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16-04 Effectiveness of Bicycle Signals for Improving Safety and Multimodal Mobility at Urban Intersections

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Effectiveness of Bicycle Signals for Improving Safety and Multimodal Mobility at Urban Intersections

FINAL REPORT

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16. Abstract

With the dramatic increase of non-motorized transportation users, more people are concerned about the non-motorized traffic safety. Unfortunately, bicyclists and pedestrians are prone to more severe injuries when involved in a crash. For bicycle crashes, failing to yield/disregarding traffic control device, and lack of non-motorized facilities were identified to be the main causes of bicycle crashes in urban intersections. This research investigated the effectiveness of two bicycle crash countermeasures with bicycle signal treatments at urban signalized intersections. These two countermeasures are the bike boxes and the protected intersections. The bicycle signal treatments that were tested simultaneously with these countermeasures are the leading bicycle interval and the exclusive bicycle phase.

A before and after bicyclist survey was conducted to measure bicyclist perception of safety of the bike box and bicycle signal heads. Additionally, these engineering countermeasures were evaluated from both traffic operation and traffic safety prospective in a virtual test environment built in VISSIM. Users delay were compared before and after implementing these countermeasures. While a surrogate safety measure "conflicts" among users was used to measure the safety impact of such treatments. Through performing benefit-cost analysis, the threshold values of traffic and bike volumes that are needed to justify the bike box and the protected intersection treatments were found. This research also provided a general guideline that can be used by the decision makers to facilitate bicyclist left turn movement at urban signalized intersections.

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CHAPTER 1

INTRODUCTION

1.1 RESEARCH PROBLEM

There is nationwide increasing interest in supporting and providing more sustainable and active transportation modes in the United States due to their associated benefits, improved health, reduced congestion, and lowered emissions. Walking and biking are considered to be the main non-motorized modes for many people these days, especially in urbanized areas. With the dramatic increase of the non-motorized transportation users, more people are concerned about the non-motorized traffic safety, as it can be a limiting factor of engaging new cyclist. According to the National Highway Traffic Safety Administration (NHTSA), there were 818 bicyclist deaths in the United States in 2015 which accounts for 2.3 % of all traffic fatalities during that year, 70% of which took place in urban areas. Furthermore, there were 5,376 pedestrians killed which accounts for 15% of all traffic fatalities during the same year in the United States. According to the (NHTSA), in 2009, walking trips and biking trips made 10% and 1 % of the total trips respectively. That is 127 million walking trips and 9 million bike trips every day in the Unites States in 2009. In the state of Michigan alone, there were 9,177 crashes that involved bicyclist, and 11,399 crashes that involved pedestrian between the years of 2013 and 2017 (MTCF). In Michigan, walking, running, and biking continue to grow every year in popularity. Unfortunately, bicyclist and pedestrians are prone to more severe injuries when involved in a crash, and the number of non-motorized crashes have been increasing in recent years. Statistics of non-motorized crash data showed that the majority of pedestrian and bicycle crashes occur at or near intersections and on urban streets. For bicycle crashes, failing to yield/disregarding traffic control was identified as one of the main causes of bicycle crashes in Michigan. Analysis indicated that lack of facilities that accommodate bicyclist (dedicated or shared) may encourage bicyclist to ride on sidewalks. Most of "failing to yield/disregarding traffic control" bicycle crashes involved a bicyclist who was riding on a sidewalk prior to the crash. Countermeasures for bicycle crashes in Michigan were limited to conventional ones while many cities began introducing advanced bicycle infrastructure, such as bike boxes, protected intersections, and bicycle signal treatments. As stated by MDOT 2017 crossing treatments guide, 60% of bicyclist in Michigan are classified as interested but concerned about their safety. Therefore, it is believed that introducing such new countermeasures may have a positive impact on engaging more bicyclist and promoting more livable and sustainable communities.

1.2 RESEARCH OBJECTIVE

The main objective of this research is to investigate the effectiveness of two bicycle crashes countermeasures with bicycle signal treatments at urban signalized intersection. These two countermeasures are: the bike box and protected intersection. The bicycle signal treatments that were tested simultaneously with these countermeasures are the leading bicycle interval and the exclusive bicycle phase. This will be done by measuring bicyclist perception of safety thought bicyclist survey. Additionally, this research will investigate engineering countermeasure from both traffic operation (e.g., impact on intersection user delay), and traffic safety prospective (e.g., conflicts among users as a surrogate safety measure). A virtual test environment for one intersection was built in VISSIM and used as a platform to test different treatments implications. This research also aims to find out when such treatment is needed. More specifically, to find out the threshold value of traffic and bike volume that are needed to justify these treatments. Furthermore, this research intended to develop and provide a general guideline to facilitate bicyclist left turn movements. This guideline will show different treatment options that can be used to help bicyclist perform a safer left turn at urban signalized intersections.

1.3 STUDY AREA, SCOPE OF THE STUDY, AND REPORT FORMAT

The study area was chosen to be an urban collector corridor in the city of Grand Rapids, Michigan. The city of Grand Rapids was selected after it had expressed a strong interest in testing bike boxes, and bicycle signal treatments in urban intersections. Recently, the city has invested good amount of resources to improve bicycle environment, not only bicycle infrastructure but also educational efforts. The selected corridor presented in figure 1, consists of four signalized intersections along the corridor of Seward Avenue NW. These intersections are: Fulton St & Seward Ave, Lake Michigan and Seward Ave, Bridge St & Seward Av, and Leonard St and Seward Avenue. However, this study exclusively focused on the intersection of Lake Michigan and Seward Ave shown in figure 1, because of its geometric characteristics such as the existence of bike lane on all approaches, and because actual field execution of bike boxes have been approved and implemented in the field. This intersection is a four-legged signalized intersection. The following applies to all intersection approaches: dedicated left turn lane, shared through and right turn lanes, and bicycle lanes. This intersection runs under fixed time signal.

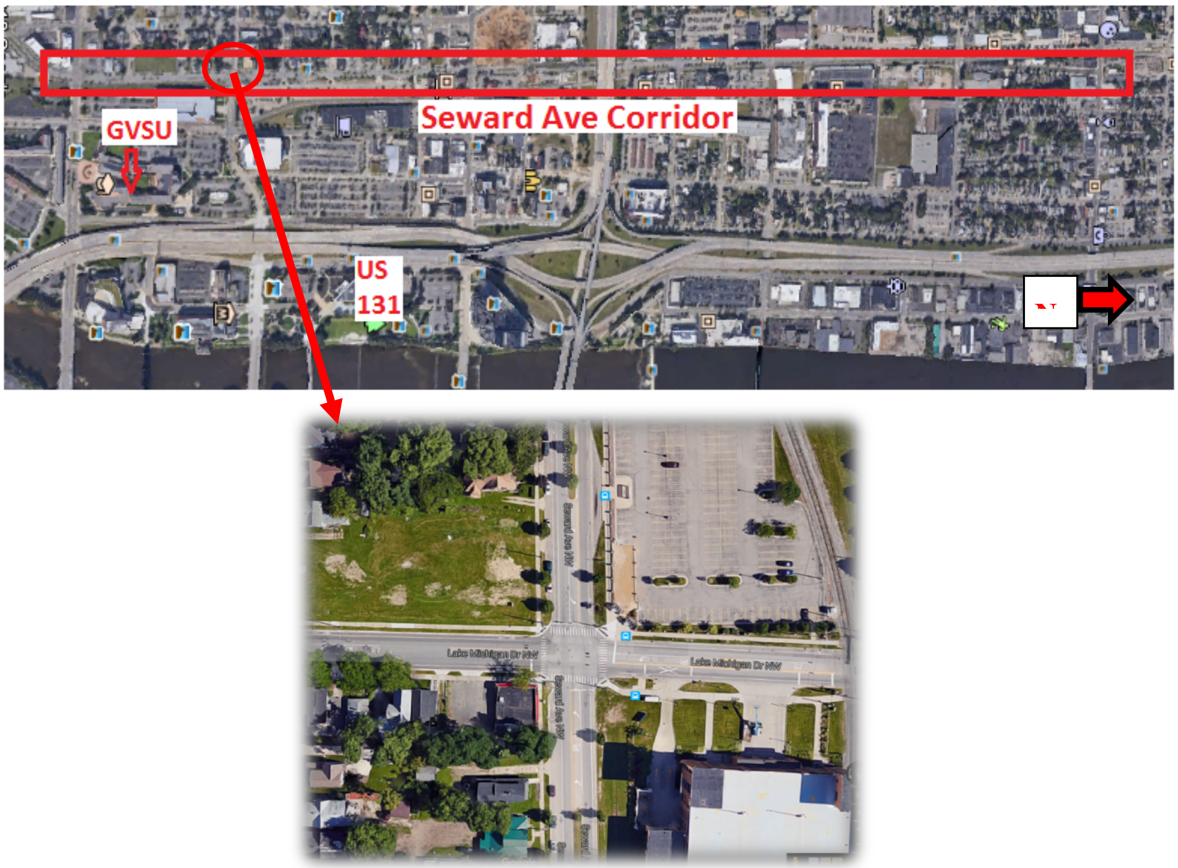


Figure 1- Selected site in Grand Rapids, MI.

The main scope of this research is limited to evaluate the effectiveness of the bike boxes and protected intersections with bicycle signal treatments in improving safety and multimodal mobility at urban signalized intersections. These relatively new intersection treatments are believed to have a positive impact on creating and promoting safer, and more livable communities in the United States. Bicyclist perception of safety was evaluated through field bicyclist survey, and both operation efficiency and safety impact from VISSIM simulation were taken into consideration in the evaluation. Delay of different road users was used for evaluating the operation efficiency, while a surrogate measure of safety "conflicts" was used to measure the safety impact of such treatments. This report consists of five main chapters. Introduction (chapter 1), literature review of the selected treatments (chapter 2), used methodology (chapter 3), data analysis and results (chapter 4), and conclusion, study contribution, and limitation (chapter 5).

CHAPTER 2

LITERATRUE REVIEW

This section is intended to review the related literatures and experiments that have been done in the past. Different literatures were reviewed to investigate the effectiveness of the bike box, protected intersections, and bicycle signal treatments in improving the safety and multimodal mobility at urban intersections. This section contains the following four sub-sections:

- Design and use of bike boxes at urban intersections
- Design and use of protected intersections
- Design and use of bicycle signal treatments at urban intersections
- Use of VISSIM microscopic simulation model and SSAM

2.1 DESIGN AND USE OF BIKE BOXES AT URBAN INTERSECTIONS

The Urban Bikeway Design Guide defines the bike box as a designated space at the head of a traffic lane at a signalized intersection that provides a bicyclist with a visible and safe space to get ahead of queuing traffic at a red signal phase. Implementing bike boxes at an urban intersection have many potential benefits, these benefits are shown below:

- Provides bicyclist with a head start at green indication to help them clear the intersection
- Facilitates bicyclist left turn movements at a red signal phase
- Prevents right hook conflict with turning vehicles
- Increases bicyclist's visibility at intersection
- Reduces signal delay for bicyclist

Figure 2 shows a typical bike box design at an intersection. Bike boxes have been used in numerous European countries for many years. However, it is still considered a new treatment in the U.S. Since bike boxes have proven its effectiveness in increasing the safety of bicyclist, and facilitating their movements, many U.S cities have expressed their interests in adopting such facility. Bike boxes have increasingly been adopted by U.S cities such as Austin, TX; Minneapolis, MN; Boston, MA; New York, NY; Portland, OR; Chicago, IL; Seattle, WA. A summary of studies that have been done to evaluate bike boxes is shown below:

Figure 2- Typical bike box design, source: NACTO

London, UK

This research study took a place at twelve intersections with an Advanced Stop Line ASL (Bike box) in the greater London area, and at two controlled intersections for comparison purposes. The research team videotaped the selected intersections to obtain quantitative information about the bicyclist and other road users' behaviors at the ASL. A total of 6041 cyclists were observed during this study. The results showed all vehicles that encroached in the controlled sites went all the way into the crosswalk, while only 12% at the sites with ASL (Allen., 2005). Additionally, it has been found that ASL may aid in reducing the number of the cyclists waiting in the pedestrian crossing area despite that 36% of cyclists experienced some form of encroachment by vehicles into the ASL. It was also found that 78% of cyclists were able to position themselves in the designated area in the sites with ASL treatments, while this percentage was only 54% at the controlled sites. Furthermore, cyclists whom traveling straight through the intersections stopped in front of traffic thus reducing the risk of conflict with vehicles turning left (driving is on the left side).

Eugene, OR

One of the first experiments that took place in the US was at Eugene, Oregon in the summer of 1998 (Hunter., 2000). The purpose of the bike box was to facilitate the movement of bicyclist riding on a left side bike lane before a two one-way intersection to move to a right-side bike lane after the intersection. The results indicated that the use of bike box was reasonably good as 22% of the bicyclist for whom the bike box was most intended used the box. This relatively lower percentage is mainly due to the high level of motor vehicle encroachment into the bike box.

Portland, OR

This research studied bike boxes effects at 10 signalized intersections (7 green colored, 3 no green color), and 2 controlled intersections in Portland Oregon (Dill., 2012). A video surveillance approach was used to collect data about different road user behavior. Furthermore, cyclists and motorists survey took place at five of the intersections to a measure the safety perceptions, and to estimate the user's knowledge and understanding of the bike boxes, and other reactions to the changes. The results showed that motor vehicle and cyclist encroachment into the crosswalk fell significantly at both the colored and uncolored signalized intersection based on the video data. Furthermore, there was an increase in the number of yielding behaviors from motor vehicles. The cyclist survey showed that 77% of the cyclists felt safer while riding on intersection with a bike box. Motorist survey showed that 89 % of the motorist thought that the green color is better. In addition, the green color decreased the number of motor vehicles encroachment into the bike lane prior to arriving at the intersection. Adding a green color to the bike box was found to be encouraging the bicyclist to stop in front of the motor vehicles stop line, and cyclists used the bike box more as intended with the green coloring.

