27	42	69	95.83%
	Non-compliance	1	2	3	4.17%
5PM-6PM	Compliance	17	26	43	95.56%
	Non-compliance	1	1	2	4.44%

APPENDIX B

TRAFFIC VOLUME DATA

This section provides collected traffic volume data and peak hour calculations. These the total counts collected and used in the traffic analysis and simulation modeling.

Table 17. Traffic volume data and peak hour calculation for Forbes Ave.-Murray Ave.

	From Forbes (Inbound)				From Murray(Inbound)				From Forbes (Outbound)				From Murray(Outbound)					
Start Time	Right	Thru	Left	Heave Vehicle	Right	Thru	Left	Heave Vehicle	Right	Thru	Left	Heave Vehicle	Right	Thru	Left	Heave Vehicle	Total	Cons. Sum
7:00 PM	6	20	13	2	15	27	9	3	19	42	11	1	6	39	10	0	217	
7:15 PM	12	28	12	3	17	34	6	2	17	40	9	0	8	38	8	1	229	
7:30 PM	8	29	14	5	12	30	8	2	21	56	14	4	9	42	9	1	252	
7:45 PM	9	18	14	2	16	38	4	1	26	51	6	2	11	46	11	1	250	948
8:00 PM	7	24	11	2	14	42	11	1	31	59	15	4	10	41	9	0	274	1005
8:15 PM	9	19	10	1	12	49	10	3	28	54	9	3	11	37	8	1	256	1032
8:30 PM	8	21	17	4	21	43	10	2	32	70	11	7	10	45	7	0	295	1075
8:45 PM	12	23	16	1	23	40	16	3	33	68	10	5	14	48	11	1	314	1139
04:00 PM	7	21	17	3	16	29	10	3	21	63	13	6	7	47	14	3	265	
04:15 PM	15	30	14	3	16	49	8	4	18	53	10	1	11	54	10	1	288	
04:30 PM	11	33	13	7	11	34	13	2	22	79	16	8	15	43	6	1	296	
04:45 PM	11	19	20	4	11	35	7	3	23	65	8	5	12	53	13	2	277	1126
05:00 PM	6	28	12	4	19	43	13	2	30	64	17	5	11	42	11	0	296	1157
05:15 PM	10	18	12	1	12	41	10	3	22	65	9	6	8	42	8	1	257	1126
05:30 PM	11	25	18	3	20	47	9	2	29	73	15	9	10	52	6	0	315	1145
05:45 PM	16	22	19	1	16	36	13	2	29	61	14	6	8	56	10	1	300	1168
Peak hour	43	93	61	9	67	167	45	9	110	263	55	26	37	192	35	2	1168	

Table 18. Traffic volume data and peak hour calculation for Forbes Ave.-Shady Ave.

	From North				From East				From South				From West					
Start Time	Right	Thru	Left	Heavy Vehicles	Right	Thru	Left	Heavy Vehicles	Right	Thru	Left	Heavy Vehicles	Right	Thru	Left	Heavy Vehicles	Sum	Consecutive Sum
7:00 AM	11	70	5	1	20	78	25	3	9	100	11	3	9	15	1	1	354	
7:15 AM	14	107	8	3	16	79	18	4	12	106	4	0	8	22	6	4	400	
7:30 AM	9	96	10	3	16	99	11	6	9	109	13	2	13	29	6	3	420	
7:45 AM	11	78	5	7	20	91	19	3	17	100	15	2	8	41	6	3	411	1585
8:00 AM	10	98	10	3	15	72	24	6	20	86	9	0	12	30	9	5	395	1626
8:15 AM	7	83	5	4	16	62	24	4	8	111	19	4	6	26	9	2	376	1602
8:30 AM	7	44	8	2	18	49	16	2	5	64	5	1	7	17	2	3	242	1424
8:45 AM	17	85	6	2	25	73	25	4	8	112	15	2	11	31	12	3	420	1433
4:00 PM	18	81	8	2	13	97	18	0	6	55	19	3	19	75	10	1	419	
4:15 PM	25	54	10	5	8	91	14	3	15	39	25	4	14	74	25	1	394	
4:30 PM	18	66	6	3	6	90	7	1	10	57	24	2	16	81	8	1	389	
4:45 PM	11	56	6	4	4	82	21	0	21	41	22	1	14	91	7	1	376	1578
5:00 PM	21	69	13	3	6	89	19	1	15	37	24	1	15	81	8	3	397	1210
5:15 PM	24	50	15	3	8	96	13	0	16	42	16	2	19	79	10	1	388	1598
5:30 PM	10	40	15	3	7	102	11	2	18	43	21	1	17	101	9	1	394	1573
5:45 PM	20	39	17	3	11	78	11	0	9	34	18	1	21	87	14	1	359	1538
Peak hour Total	**44**	**379**	**33**	**16**	**67**	**341**	**72**	**19**	**58**	**401**	**41**	**4**	**41**	**122**	**27**	**15**		

Table 18. Traffic volume data and peak hour calculation for Fifth Ave.-Wood St.