Minneapolis, MN

This study was conducted at two intersections in the downtown area of Minneapolis city in MN (James., 2011). The test intersection has a bike box in its north west bound, while the controlled intersection does not. Data were evaluated based on both field observation and an online survey to compare the stated behavior with the observed behavior of bicyclist using the bike box. Bicyclist survey showed that 87 % of bicyclist would stop inside the box, and 83% would stop in the far-left side of the box for through movements and left movements respectively at a red signal. However, field observation showed that only 40% of bicyclist stopped inside the bike box. The survey showed that 54% of bicyclist would use the bike box to turn left on a red signal, while this percentage dropped to 7% based on the field observation. Both motorists and bicyclist crosswalk encroachment decreased from 4% to 1%, and from 33% to 10% respectively in the test intersection.

Austin, TX

The research team of this experiment studied two intersections in Austin Texas over a period of 18 months. The first intersection had only one bike box installed at its southbound lanes, while the second intersection had two bike boxes installed at its North and South bound. This study (Loskorn.,2013) was characterized by its staged approach; studying the bike box effects on bicyclist and motorist behavior over three stages by using videotaping before the installation, after installation of the bike box (Skeleton), and after adding the green color to the bike box. After coding and analyzing the video-footage, the result came as following: the percentage of bicyclist who used the bike lane when approaching the intersection significantly increased (77% to 93%) after adding the green color in the first intersection, while there was a steady increase in that number for the second intersection over the three stages. The number of bicyclist that stayed behind the stop line within the bicycle box, and then departed first at the intersection were steadily increased over the three stages in both intersections. The total percentage of bicyclist who waited in the bicycle box or bicycle lane area increased from 52% to 92%, and from 36% to 49% in the first and second intersection respectively. Due to the inconsistent results, there was no significant conclusion can be made about motorist encroachment into the stop line.

2.2 DESIGN AND USE OF PROTECTED INTERSECTIONS

Protected intersection is an innovative intersection design that can further separate non-motorized road users from vehicle traffic. The concept of protected intersection is borrowed directly from the Netherlands and Denmark as it has been in use for long time compared to the U.S. Even though, engineers in the U.S were aware of such design since 1972, no protected intersection was implements up until recently. The spread of bike lanes, specifically, protected bike lanes, breathed a new life in the concept of protected intersection in the U.S. The first protected intersection is believed to be installed during 2015 in Salt Lake City. The protected intersection design was then implemented in many U.S cities such as, Berkeley, Chicago, Davis, Boston and many more. According to Alta Planning + Design report, the protected intersection can lead to many benefits if adopted correctly, these benefits are:

- Increases bicyclist visibility and provide them with a head start
- Facilitates protected two-stage left turns for bicyclist
- Provides secure and free right turn for bicyclist
- Provides more reaction time for all road users
- Increases yielding to crossing pedestrian and bicyclist

Figure 3 below illustrates the concept of the protected intersection

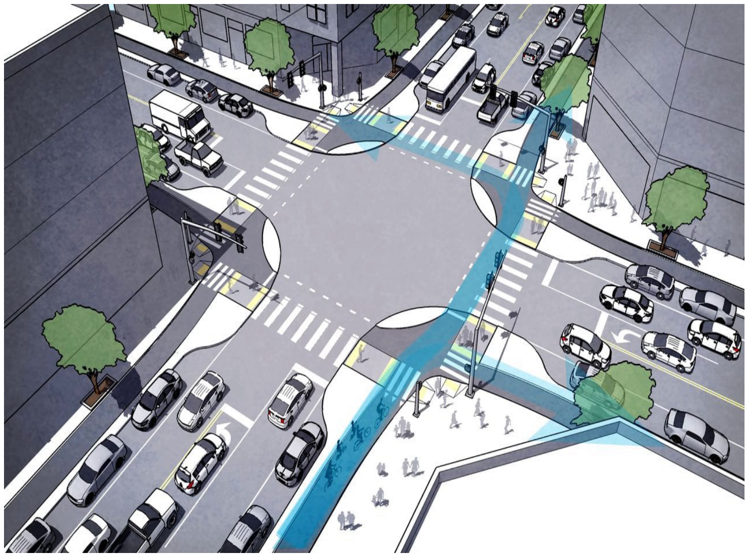


Figure 3- Typical protected intersection design

The protected intersection uses the following elements to make cycling safer, and comfortable:

Corner refuge island:

This is very similar to a curb extension for bicyclist that separate cyclist waiting to go through or left from turning vehicles. This island can also be used to manage the speed of turning vehicles.

Forward stop bar:

This advanced stop bar is used to place bicyclist farther ahead in the intersection, by doing so, bicyclist will be more visible to vehicle waiting at a red light and will provide physical separation and head start for bicyclist at the beginning of green light.

Set back crossing:

Unlike conventional intersection, protected intersection comes with setback crossing for both pedestrian and bicyclist. The critical dimension is a one car length of space between the traffic and the bicycle crossing. Set back crossing can improve the sightline and establish priority.

The protected intersection can be used along with/without bicycle friendly signal phasing. For example, exclusive bicycle signal phase can be used to prevent all bicyclist conflict with motor vehicle. Another variation can be by providing a leading interval for bicyclist and pedestrian to help them clear the instruction earlier. To the Author's best knowledge, there have been no published studies that evaluated the protected intersections in the U.S.

2.3 DESIGN AND USE OF BICYCLE SIGNAL TREATMENTS AT URBAN INTERSECTIONS

A recent advanced operational infrastructure that has been used for bicyclist is bicycle signal face. A bicycle signal is an electrically powered traffic control device that should only be used in combination with an existing conventional traffic signal or hybrid beacon (Urban Bikeway Design Guide., 2014). Figure 4 shows a typical bicycle signal face. Bicycle signal faces can be used either alone, or when providing a leading bicycle interval, or when adding an exclusive bicycle signal phase. Adding bicycle signal head at an existing intersection has many proven benefits, these benefits are as shown below:

- Separates bicycle movements from conflicting motor vehicle movements
- Increases bicyclist safety and visibility at intersections
- Provides priority to bicycle movements
- Helps simplify bicyclist movements
- Protects bicyclist at intersection

For optional use of bicycle signals, the Federal Highway Administration (FHWA) recently issued an Interim Approval in 2013 that allow cities in the U.S. to start installing bicycle signal heads at their intersections. This interim approval explained the general condition for the use of bicycle signal face, and design features.

Figure 4- Typical bicycle signal head

2.3.1 Leading Bicycle Interval (LBI)

A leading bicycle interval is a countermeasure to increase the safety of non-motorized traffic, specifically bicyclist at signalized intersections. LBI gives a head start of 4-7 sec (usually 5 sec) for bicyclist at signalized intersections to reduce the conflicts between vehicle turning movements and bicyclist. One of the major benefits of the LBI is to increase bicyclist chance to establish themselves in the driver's visual field by giving them a head start interval, thereby, reducing the probability of a collision. No turn on red sign should be considered with LBI treatment. Figure 5 below illustrates how the LBI system works. During the first portion of the green phase, the bicyclist and pedestrian are allowed to start entering the intersection, while the corresponding thought traffic movement, and turning vehicles are restricted. Later and in the second portion, corresponding through vehicles can proceed and turning vehicles are given a permissive turning phase as they are expected to still yield to bicyclist and pedestrian.

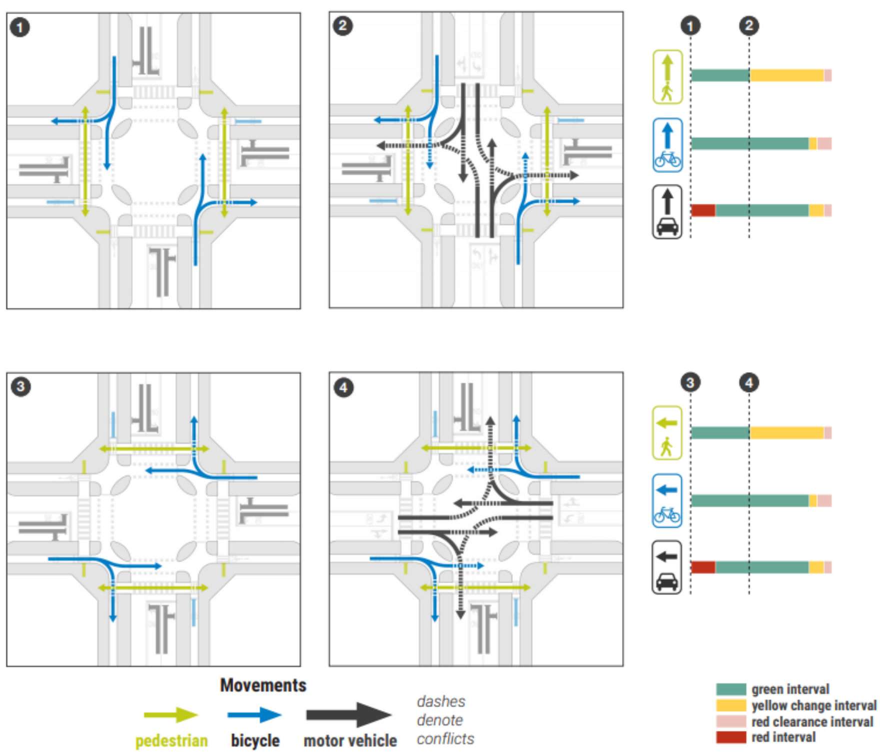


Figure 5- Typical leading Bicycle interval, Source (MassDot 2015)

Another variation of the LBI is the Split Leading Bicycle Signal (Split LBI). This treatment is very similar to the LBI treatment in the sense of mitigating bicycle and turning vehicle conflicts.

However, the split LBI is more advantageous toward vehicle traffic than LBI, as it allows through movement to proceed during the leading interval and only prohibit turning vehicle movements. Figure 6 below illustrates how the split LBI system works. At the beginning of green, bicycles, pedestrian, and through vehicle movements are shown a green indication, whereas turning vehicle movements are restricted by a red indication. This scheme is followed by a green indication for turning vehicle movements.

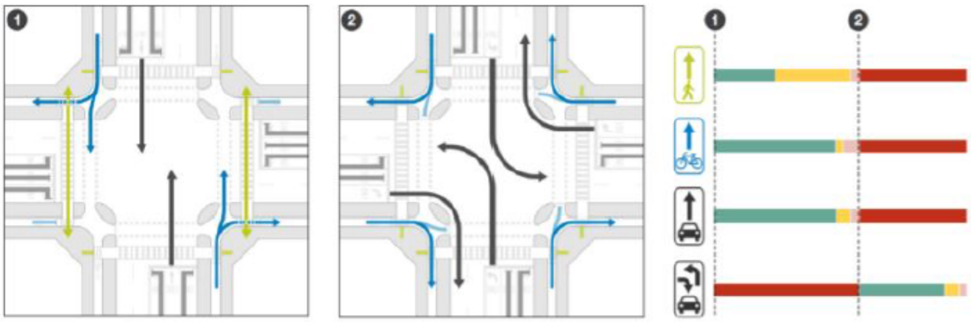


Figure 6- Typical split LBI, Source: (Kothuri., 2018)

Installing LBI is usually combined with a Leading Pedestrian Interval (LPI) as they both function with the same logic. The benefit of adding LPI according to the (Urban Street Design Guide., 2014) is to increase pedestrian's visibility when crossing by giving them priority. Additionally, LPIs have shown its effectiveness of reducing pedestrian-vehicle collisions by up to 60 %. There was one field study in which adding LPI phase has been evaluated at three urban signalized intersections in Florida (Houten., 2000). Results demonstrated that adding three seconds leading pedestrian phase reduces the conflict between pedestrians and turning vehicles by increasing the chances of auto vehicles yielding the right of way to pedestrians. Furthermore, LPI can provide a safer walking environment, and can improve pedestrian's comfort and perceived safety. (Fayish, A., & Gross, F. 2010) studied the safety effects of LPI implementation at ten signalized intersections in the CBD in Pennsylvanian. Data analysis revealed that LPIs can significantly reduce the number of pedestrian-vehicle crashes when available. In fact, a reduction rate of at least 46 % is expected in pedestrian- vehicle crashes with the installation of LPI. The same study showed that implementation of the LPI has the potential of reducing pedestrian-vehicles crashes. Pedestrian- vehicle crash analysis study after implementing LPIs is available from (King., 2000). The New York State Department of Transportation compared the crash rates of 26 locations with LPI with a group of similar intersection without the LPI. After analysis the available crash data, results showed that LPIs have a positive effect on pedestrian crossing safety, and there was a 28% reduction in the percentage of crashes that involved a pedestrian and turning vehicle.