	From North				From East				From South				From West					
Start Time	Right	Thru	Left	Heavy Vehicles	Right	Thru	Left	Heavy Vehicles	Right	Thru	Left	Heavy Vehicles	Right	Thru	Left	Heavy Vehicles	Sum	Consecutive sum
7:00 PM	6	34	1	6	1	21	2	7	8	24	4	12	9	35	1	2	146	
7:15 PM	8	28	2	5	2	17	2	8	6	19	1	14	12	31	0	1	128	
7:30 PM	8	32	4	5	0	14	5	9	5	22	3	11	8	38	1	2	140	
7:45 PM	9	33	2	8	0	21	3	11	7	27	2	10	9	39	1	2	153	567
8:00 PM	11	34	1	4	1	26	1	6	6	26	3	9	6	32	0	1	147	568
8:15 PM	7	17	1	2	1	18	2	4	5	14	1	8	8	28	1	2	103	543
8:30 PM	10	42	2	3	0	12	2	8	4	26	1	12	12	46	1	2	158	561
8:45 PM	12	30	1	4	1	26	4	7	8	29	3	11	14	45	1	2	174	582
4:00 PM	9	38	0	7	0	24	0	9	10	38	5	13	15	51	0	5	190	
4:15 PM	13	36	3	8	2	21	2	8	7	24	1	15	14	45	0	3	168	
4:30 PM	16	43	4	7	0	20	10	8	6	23	5	12	17	52	1	3	197	
4:45 PM	9	36	5	15	1	22	3	12	15	31	1	14	21	50	4	2	198	753
5:00 PM	8	39	1	5	0	17	2	8	9	34	4	10	12	48	0	3	174	737
5:15 PM	14	42	2	9	1	19	2	5	7	21	1	12	11	41	0	2	161	730
5:30 PM	12	37	5	4	1	21	8	7	5	25	3	11	14	47	1	1	179	712
5:45 PM	8	34	2	13	1	21	1	6	11	24	1	15	17	46	3	2	169	683
Peak hour	47	153	12	37	3	87	15	37	38	116	12	54	67	198	5	13		

Table 18. Traffic volume data and peak hour calculation for Bigelow Blvd.-Parkman Ave.-O'Hara St.

	From North				From East				From South				From West					
Start Time	Right	Thru	Left	Heavy Vehicles	Right	Thru	Left	Heavy Vehicles	Right	Thru	Left	Heavy Vehicles	Right	Thru	Left	Heavy Vehicles	Sum	Consecutive sum
7:00 PM	2	17	16	1	28	12	18	1	14	46	4	0	4	6	1	2	168	
7:15 PM	4	26	18	2	32	18	15	1	12	56	5	1	0	5	5	0	196	
7:30 PM	5	21	14	1	38	15	12	0	18	52	8	2	3	4	6	3	196	
7:45 PM	6	23	17	3	42	10	18	1	19	59	4	1	2	3	3	2	206	766
8:00 PM	7	21	19	1	45	9	14	4	18	62	5	1	3	8	4	1	215	813
8:15 PM	5	26	23	1	40	17	19	2	26	58	6	2	4	9	2	4	235	852
8:30 PM	6	22	18	4	28	15	15	1	23	76	8	5	2	7	8	2	228	884
8:45 PM	7	28	20	2	39	14	14	3	25	72	1	2	1	5	4	3	230	908
4:15 PM	7	33	26	1	36	12	18	2	19	88	8	3	4	11	5	2	267	
4:30 PM	6	31	23	2	41	18	15	1	16	93	7	1	0	12	6	1	268	
4:45 PM	5	38	14	4	38	15	12	2	21	74	5	1	3	8	8	4	241	
5:00 PM	8	26	23	2	51	6	18	1	22	82	3	3	2	11	8	1	260	1036
5:15 PM	7	32	21	1	48	12	14	1	19	76	5	1	1	9	4	3	248	1017
5:30 PM	6	26	15	3	42	13	12	3	17	81	2	2	4	5	5	1	228	977
5:45 PM	5	28	16	2	39	10	17	2	25	74	1	2	2	6	8	1	231	967
Peak hour	8	128	86		166	51	63		78	337	23		9	42	27			

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