2.3.2 Exclusive Bicycle Phase (EBP)

This countermeasure is considered a safer treatment that the LBI as it stops all traffic movements, while bicycles are given unrestricted access to the intersection. This treatment is very similar to the exclusive pedestrian phase, also called a Barnes dance from operational point of view. Exclusive bicycle signal phase can protect cyclist from conflicting with traffic movements and therefore significantly increasing their safety. However, the main drawback of such treatment is that it can lead to a significant increase in all intersection users' delay. Figure 7 below shows how exclusive bicycle signal phase works. A protected phase is given for bicyclist and pedestrian to freely maneuver the intersection, while other traffic movements are given a red indication. Once this exclusive phase is terminated, other traffic movements will proceed. According to the interim approval for optional use of bicycle signal face from the MUTCD, installing a bicycle signal head can help in either reducing the overall number of bicycle crashes, or decrease the bicycle crash rate by up to 45 percent while bicycle volume concurrently increases. Also, providing a bicycle signal can maintain a physical separation whether space or time between bicyclist and motor vehicles (DiGioia., 2017). This separation will decrease the reaction time and will help prevent the two modes from colliding. In terms of the effect of bicycle signal head on signal compliance rate, it has been found that bicycle signal head, is in fact, effective in improving bicyclist compliance rate with traffic control signals (Denver., 2016). Another Study was conducted in Melbourne, Australia to measure signal compliance rate at 10 signalized intersections (Johnson., 2011). The study showed that the signal non- compliance rate is 6.9 % of the total number of riders. Researchers also found that bicyclist turning left (Traffic travel on the left side) are 28.4 times more likely to not complain with the signal than those who are riding straight. Also, the infringement rate changes with the cross-traffic volume; infringement rate higher when the cross-traffic volume is low, and lower when the cross-traffic volume is high.

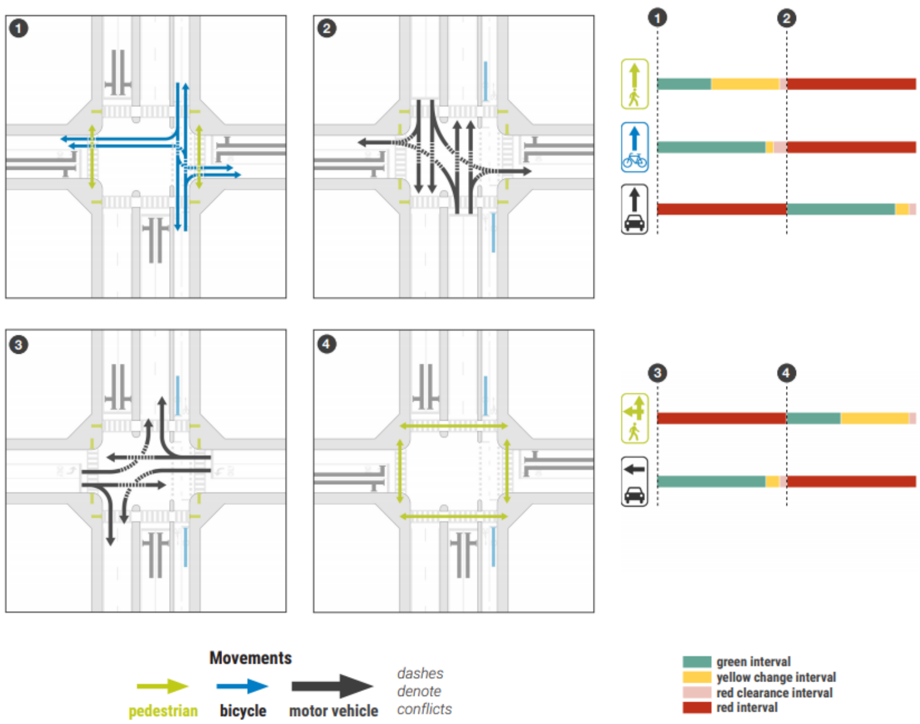


Figure 7- Typical exclusive bicycle phase, Source (MassDot 2015)

Recently, the National Institute for Transportation and Communities (NITC) released a report about a study that assessed the operational impact of the LBI, Split LBI, and the EBP in a microsimulation environment for one signalized intersection. Results of this study (Kothuri., 2018) showed that there is a uniform increase in vehicle delay across all approaches (almost by the same amount of the leading interval time, which is 5 seconds), and a little overall change in bicyclist delay. The split LBI treatment showed a nearly negligible impact on vehicle delay for the unaffected through movements, and relatively low on the right turn movements. Also, through bicyclist movements appeared to show minor changes in delay. The impact of the EBP on vehicles and bicyclist delay were also studied and the results showed a mixed outcome. Bicyclist and pedestrian movements showed a general increase in delay due to the implementation of the EBP.

2.4 USE OF VISSIM MICROSCOPIC SIMULATION MODEL AND SSAM

2.4.1 VISSIM Overview and Background

Progressing mathematical and computational technology along with advanced roadway design and management have created an environment in which traffic simulation models became a leading analysis tool for transportation engineers. Not surprisingly, simulation models have become one of the most popular tools for analyzing and evaluating of a transportation system. Simulation models can be used for various purposes in different transportation areas, such as: different signal timing plans, geomatics changes, and emerging technologies like intelligent transportation system (Park & Schneeberger., 2003). Also, simulation models became a valuable aid in assessing the performance of a transportation systems (Park & Qi 2005). Clearly, the Highway Capacity Manual (HCM) is the most used engineering guidebook in the analysis of a transportation system. However, it cannot be used to analyze a large-scale transportation system. On the other hand, simulation models are capable to do such analysis for any transportation system size. Microscopic traffic simulation models have been widely used in both the research and the industry area, because simulation is inexpensive, fast, flexible, and risk-free. Additionally, their attractive animations and stochastic variability to represent the real-world traffic condition increased their popularity. Though, there are different simulation models currently available (CORSIM, VISSIM, SimTraffic...etc.) few have proven their ability to reflect the stochastic nature of traffic. VISSIM by PTV Group is a widely used microscopic and stochastic simulation software in various transportation studies. VISSIM was originally created and developed by the University of Karlsruhe in Germany in early 1970s. VISSIM is a time step model that use a psychophysical driver behavior model to simulate traffic movements and to test different traffic scenarios before its realization. As a result of its proven credibility, many studies have used VISSIM as their main tool for analysis and evaluation. For example, Tian 2002 investigated the variation in the performance measure generated by different microscopic simulation models. This study (Tian., 2002) showed that VISSIM can produce the highest capacity and the lowest delay estimates when compared to CORSIM and SimTraffic. VISSIM was also used to estimate traffic vehicle emissions in different studies (Jie., 2013, Hirschmann., 2010, Song.,2012, & Stevanovic., 2009). Additionally, VISSIM has expanded its applications to be integrated with other programming language to be used with other innovative projects, such as autonomous and connected vehicles. One study (Goodall., 2013) used VISSIM to simulate connected vehicles environment in their research to test a new traffic control algorithm. Another study (LI., 2013) showed a way to model an autonomous intersection using VISSIM to reduce delay and increase capacity and safety of intersections.

2.4.2 SSAM Development and Workflow

As we can see, there are many applications of the software VISSIM. However, one of the limitations of microscopic traffic simulation models in general and VISSIM in particular is that it cannot be used for safety assessment purposes. Safety analysis has traditionally relied on crash data analysis to evaluate the safety performance of a new traffic facility. Obtaining enough and reliable crash data may not always be available to researchers and may come with few drawbacks. Non-motorized traffic crashes are rarely recorded, and incomplete/ insufficient crash report information also led to a much small population data to be used in safety analysis. For these reasons, a traffic conflicts possibility has been used as a surrogate safety measure instead of crashes. Collecting conflict data for safety analysis purposes has been limited to video recording or by field observation. However, both techniques required an excessive amount of time and effort. Also, the human error is involved and may lead to inaccurate data due to the observer's subjective judgment. On top of that, collecting traffic conflict data in the field is associated with high cost. All these limitations of collecting non-motorized traffic conflict data for safety analysis purposes led to an increasing interest in finding another affordable technique. In previous years, using microscopic traffic simulation software to assess safety of transportation facilities has increased dramatically. The Federal Highway Administration (FHWA) has developed a software called Surrogate Safety Assessment Model (SSAM) to develop the process of identifying traffic conflicts and calculating the surrogate safety measures in different simulation packages. This software can process the output trajectory data file from VISSIM, Aimsun, Paramics, and TEXAS) of the vehicles driving through a traffic facility and utilize several algorithms to identify potential conflict points (Gettman., 2008). SSAM can calculate surrogate measure of safety corresponding to each vehicle to vehicle interaction and determines whether or not each interaction satisfies the criteria to recognize a conflict. Figure 8 below shows the workflow of SSAM software.

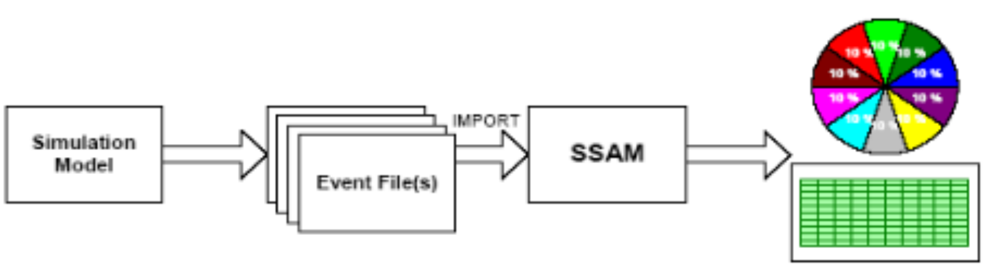


Figure 8- SSAM work flow

The used conflict Identification algorithm in SSAM is summarized in the following steps:

- **Step 1**: determine the dimensions of the analysis area: construct a zone grid, typically 50*50 ft. to cover the entire analysis area.
- **Step 2**: analyze a single time step of the trj. file for all vehicles.
- **Step 3**: find the location and orientation of all vehicles at its projected future position in the zone grid and identify all conflict vehicle pairs.
- **Step 4**: perform a more detailed processing of all conflicting pairs.

A Conflict in SSAM is defined as an event involving the interaction of two or more road users where one or both drivers took evasive maneuvers to avoid a collision. The software uses two threshold values for surrogate measure of safety to determine which vehicle to vehicle interaction should be classified as a conflict. These two threshold values are Time to Collision (TTC), and Post Encroachment Time (PET). The software default values for these two thresholds are 1.5 seconds, and 5 seconds respectively. SSAM classifies a conflict based on the approximate angle of a hypothetical collision between two conflicting vehicles. Simulated conflict types as shown in figure 9 below are categorized based on conflict angles as: rear end (<30°), crossing conflict (>85°), or lane change (otherwise).

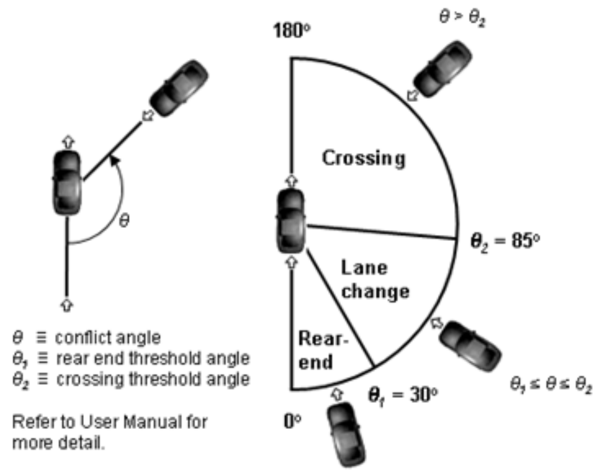


Figure 9- Conflict types by angles in SSAM

2.4.3 SSAM Surrogate Measures and Time Line of a Conflict Point Event

Currently, SSAM can generate the following as a surrogate safety measures: Time to Collision (TTC), Post encroachment Time (PET), the speed differential (DeltaS), Maximum Speed (MaxS), and Deceleration Rate (DR). These surrogate safety measures are defined and shown in this section by (Gettman., 2008 & 2003):

Time to Collision (TTC): is the time for a potential collision to happen between two road users if they did not change their velocity or direction. This estimate is based on the current location, speed, and trajectory of two vehicles at a given Instant.

Post Encroachment Time (PET): is the minimum post-encroachment time observed during the conflict. Post encroachment time is the time between when the first vehicle last occupied a position and the second vehicle subsequently arrived at the same position. A value of 0 indicates an actual collision.

Speed differential (DeltaS): is the difference in vehicle speeds as observed at tMinTTC. More precisely, this value is mathematically defined as the magnitude of the difference in vehicle velocities (or trajectories), such that if v_1 and v_2 are the velocity vectors of the first and second vehicles respectively, then DeltaS = $\| v_1 - v_2 \|$.

Maximum Speed (MaxS): is the maximum speed of either vehicle throughout the conflict (i.e., while the TTC is less than the specified threshold). This value is expressed in feet per second or meters per second, depending on the units specified in the corresponding trajectory file.

Deceleration Rate (DR): is the initial deceleration rate of the second vehicle. This value is recorded as the instantaneous acceleration rate. If the vehicle brakes (i.e., reacts), this is the first negative acceleration value observed during the conflict. If the vehicle does not break, this is the lowest acceleration value observed during the conflict. This value is expressed in feet per second or meters per second, depending on the units specified in the corresponding trajectory file.

Maximum Deceleration (MaxD): is the instantaneous acceleration rate observed during the conflict. A negative value indicates deceleration (braking or release of gas pedal). A positive value indicates that the vehicle did not decelerate during the conflict.

Max Delta V (Max ΔV): is the maximum Delta V value of either vehicle in the conflict.

The timeline of conflict event is shown in figure 10 below. The upper curve represents the time-space trajectory of the crossing vehicle, while the bottom curve represents the time-space trajectory of the through vehicle. While these curves are represented as continuous, smooth functions in the following figure, in a traffic simulation, the vehicle time-space trajectories are actually a set of straight lines between time steps. As the number of time steps per second increases, the curves become closer and closer approximations to a smooth curve. Time t1 through time t5 are defined by Gettman as followed:

At time t1, the crossing vehicle enters the encroachment area (i.e., starts to turn left).

At time t2, the through vehicle realizes that a collision might occur and begins braking to avoid the collision.

At time t3, the corner of the rear bumper (either right or left rear corner, depending on the travel direction) of the crossing vehicle leaves the encroachment point.

At time t4, the through vehicle was projected to arrive at the conflict point if the vehicle continued at the same speed and trajectory before it started braking.

At time t5, the through vehicle arrives at the conflict point.

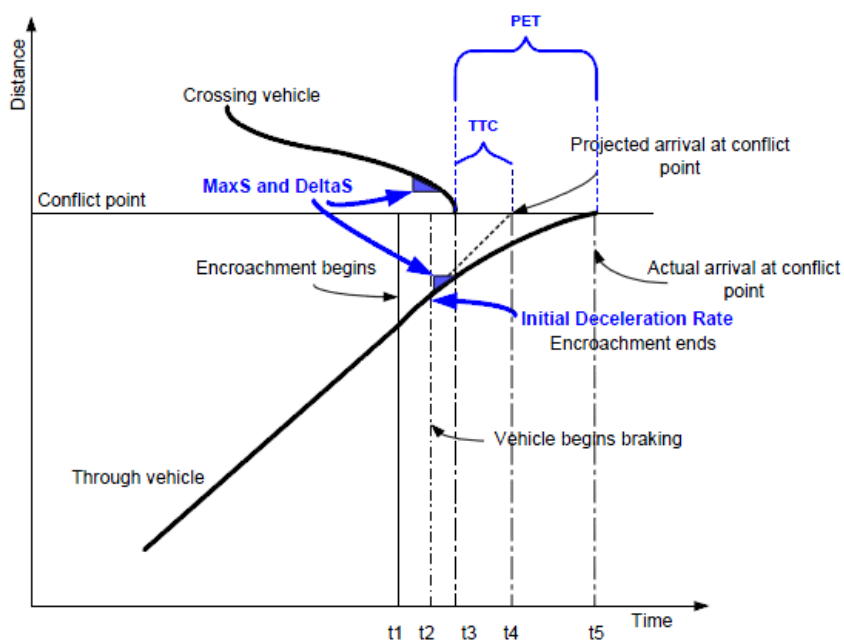


Figure 10- Surrogate measures on conflict point diagram

Gettman and Head also mentioned that a conflict point can occur at the intersection of a flow from a right- or left turning vehicle that proceeds in the same direction as the conflicted vehicle, but in a different lane. This situation can only be evaluated in simulations where the entering path can vary by lane. For example, in the real world, many maneuvers of this type occur on purpose by drivers that want to accept a particular gap of the size required to enter the flow, but that gap size was not available in the closest lane, because of the acceleration needed by the entering vehicle to avoid an approaching vehicle in that lane. A smaller gap size could be accepted, however, if the entering vehicle crosses in front of the approaching vehicle and begins accelerating in the adjacent lane (no vehicle is approaching in the adjacent lane, or the approaching vehicle in the adjacent lane is farther away). Thus, a conflict point event can occur when the driver crosses the first lane to enter the second one and begins accelerating. This occurs even if the driver then re-enters the crossed lane after the approaching vehicle has passed.

2.4.4 Use of SSAM in Previous Studies

Recently, some studies have been conducted to identify if VISSIM simulation models and SSAM can be used to assess the safety impact of a new traffic facility. (Gettmann., 2008) evaluated the capability of SSAM by conducting a theoretical validation, field validation, and sensitivity analysis. The theoretical validation was performed through eleven theoretical validation tests to compare the surrogate and safety assessment results of a pair of simulated design alternatives. For the field validation, eighty-three intersections from British Columbia and Canada were simulated in VISSIM and processed in SSAM to compare with a real-world crash data. The sensitivity analysis was performed to identify the differences between the SSAM outputs of each simulated model vendors system on the same traffic facility design. The theoretical validation results showed that under equivalent traffic conditions and for both intersection design and interchange design alternatives, SSAM can distinguish significant statistical differences in the total number of conflicts, conflicts types (i.e., lane change, rear end, crossing) and among conflict severity indicators (i.e., TTC, PET, ΔV). At the same time, the author also mentioned that, the comparison between two design alternatives did not reveal a clear preferable design over the other. For example, one design can exhibit a higher conflict frequency than the other but with a lower severity level than the other design alternative. It is important to note that the author expressed concern that this type of assessment can affect the decision-making process about which design alternative would be safer. In terms of the field validation, this study showed that there is a significant relationship between the simulated based conflicts and the actual crash data collected in the field. The relationship between the simulated conflicts and the total number of crashes exhibited an R^2 value of 0.41 which is considered to be consistent with the typical reported traditional crash prediction models of urban signalized intersection. However, the author noted that a better correlation can be exhibited with an R^2 value of 0.68 between the traditional volume-based crash prediction models and simulated conflict in SSAM. (Gettmann., 2008) also reported that different wide range of results could be obtained from applying different simulated models to the same traffic facility design. Generally, intersections that were modeled in VISSIM showed the fewest total conflicts, while intersections that were modeled in TEXAS exhibited the highest conflict frequency at approximately ten times higher than VISSIM. Conflicts from Aimsun and Parmics fell between these two extremes. Another research that was recently done in 2017 studied the effect of converting a two-way left turn lane into a raised medium on a section of 1.2-mile urban street in a simulated environment. The goal of this study was to compare the safety impact of different accesses management alternatives with less time and cost. This study showed that VISSIM combined with SSAM can be a viable tool to evaluate the safety impact of access management alternatives without the need for physical installation of alternatives (Saito., 2017). Another recent study done by (Ledezma., 2018) used VISSIM and SSAM to evaluate the impact of different traffic signal designs at general intersections geometry. The study showed that SSAM can be integrated with simulation models such VISSIM to assess the delay and safety impact of different traffic operation changes, like different signal phasing. Other researchers studied if VISSIM and SSAM can be used to provide a reasonable estimate between generated conflicts in VISSIM and observed traffic conflicts of a signalized intersections in the field (Zhou., 2010, Huang., 2013, and Wu., 2017), and (Fan., 2013) at freeway merging areas. All studies showed a promising result that reflects the feasibility of such tools in conflict analysis. Furthermore, Zhou (2010) showed that calibration of VISSIM models and adjusting the threshold values to identify conflicts in SSAM can improve the consistency between the simulated and observed conflicts. Also, Huang, proposed a two-stage procedure for calibration that can improve the goodness of fit between the simulated conflicts and the real worlds conflicts. In addition, Wu (2017) research tested if VISSIM and SSAM can be used to evaluate pedestrian safety at signalized intersections. The results showed that the number of simulated vehicle-pedestrian conflicts was significantly related to the number of observed conflicts in the field. Vasconcelos (2014) also conducted a research to validate the use of SSAM as a tool for assessing intersection safety. The two methods for validation are by comparing the number of simulated conflicts in SSAM with the predicted number of accidents from conventional accident prediction models in three reference intersection layouts. The second approach was to compare SSAM results with conflicts observed on site in four intersections. The results indicate that, despite some limitations related to the nature of current traffic microsimulation models, SSAM analysis is an extremely promising approach to assessing the safety of new facilities or innovative layouts.

2.4.5 SSAM Limitations

SSAM has proven itself to be a viable tool to help in assessing the safety performance of a transportation facility. However, there are some limitations that comes with this promising technique. In simulation models, there are some situations that result in a simulated crash, referred as “virtual crashes” in (Gettman., 2008), this type of crashes in which SSAM identify a conflict with TTC =0 is because the trajectory file data are being analyzed at an extremely nanoscopic scale. These are situations where the logic in the simulation model does not accurately and completely represent the physical possibility of a particular maneuver. Another limitation of SSAM is that it identifies conflicts among low-speed events (MaxS ≤ 10 Mph). For instance, vehicles interacting in queues at close-proximity in which the TTC value can be less than the identified threshold value, but no responsible human observer would count these events as a conflict in a typical field conflict study. The value of Moreover, SSAM in some cases can identify conflicts among pedestrians interacting in the crosswalk. For example, pedestrians are being simulated as a vehicle in VISSIM, and since they interact in very close proximity to each other on their links (Crosswalks), that leads SSAM to define their interactions as a conflict. Furthermore, in VISSIM, pedestrian’s crosswalks are sometimes being built in overlapping links which lead SSAM to identify these interactions among pedestrians as a conflict. These three types of conflicts (virtual crashes, low-speed events, and pedestrian-pedestrian conflicts) should be eliminated or at least be limited to a very rare events.

CHAPTER 3

METHDOLOGY

This section covers the two methodological approaches that were used to evaluate the effectiveness of the bike boxes, protected intersections, and bicycle signal treatments: bicyclist survey and VISSIM simulation. Bicyclist survey approach was used to measure bicyclist perception of safety of bike box and bike signal, and to assess bicyclist knowledge, understanding, and other reactions to the new treatments. VISSIM simulation approach was used to assess the impact of the studied treatments from both safety and operation prospective.

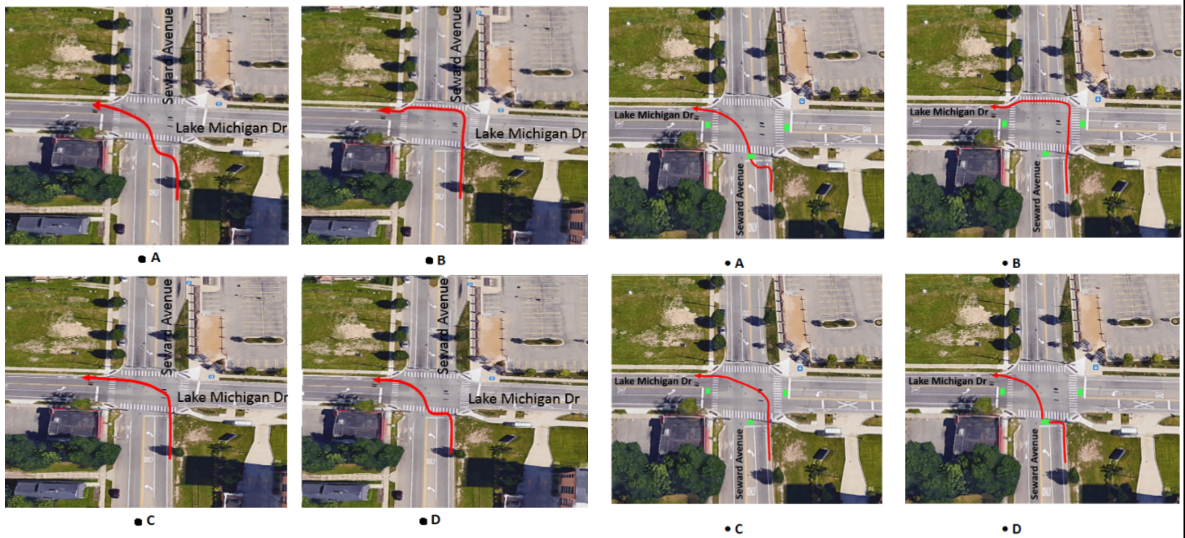
This section contains the following two subsections:

- Bicyclist Survey
- VISSIM Simulation

3.1 BICYCLIST SURVEY

A before and after bicyclist survey was conducted to measure bicyclist perception of the bike box and bike signal at urban intersections. A field bicyclist survey along with an online survey among the bicyclist community in the city of Grand Rapids was conducted. Survey was reviewed and approved by the Western Michigan University's Human Subjects Institutional Review Board (see appendix D and E). The primary purpose of the survey was to measure bicyclist perception of safety of bike box, bike signal, and to assess knowledge, understanding, and other reactions to the new intersection treatments. The survey was of MCQ form that consists of 13 and 14 questions in before and after case respectively. Both before and after surveys are almost identical in terms of the asked questions. The purpose of each question is summarized below:

- Question 1-6: These questions were designed to collect basic demographic details of participants, purpose, and level of cycling.
- Question 7-8: Question 7 shows a picture like that in figure 11 for the intersection of Lake Michigan and Seward Avenue with different left turn patterns and asked participants to pick the best way they would make a left turn. Question 8 asks the participants about the reason of their choice.



(a) Before bike box installation (b) After bike box installation

Figure 11- Coded left turn patterns in (a) before bike box installation; (b) after bike box installation

- Question 9: This question shows a general intersection design with a bike box on its northbound approach like that in figure 12 and asked participants on the location they would stop at if they were to make a left turn on a red signal. In total, there are nine options for the participant to pick from. Multiple responses were allowed for this question.

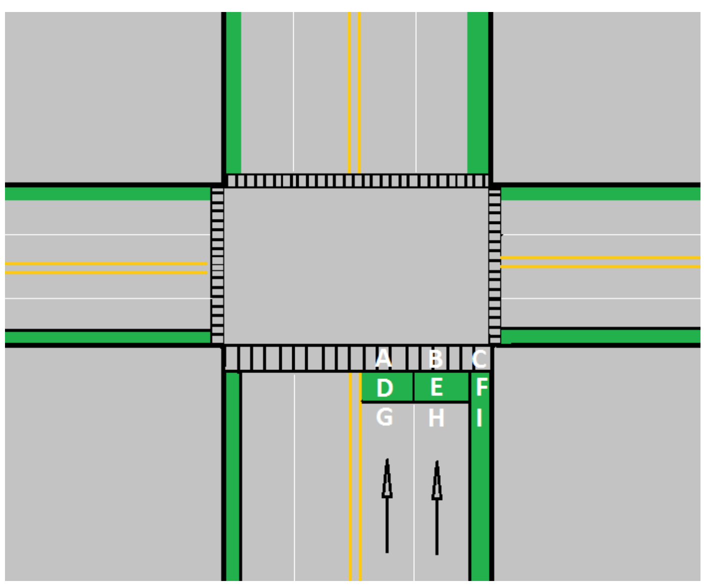


Figure 12- Bicyclist stopping position when making left turn on red signal

- Question 10: The main purpose of this question was to ask participants to rate four features about the four intersections of this study. These features are: safety, space, signal timing, and ease to navigate for bicyclist at that particular intersection.
- Question 11: In this question, the participant was shown a picture of a typical bicycle signal head and was asked to rate the bicyclist neediness for such signal at intersections.
- Question 12: The purpose of this question was to determine the participant's awareness of the purpose of the bike box. A total of five responses were listed including "I don't know." Multiple responses were allowed for this question.
- Question 13: In this question, the participants were asked about their level of agreement that bike box will promote bicycling and will enhance safety. Hint: this question is number 14 in the after-survey case.
- Question 14: This question asked participants if they have noticed the installed bike box in the after-installation case. This question was only in the after case survey.

See Appendix B and C for both versions (before and after case) of the conducted survey questioners. A before installation case survey was conducted in early June of 2017. A trained team of two students was the main personnel to conduct the survey. Both the author and another student volunteer wore a safety vest and stood on the sidewalks adjacent to the intersection. All bicyclist near or at the intersection were asked to take the survey at the site, if the subject stated that he/she did not have time to finish the hard copy of the survey, he/she was then given a postcard to take the survey on his/her own time. The postcard has some information about the project, link and a QR code for the online version of the survey. See Appendix A for the distributed postcards. Responses were mainly from the intersection of Lake Michigan Ave & Seward Ave since the city showed interest in implementing bike boxes in this intersection only. During this field visit, the team was able to collect 24 survey responses in that day. In addition to the field survey and distributed postcards, an email invitation with a brief project summary and survey links was sent to different bicyclist groups, clubs, and cycling shops in the city. Online responses were collected during the period from June through August of 2017 (6/06/2017 to 8/06/2107). A total of 21 online responses were recorded during the before period. The total number of valid responses for the before installation case is 45 responses. The city installed bike boxes in three approaches at the intersection of Lake Michigan and Seward Avenue on Sep 29th of 2017. No bike box was installed in the SB approach due to the close construction activities that were taking place at that time. Another survey for after installation case then took place. The team waited for two weeks to conduct the new survey to give bicyclist some time to get to notice the new intersection's treatment and to acclimate themselves with such a new facility and how to use it. Similarly, to the before installation case, the team went out to the field and conducted the survey. Due to the fact that the response rate from both field and online survey was very low compared to the before case, the team had to conduct the survey for three days in the after case. A total of 37 responses were collected from both the field visits, and online in the after case. Table 1 shows a summary of the survey dates and weather condition for the field survey in before and after case.

Table 1- Summary of field survey dates and weather condition

Before bike box installation		
Survey date	**Temperature**	**Condition**
June 6th	65 °F	Sunny, clear all day
After bike box installation		
Survey date	**Temperature**	**Condition**
October 13th	62 °F	Cloudy all day
October 19th	56 °F	Sunny, clear all day
October 26th	41 °F	Dry, clear all day

Table 2 summarizes the number of survey responses from both the field and online surveys for before and after cases.

Table 2- Summary of the obtained number of survey responses

	Field responses	Online responses	Total responses
Before bike box	24	21	45
After bike box	19	18	37

To test for statistical significance among the result, Chi-Squared test was used to determine if the changes among the results were significant or due to a chance only for the following pair of results: (1) before the installation of the bike box, and (2) after the installation of the bike box. The general formula for the Chi-Square test is shown below:

$$X^2 = \sum_{i=1}^{n} \frac{(o_i - e_i)^2}{e_i}$$

Where:

- O_i= Number of the actual observations
- E_i= Number of expected observations

Assuming:

- Independence of events
- No cell of 2*2 matrix may have an expected value of less than 5 in the contingency schedule
- Sum of the expected frequency of all cells must equal the sum of the observed frequency for all cells
- The sum of all observed frequencies minus the sum of all expected frequencies equal 0

In case of the sample size was not big enough to use Chi-Squared Tests, a Fisher Exact Test was used instead with the following assumption:

- Total number of cells in a 2*2 matrix is less than 20, or more than 20, but expected cell count is 5 or greater is less than 80 % of the cells

The P value was calculated using Excel software and then was compared against a value of 0.05 for 95% significant level. For example, a p-value of less than 0.05 means that the difference in the distributions could be due to chances less than 5 % of the time.

3.2 VISSIM SIMULATION

3.2.1 Simulation Flowchart

VISSIM Microscopic simulation was chosen for this project because it is characterized by its high level of details flexibility and accuracy with modeling bicyclist and pedestrian. In order to assess the impact of the bike box, protected intersection, and bicycle signal treatments on intersection operation and safety, a comparison between the intersection under its current condition, and the intersection with the proposed improvements is needed. In this study, VISSIM 9.08 simulation software was used to build a virtual environment for the intersection of Lake Michigan and Seward Avenue. Building such an environment was utilized as a platform to test various scenarios as shown below:

- **Base Model:** represent the intersection under its current condition (without improvements).

- **Model 1:** represents the intersection after adding 5 seconds of leading bicycle and pedestrian interval.
- **Model 2:** represent the intersection after adding the bike box to the base model, and there are three scenarios of this model:
  - **Scenario 1:** represent the intersection after adding the bike boxes only to all approaches (without bicycle signal treatments).
  - **Scenario 2:** represent the intersection after adding bike boxes and 5 seconds of leading bicycle and pedestrian interval**.**
  - **Scenario 3:** represent the intersection after adding bike boxes and 11 seconds of exclusive bicycle phase.
- **Model 3:** Represent a protected intersection design.

Hint: see section 3.2.4 below for detailed information about the modifications in each model. It is important to note that RTOR is allowed in the base model only, while it is prohibited in all of the other three models. In total there are six scenarios that will be evaluated.

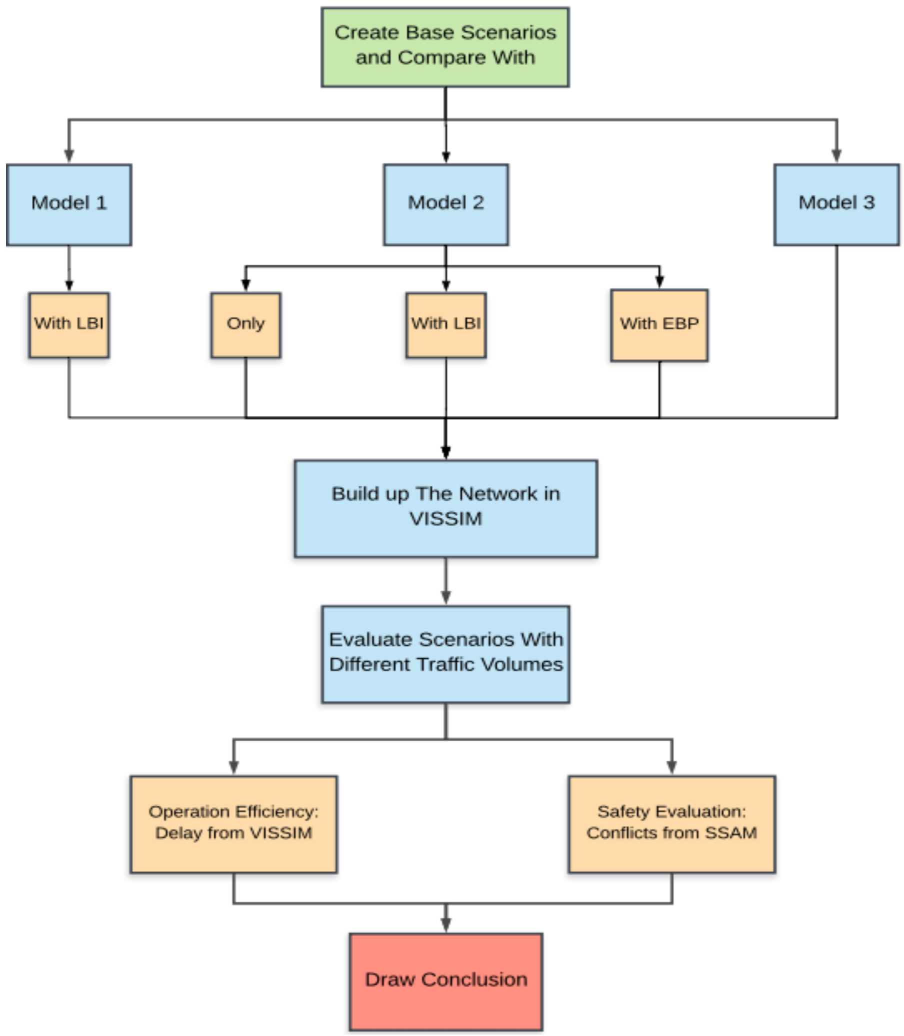


Figure 13- Simulation flow chart

3.2.2 Model Development in VISSIM

The first step in building the VISSIM model was to obtain an aerial photo of the site and draw the intersection geometry. This was done by specifying the number of lanes, width, and length of lanes for each approach; creating links, connecting them through connectors, and creating the bike lane and connecting them with the bike boxes when applicable. Secondly, traffic volume was assigned for each approach. Traffic flow parameters such as traffic volume, turning volume, and vehicle composition per approach were gathered from the processed video data in the laboratory. Furthermore, bicyclist and pedestrian volumes were assigned for each approach of the intersection. Thirdly, traffic signals then were created and coded from Synchro and VISSIM model according to the obtained traffic volume. Finally, conflict areas were identified and modified to properly reflect traffic rules. Additionally, conflicts and reduced speed areas were added to the network to simulate different road movements more properly. For example, right turning vehicles speed was set at 9 mph, and left turn vehicles was set at 12 mph. VISSIM requires the user to input traffic volume for all kind of users to simulate the different proposed treatments. Traffic volumes and vehicle turning ratios were obtained from the collected video data at the intersection in three days. The simulated study hour is from 4:00 pm- 5:00 pm, and the used traffic volume is the average of the collected three days volume during the same study hour. By using the obtained motorized traffic volume from the video data as a base, traffic volume was increased and decreased at 20% increment up to 20% increase in the base volume, in which the simulation models began encountering error beyond that volume indicating that the model cannot handle more than that volume level. For instance, 1.2 indicates that the simulated traffic volume is 20 more percent above the base traffic condition volume. Table 3 below shows the used traffic volume per approach.

Table 3- Motorized traffic hourly volume per approach

Motorized traffic volume (Veh/hr.)			
Approach	0.8	1	1.2
NB	235	294	353
SB	204	255	306
EB	154	193	232
WB	333	416	499
Total entering volume	926	1158	1390

Bicyclist volumes during the study hour at the intersection were very low (15 bikes/hour in all approaches). This small number of bicyclist volume caused an issue in the model since more bike volume input is needed to effectively test the proposed treatments. To solve this issue, a bike volume of 30 bikes/ hr. in the EB and WB, and 16 bikes/ hr. in the NB and SB were adopted as a base volume for later analysis. It was further decided to adopt the average bicycle turning ratio obtained from the video data: 13% turning right, 65% moving through, and 22 % turning left (16 % followed one stage left turn, and 6% followed two stage-left turn). Right turning bicyclist turn from their bike lane to another bike lane. Left turn bicyclist patterns were obtained from the collected survey data, where bicyclist doing one stage would merge across traffic to a left turn lane to complete their movement into the destination bike lane. While the two-stage left turn bicyclist were mimicked by moving their portion to the through moving bicyclist of the crossed street. Similarly, to changing the motorized traffic volumes, bicyclist volume was changed as well;

bicyclist volume was increased by using a multiplier factor to ensure the use of wider range of bicyclist volume. The used bicyclist volumes are shown in table 4 below. Also, a pedestrian volume of 25 ped/hr. per link per moving direction was added to the model.

Table 4- Bicycle hourly volume per approach

Bicycle hourly volume (bike/hr.)					
Approaches	0.5	1	2	3	4
NB	8	16	32	48	64
SB	8	16	32	48	64
EB	15	30	60	90	120
WB	15	30	60	90	120
Total entering volume	46	92	184	276	368

3.2.3 Model Calibration and Validation

Simulation models cannot produce a reasonable estimate of field conditions unless calibrated. To make the model look real, model calibration and validation should be conducted. Model calibration can be defined as the process of which the individual components of the simulation model are adjusted to accurately represent field condition. The universal measure GEH was used to compare the observed traffic volume in the field with that from the simulation output. This empirical formula was established in 1970 and is commonly used among traffic engineers to compare two sets of traffic volumes. The formula is given by:

$$GEH = \sqrt{\frac{2(m-c)^2}{m+c}}$$

Where:
m: is the output traffic volume from the simulation model (vph)
c: is the input traffic volume (vph)
A GEH value of 5 or less is considered an acceptable and satisfactory value in the engineering community. The GEH analysis revealed a GEH < 5 for all vehicles in the network, meaning that the simulated intersection was considered to have an acceptable fit. Another critical calibration

criterion is through changing the number of simulation runs. VISSIM allows the user to define the number of simulations runs to get more meaningful and stable results. The following equation was used to determine the number of simulation runs needed:

$$N = (2 * t_{0.025,N-1} * \frac{S}{R})^2$$

$$N = (2 * 2.05 * \frac{0.82}{0.95})^2 = 12.52\ runs \text{ (15 runs were used)}$$

Where:

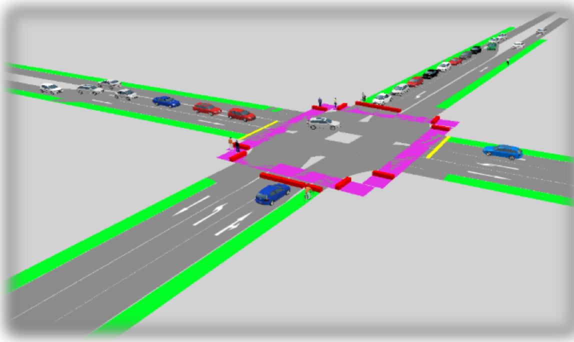
N: number of required simulations runs

$t_{0.025,N-1}$: Student's t-statistical test for two-sided error of 2.5 percent each

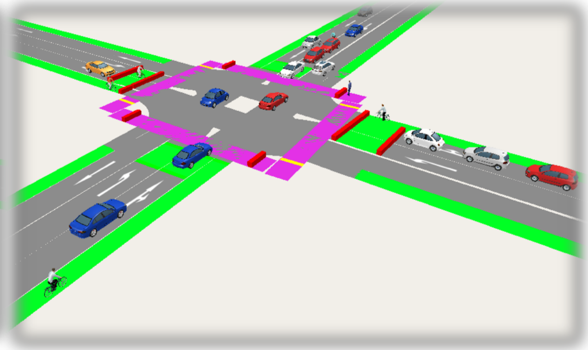
S: standard deviation about the mean for delay

R: confidence interval for the true mean

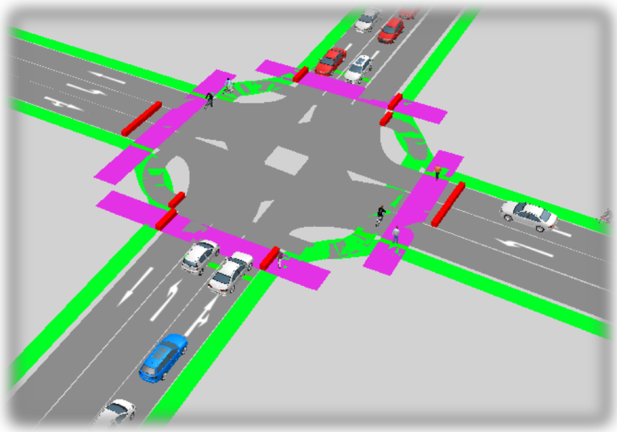
To obtain stabilized and reduced error, the seed number was also increased by one for each run to ensure maximum randomness for each scenario. The duration of each run was set to 3,600 sec. In order to better reflect the true nature of traffic behavior of this model, Wiedemann 74 car following model was used because it was recommended for urban traffic and merging areas by (PTV VISSIM 9- user manual). After that, a visual inspection check of the running model was done to make sure that the animation of the model represents the real-world condition; a model cannot be claimed to be calibrated if the animation is not realistic. Several unrealistic simulated crashes were detected and fixed by correcting overlaps between some of the links and connectors in the network. The calibrated model was then validated with a new set of collected traffic volume data. Finally, the VISSIM simulation model is calibrated and validated. The intersection of Lake Michigan and Seward Avenue under different treatments condition is shown in figure 14 below. After that, each volume combination was run a total of 15 times for 3,600 sec (1 hour) for each model with different random seeding number. In total, the VISSIM model was run for = 3*5*6*15= 1350 times.



(a)- Base Model + Model 1



(b)- Model 2 with bike box



(c)- Model 3 protected intersection

Figure 14- VISSIM simulation model for (a) base model and model 1, and (b) for model 2, and (c) for model 3

3.2.4 Modifications for Each Model

Base model

It is essential to set up the baseline model in which all other models would be compared. The base model reflects the intersection without any treatments. In order to assure a valid and equal comparison, this model was copied, and all treatments were later implemented in that copy. The following figure shows the current phasing and movement diagram for the intersection of Lake Michigan and Seward Avenue.

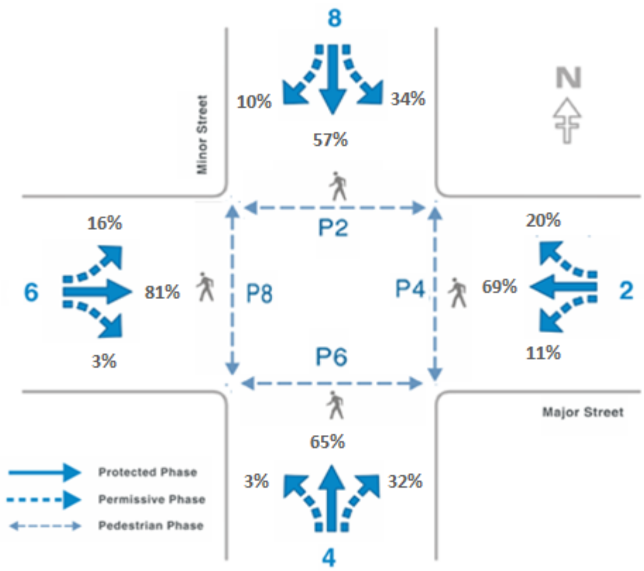


Figure 15- Phase and movements diagram for Lake Michigan and Seward Ave

One notable difference between the base model and all other models is that Right Turn on Red is allowed in the base model. In the real life, this would be done by installing signage like "No Turn on Red" or a dynamic NRTOR sign at the intersection. In the simulation, however, this can be done by adding a secondary set of signal heads. These new set of signal heads would mimic the dynamic sign. These signs named RTOR stop sign would only work if the associated signal heads are on red and the first vehicle in queue want to make a right turn, and there are no conflicting movements from other sides of the street. This setup in simulation is illustrated in figure 16 below.

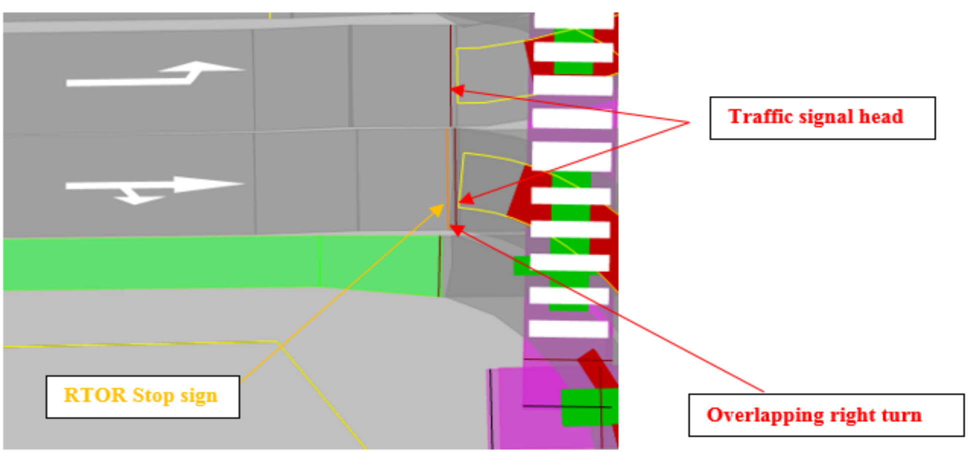


Figure 16- RTOR signal head set up in VISSIM

Model 1 (LBI)

Model 1 differ from the base model by the addition of the 5 seconds of leading bicycle interval and prohibiting the RTOR in all approaches. Installing LBI is usually combined with a leading pedestrian interval (LPI), so it was decided to provide a 5 seconds leading bicycle and pedestrian interval at the same time. It is important to note that only bicyclist that going through and right would benefit from this leading interval. Bicyclist making a left turn must wait to proceed with the corresponding through and left turn movements. Operational changes have been done to the bicyclist's and pedestrian's signal heads to give them ahead start before the corresponding motor vehicle movements start. Providing bicyclist and pedestrian by this leading interval will allow them to clear the intersection or at least to place them in a more visible position to moving vehicles. The LBI system will operate as followed; every cycle the bicyclist were shown a green signal indication for 5 seconds before the other corresponding vehicle movements were. All lanes that include bike lane, left turn lane, and shared through and right will later end at the same time by using the same amber and all red clearance time.

Model 2 (Bike box)

Scenario 1 (Bike Box only)

Scenario 1 of model 2 differs from the base model by the addition of the bike box in front of the traffic lanes, and by prohibition of right turn on red on all approaches. In real life, the same signal heads would work for both bicyclist and motor vehicle traffic. However, in simulation, it requires a new set of signal heads at the front and back of the bike box to control bicyclist movements, and to place the motorized traffic signal head behind the bicycle box. Introducing the bike box would give a physical separation of approximately 15 ft. between bicycles and vehicles, and a natural head start for bicyclist waiting in the box area.

Scenario 2 (Bike box + LBI)

Scenario 2 of model 2 differs from the base model by having bike boxes and the addition of the 5 seconds of leading bicycle interval and prohibiting the RTOR in all approaches. Installing LBI is usually combined with a leading pedestrian interval (LPI), so it was decided to provide a 5 seconds leading bicycle and pedestrian interval at the same time. Unlike model 1, all bicyclist turning movements would benefits from the leading interval in this scenario including left turn bicyclist due to the existence of the bike box. Operational changes have been done to the bicyclist's and pedestrian's signal heads to give them ahead start before the corresponding motor vehicle movements start. Providing bicyclist and pedestrian by this leading interval will allow them to clear the intersection or at least to place them in a more visible position to moving vehicles. The LBI system will operate as followed; every cycle the bicyclist were shown a green signal indication for 5 seconds before the other corresponding vehicle movements were. All lanes that includes bike lane, left turn lane, and shared through and right will later end at the same time by using the same amber and all red clearance time.

Scenario 3 (EBP)

Scenario 3 of model 2 replaces the leading interval of scenario 2 with exclusive bicycle phase where bicyclist are free to maneuver the intersection without worrying about conflicting with any vehicle traffic movements. One faced challenge was determining the required signal timing for such phase. The AASHTO guide was used to determine the minimum green time for the bike signal. AASHTO provides formula to estimate minimum green time for bicycle from a standing position as follows:

$$BMG + Y + R = (PRT + \frac{V}{2a}) + \frac{(W + L)}{V}$$

Where:

BMG = bicycle minimum green interval (s),

PRT = perception and reaction time = 1 s,

W = intersection width (ft.),

L = typical bicycle length = 6 ft.

a = bicycle acceleration = 1.5 ft. /s2, and

V = bicycle crossing speed = 14.7 ft. /s or 10 mph.

$$BMG + Y + R \ = (6) + \frac{(55 + 6)}{14.7} \simeq 10.04\, sec$$

Additionally, CA MUTCD limit this time by the following equation:

$$Gmin + Y + R > (6) + \frac{(W + 6)}{14.7} \simeq 10.14\, sec$$

So, it was decided to go with a split of 11 seconds for the bicyclist phase. Another challenge encountered was determining the clearance interval for bicyclist. NACTO require that an adequate clearance interval shall be provided for bicyclist to ensure that bicyclist entering the intersection during the green phase have enough time to safely clear the intersection before conflicting movement receive a green indication. Also, the interim approval requires a minimum of 3 seconds of yellow change interval for bicyclist. The following equation was provided to calculate the total clearance time for cyclist:

$$C_i = 3 + \frac{W}{V}$$

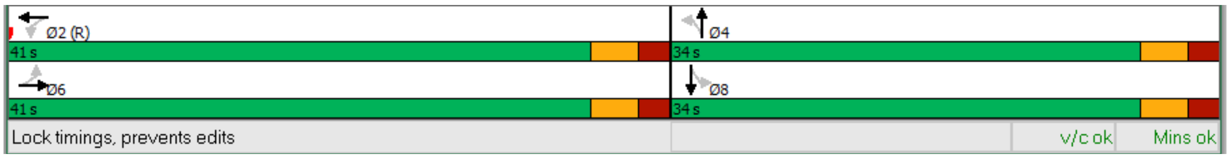
$$C_i = 3 + \frac{55}{14.7} \simeq 7\ sec$$

Finally, the following bicyclist phase was added into scenario 3 of model 2 in VISSIM: 4 sec of green time, 3 sec of yellow time, and 4 sec of red clearance time. The EBP system will operate as followed: every cycle the bicyclist will have unrestricted access to the intersection during the EBP interval including left turn bicyclist. After that, signal heads that controls through and right turn bicycle movements will terminate by using the above mentioned clearance interval. Bicycles making a left turn will still have access to the intersection with the corresponding traffic movements.

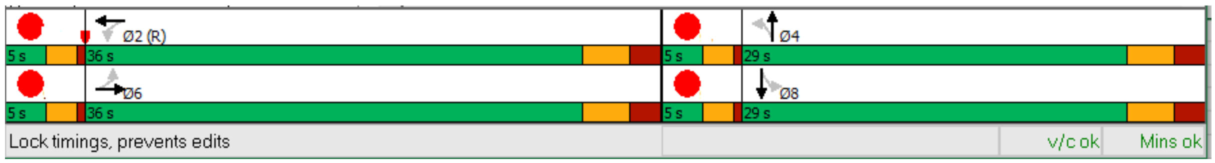
Model 3 (Protected intersection)

Model 3 differ from the base model by changing the conventional intersection design to a protected intersection design. This includes adding the major elements of the protected intersection to the base model. Signal heads that controls bicyclist movements were moved farther ahead of the intersection. By doing so, bicyclist will have an effective head start and a shorter crossing distance. The signal will operate in the same manner as of the base model except of no right turn on red is allowed here. All bicyclist making a left turn are assumed to make a two-stage left turn in this model.

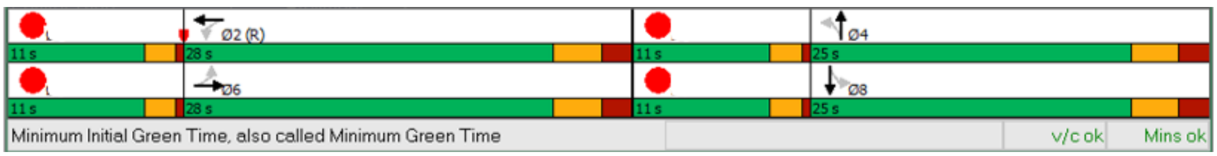
The software Synchro was used to perform traffic signal optimization and characteristics (e.g. phasing splits and cycle length). The optimized traffic signals were constructed in Synchro for all the different traffic volume combinations for the selected intersection before and after implementing the selected treatments. One challenge that encountered was the development of the bicycle signal treatments scheme in the software Synchro. So, in order to represent the leading bicycle and pedestrian interval in Synchro, a 5 sec of "Hold" interval was placed per movement direction before the start of the corresponding through movement. Similarly, a hold interval of 11 seconds (green=4s, yellow= 4s, and all red= 4s) was used to represent the exclusive bicycle phase. Also, the same cycle length was used in all models of the same traffic volume level to establish a fair comparison among models, thereby eliminating the effect of different cycle length from further complicating the analysis. Figure 17 below shows an example of the split and phasing diagrams used at traffic volume level of 1.0.



(a) Signal timing for all models without bicycle signal treatments



(b) Signal timing for models with leading bicycle signal treatment



(c) Signal timing for model with EBP signal treatment

Figure 17- Synchro splits for all models at 1.0 traffic volume level

3.2.5 Conflicts Identification in SSAM

Since this study is heavily focusing on the impact of the bike box, protected intersection, and the bicycle signal treatments on non-motorized traffic safety, safety analysis of different road users is very crucial at this point. Given the limitations of the typical safety assessment techniques discussed in chapter two earlier, the need for a better alternative raised recently. This study is using SSAM software as it is currently considered to be the only possible way to use microscopic traffic simulation model for safety assessment of a traffic facility. Therefore, this study incorporated SSAM with VISSIM to measure the effectiveness of the studied treatments in improving the safety of non-motorized users. SSAM 3.0 is used in this study. The output vehicle trajectory files from VISSIM were used as input in SSAM to automate conflict analysis for each simulation model with all volume combinations. The two threshold values that can be used to identify a conflict in SSAM are maximum TTC, maximum PET. Since the simulated intersection is considered low speed (25-30 mph) urban signalized intersection and according to (Souleyrette., 2012), the recommended threshold value of 1.5 seconds was used for TTC. Also, conflicts with TTC values larger than 1.5 seconds are not considered in the safety community sever enough events to be recorded in a traditional field conflict study. For PET threshold, a default value of 5.0 second was used. An example of SSAM window with the uploaded trj. Files and the defined TTC, and PTE threshold values is shown in figure 18 below.

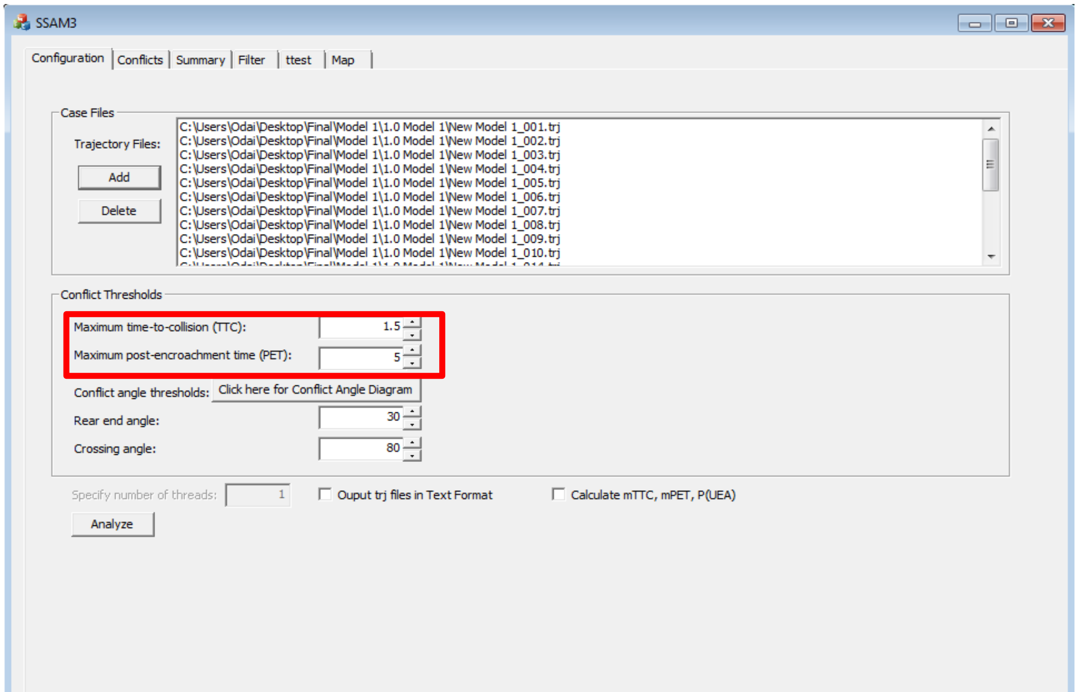


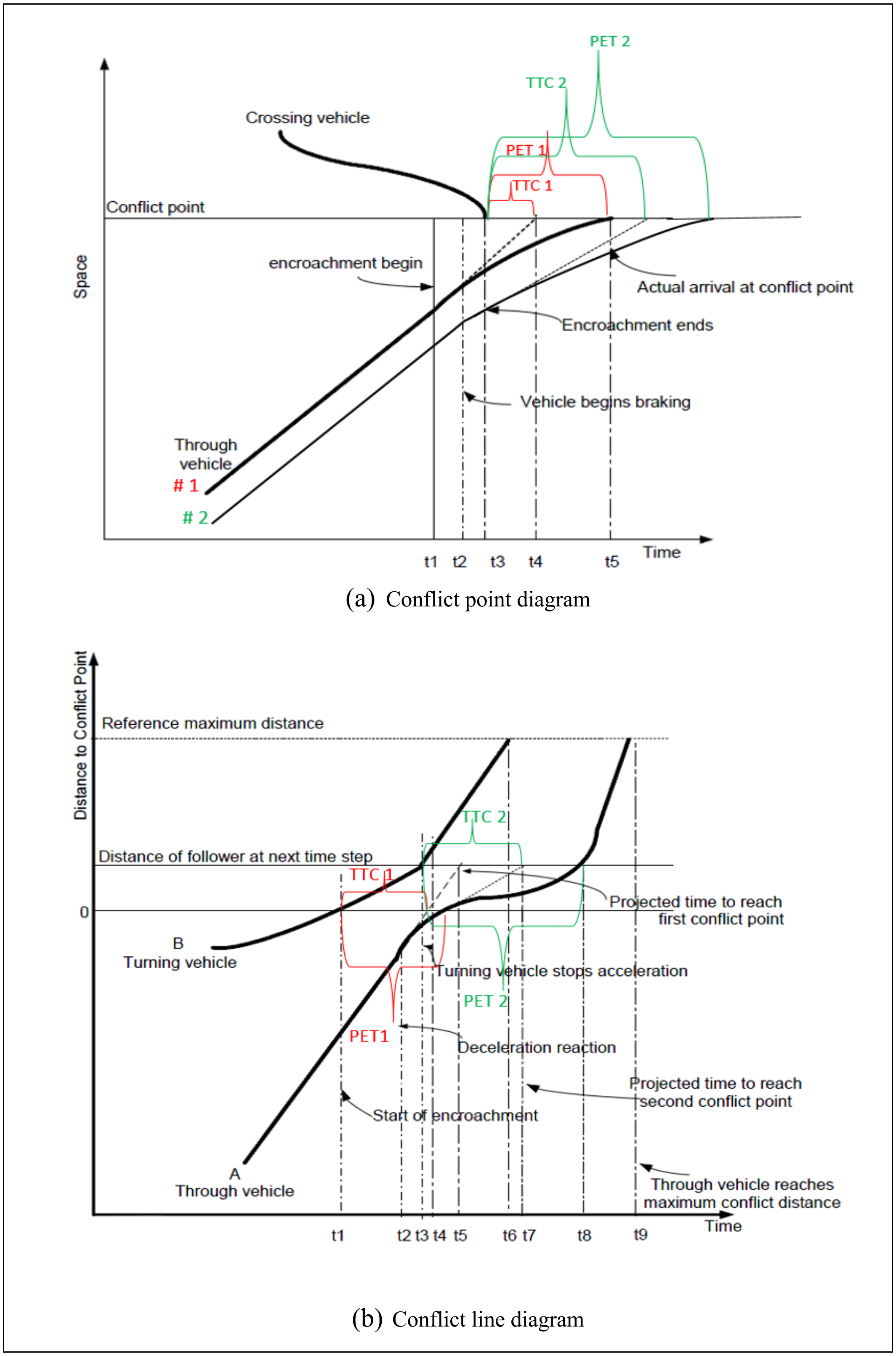
Figure 18- SSAM configuration window with selected TTC and PET threshold

SSAM uses the trajectory of vehicles in the network to identify a conflict. Any conflict can be classified as either conflict point or a conflict line. A conflict point represents a fix point in the space where a crossing vehicle interrupts the progress of another vehicle. While a conflict line represents an interaction of two vehicles in the same lane for a period of time. A typical conflict point, and a conflict line diagrams are depicted in figure 19 below. As shown in part (a) of the figure, the bottom line represents the through vehicle, while the top line represents the crossing vehicle. This figure also shows that there are two through vehicles following each other and are projected to conflict with the crossing conflict at the conflict point. SSAM will identify a conflict with TTC and PET value for each through vehicle with the crossing vehicle. For example, TTC 1 and PET 1 represent the conflict value between thought vehicle #1 and crossing vehicle. It is also important to note that, in a conflict line diagram and unlike the conflict point diagram, there could be more than one conflict point. SSAM will record the minimum TTC value observed over the entire course of event. For instance, SSAM will record the first conflict with TTC1 and PET 1 in part (b) of figure 19 below. The result from SSAM was then extracted as csv file format. As discussed earlier in chapter two, there are some limitations of SSAM, and there are three kind of conflicts that should be filtered out to remove any uncertainty. First, conflicts with TTC= 0 "virtual crashes "were filtered out because the logic in the simulation model does not accurately and completely represents the physical possibility of a particular maneuver. Secondly, all low-speed events that represents vehicles interacting in queue at close proximity (Max S ≤ 10 mph) were filtered out from the data analysis since such conflicts cannot be captured in a typical field conflict study. Lastly, pedestrian -pedestrian, and bicyclist- bicyclist conflicts were removed from the data analysis. The reason for leaving out such conflicts is because this study is focused on the interaction between motorized and non-motorized users. Furthermore, there are no data available for neither pedestrian-pedestrian conflicts, nor bicyclist-bicyclist conflict.

Since this study is focused on the interaction between motorized and non-motorized users, there are three types of conflicts that were identified for later analysis. These conflicts are: vehicle- bike conflict, vehicle-pedestrian conflict, and vehicle-vehicle conflict. To do that, the results in csv file were filtered based on the vehicle dimension. The length of a vehicle is usually defined to be between 3.75 and 12.5 meters, while it is 1.77 meters for bicycle, and less than 0.46 meter for pedestrians. For the purpose of this research, the total number of conflicts was then converted to a crash by using the following equation:

$$\frac{Crashes}{Year} = 0.119 * \frac{Conflicts}{Hour}^{1.419}$$

This equation was developed by (Gettman., 2008) in an effort to relate actual crash data in 83 real-world intersections with the corresponding surrogate measure (conflicts) that SSAM derives from simulation models. This effort used a non-linear regression model to construct a conflicts-based model to predict intersection crash frequency. The R-squared value for this model is 0.41.



(a) Conflict point diagram

(b) Conflict line diagram

Figure 19- Conflict diagrams in SSAM (a) conflict point, (b) conflict line

3.2.6 Economic Analysis

Understanding the operation costs and safety benefits of a countermeasure is very important aspect to consider before actual implementation takes place. This section intent to discuss the economic analysis of implementing the bike box, protected intersection, and the bicycle signal treatments at urban intersections. For this research, crash savings, delay costs, and infrastructure cost were considered in the benefit-cost analysis and are explored in detail below.

Crash cost

Crash frequency per severity level during the year of 2017 in the state of Michigan were obtained, and then the unit crash cost per severity level were obtained from old study conducted by (Kostyniuk., 2017). The unit crash cost for each severity was the sum of the following costs: medical care, lost wages due to the accident, loss in public service, property damage, and loss in the quality of life. The dollar amount specified in the report was from the year of 2015. So, in order to convert that cost to match the year of the analysis which was 2018, a real discount rate of 1.4 percent was used. The discount rates were obtained from the Executive Office of the President, Office Management and Budget. After that, the average weight cost per crash was found using the following equation:

$$Weighted\ average\ crash\ cost = \frac{\sum_i^n Cost\ per\ crash\ i * crashes\ i}{total\ number\ of\ crashes}$$

Finally, Savings that comes from crash reduction due to the implementation of the studied treatments were calculated by using the following equation:

$$Crash\ Savings = Estimated\ total\ number\ of\ crash\ savings * Average\ crash\ cost$$

Table 5 below shows the weighted average crash cost in 2018.

Table 5- Estimated crash cost for KABCO crashes in Michigan

Estimated crash cost per severity level			
Severity and frequency (2017)	Cost 2015	Projected cost 2018	total cost
K (883)	$ 8,875,391	$ (9,253,401)	$ (8,170,752,646.78)
A (5153)	$ 487,390	$ (508,148)	$ (2,618,488,203.91)
B (17166)	$ 134,943	$ (140,690)	$ (2,415,090,080.63)
C (39279)	$ 67,200	$ (70,062)	$ (2,751,969,147.22)
O (443884)	$ 4,347	$ (4,532)	$ (2,011,745,303.62)
Total (506365)			
Average cost (KABCO)	$ 38,555	$ (40,197)	
Total cost			$ (17,968,045,382.16)
Weighted average cash cost			**$ (35,484.37)**

Delay cost

The value of time for passenger vehicle was obtained from old study conducted by (Savolainen., 2014). The value of time in this report was in 2014, so by using consumers price indices (CPI) obtained from the U.S Department of Labor. Bureau of labors Statistics. The price index for 2014 was 236.736, while for 2018 was 244.607. Then the ratio of CPI in 2014 and 2018 was found and multiplied by the value of time-based on 2014 dollar to obtain the value of time for the year of 2018 which was the year of analysis for this study. This is shown in table 6 below:

Table 6- Estimated time cost per passenger vehicle

Parameter	Value
Time cost per passenger vehicle (2014)	18.28
Consumer price index in 2014	236.736
Consumer price index in 2018	244.607
Ratio of CPI 2018/2014	1.033248
Time cost per passenger vehicle (2018)	18.89

Finally, the costs that comes from increase in delay due to the implementation of the studied treatments were calculated by using the following equation by taking into account the different volume levels:

$$Delay\ costs = \Delta\ in\ Delay\ per\ hour * AADT * 365 * time\ cost$$

Infrastructure cost

There are associated costs that comes with the actual implementation of the studied treatments. An estimate for each studied treatment cost was obtained from (Lynn., 2013). The following table shows detailed information of the infrastructure cost that comes from switching from the base model to each of the three other models studied in this research.

Table 7- Estimated infrastructure cost per each model

Treatments cost by scenario					
Scenario		Item	Quantity	Price ($)	Total cost ($)
Switching from base to model 1		signal heads	4	5000	20000
		traffic signal modifications	1	9500	9500
		Total cost			29500
Switching from Base to model 2	Base to bike box only	Bike Boxes	4	5000	20000
		Total			20000
	Base to bike box +LBI	signal heads	4	5000	20000
		traffic signal modifications	1	9500	9500
		Bike boxes	4	5000	20000
		total			49500
	Base to bike box + EBP	signal heads	4	5000	20000
		traffic signal modifications	1	9500	9500
		bike boxes	4	5000	20000
		total			49500
Switching from base to model 3		signal heads	4	5000	20000
		traffic signal modifications	1	9500	9500
		curb extension	4	15600	62400
		refuge island	4	4000	16000
		total			107900

CHAPTER 4

DATA ANALYSIS AND RESULTS

Using the method described above, this section shows data analysis and results of the major findings from both the bicyclist survey and VISSIM simulation. This section contains the following two subsections:

- Bicyclist survey results
- VISSIM simulation results

4.1 BICYCLIST SURVEY

The main purpose of the survey was to measure bicyclist perception of safety of bike box and bike signal, and to assess knowledge, understanding, and other reactions to the new intersection treatments. This section will only show the major findings from the bicyclist survey. Detailed information related to other survey questions responses are shown in appendix F. While the survey is more focused on the bicyclist perception of safety of the bike box, the following demographic data about bicyclist using the intersection was found and presented in table 8 below. The majority of survey respondents were aged between 16- 49 years old. Also, survey respondents were predominantly male, and the majority classified themselves as an experienced bicyclist.

Table 8- Demographic information summary of the surveyed bicyclist

Bicyclist Age	**Before**	**After**	**Total**
<16	1	0	
16-24	9	15	
25-34	10	8	
35-49	10	7	
50-64	11	7	
65+	4	0	
Total	45	37	
Total Response to question			82
Bicyclist Gender	**Before**	**After**	
Male	38	31	
Female	7	6	
Prefer not to say	0	0	
Total	45	37	
Total Response to question			82
Level of Experience	**Before**	**After**	
Beginner	3	2	
Intermediate	13	16	
Experienced	29	19	
Total	45	37	
Total Response to question			82
Trip Purpose	**Before**	**After**	
Exercise & Health	27	11	
Recreation	20	7	
Commuting (Work/School)	18	28	
Errands/Shopping	14	3	
Other	4	1	
Total (More than one was picked)	83	50	
Total Response to question			133

Bicyclist left turn pattern (Question 7)

Both before and after surveys asked bicyclist to indicate the way they would make a left turn at an intersection by showing four different alternatives: pattern A, B, C, and D as shown earlier in figure 11 (a) and (b). Table 9 shows the bicyclist preferable way of making a left turn at a signalized intersection in both cases. Using the Chi-Square test/ Fisher test, a statistical analysis was done to determine if there were any significant difference in the way bicyclist would make a left turn after installing the bike box. Data analysis showed that there is no significant difference in pattern A, B, or C of making a left turn. However, there is a significant increase in pattern D with *p*-value of $0.0094 < 0.05$ at *95%* significant level. This increase of almost 19 % in pattern D indicates that bicyclist will use the bike box more as intended by approaching from the bike lane and then making a left turn by using the bike box area. When people asked why they would follow pattern D, 8 respondents (100 % in after case) mentioned it makes them feel safer. Furthermore, there is a slight decrease in the proportion of respondents that picked pattern A (- 4.2%) which is considered a less safe way of utilizing the bike box. In before case, there are ten respondents (22%) picked pattern C. Conversely, there is only 3 respondents (8 %) that correspond to a reduction of 14.1 % in the number of respondents that selected pattern C after installing the bike box. Pattern C is considered the most dangerous way of making a left turn among all other patterns; bicyclist is subject to four potential conflict points with auto-vehicles.

Table 9- Bicyclist left turn patterns from survey data

Pattern Type	Before	After	P value	95 % Significant	% diff
Pattern A	25 56%	19 51%	0.7	No	-4.2%
Pattern B	9 20%	7 19%	0.9	No	-1.1%
Pattern C	10 22%	3 8%	0.08	No	-14.1%
Pattern D	1 2%	8 22%	0.0094	Yes	+ 19.4%
Total	45	37			

<u>Bicyclist stopping position on red when making a left turn (Question 9)?</u>

Surveyed bicyclist were shown a picture of an intersection with bike box (without mentioning the word bike box) and asked to pick where they would stop if there were to make a left turn at a red signal in both surveys. As shown in figure 20, there are nine potential stopping positions for bicyclist. Point A, B, and C indicates that bicyclist is stopping at the crosswalk. Point D and E demonstrates that bicyclist is stopping right inside the bike box, while point G, H shows that the bicyclist is stopping on the road behind the bike box. Point F and I indicates that bicyclist is stopping in the bike lane area. A preliminary review of the data showed that the highest percentage of the respondents (51% in before case and 68% in after case) stated that they would stop inside the bike box ahead of the motor vehicle stop line (areas D and E in figure 20). Further data analysis revealed that there is a reduction in the percentage of respondents whom picked to stop in the crosswalk at point B and C, and on the bike lane at point F and I, or on the road behind the bike box at point G. Using Chi-Squared test/ Fisher test, it can be noted that there is a significant increase in the proportion of respondents who picked to stop ahead of motor vehicle waiting area (at point A and D in figure 20) with *p*-value of *0.015, 0.046 < 0.05* respectively at *95%* significant level. This addition of percentage of bicyclist whom chose to stop in front of the motor vehicle can result in a potential increase in the safety of bicyclist. However, the increase in point A proportion may increase the conflicts between bicyclist and pedestrian. Additionally, there is a significant decrease in the proportion of respondents who picked to stop on point F with *p*-value of $0.048 < 0.05$, and a 9 % reduction in the proportion of point F on the bike lane area. A summary of bicyclist stopping position inside the bike box is shown in table 10 below.

Table 10- Bicyclist stopping position in the bike box from survey data

Stopping Position	Before	After	P value	95 % Significant	% diff
A	2 3%	8 17%	0.015	Yes	14.4%
B	3 4%	0 0%	0.269	No	-4.5%
C	7 10%	3 7%	0.525	No	-3.9%
D	28 42%	28 61%	0.046	Yes	19.1%
E	6 9%	3 7%	1.000	No	-2.4%
F	11 16%	2 4%	0.048	Yes	-12.1%
G	4 6%	2 4%	1.000	No	-1.6%
H	0 0%	0 0%	N. A	No	0.0%
I	6 9%	0 0%	0.080	No	-9.0%
# of responses to question	67	46			
Total	45	37			

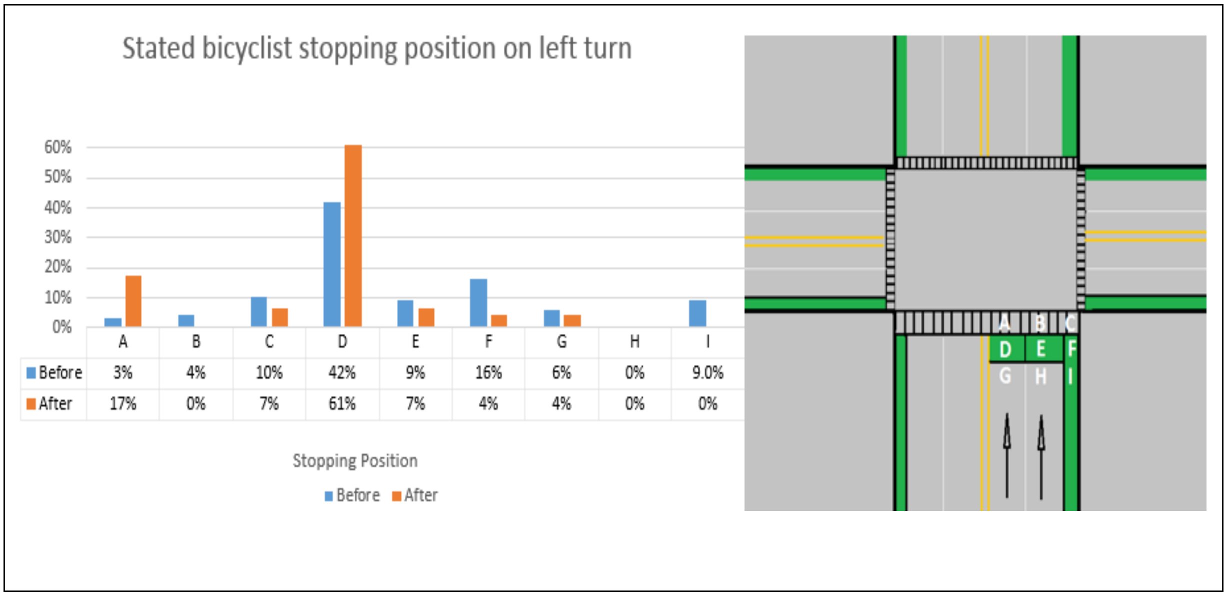


Figure 20: Bicyclist stated stopping position on a left turn inside the bike box

Further statistical analysis was done for a grouped set of points instead of each point individually as shown in table 11 below. This new grouped set of points would help in describing if there were any significant changes in the bicyclist stopping position as a group of points. For example, points A+B+C indicates the use of pedestrian crosswalk. Similarly, points A+D+G indicates the use of the most left side of the road. Statistical analysis revealed a significant increase of 31.9% (*p*-value of $0.002 < 0.05$ at *95%* significant level) exist in the proportion of cyclist who would stop in the most left side of the road when making a left turn (group A+D+G in figure 20). Importantly, almost 74% on average of the 31.9% would stop at point D inside the bike box, which is considered the most desirable point for a bicyclist to stop inside the bike box when making a left turn on a red signal. Moreover, there is a significant increase of 22% ((*p* value of $0.007 < 0.05$ at *95%* significant level) in the proportion of bicyclist who would stop in the bike box area in front of the auto vehicles (group D+E+F in figure 20).

Table 11- Bicyclist stopping position as a group in the bike box from survey data

Stopping Position	Before	After	P value	95 % Significant	% diff
A+B+C	12	11	0.436	No	6.0%
D+E+F	45	33	0.007	Yes	22.0%
G+H+I	10	2	0.073	No	-10.6%
A+D+G	34	38	0.001	Yes	31.9%
B+E+H	9	3	0.241	No	-6.9%
C+F+I	24	5	0.003	Yes	-25.0%
# of responses to question	67	46			
Total	45	37			

Also, there is a significant decrease in the proportion of cyclist who would stop in the bike lane area (group C+F+I in figure 20) of the street (*p* value of $0.003 < 0.05$ at *95%* significant level). In other words, the existence of the bike box encouraged bicyclist to stop in front of the auto vehicles, and helped bicyclist switching their stopping position from the most right-hand side to the most left-hand side of the street when making a left turn. All of that illustrates a potential increase in the bicyclist safety at signalized intersections with bike box.

Intersection features rating (question 10)?

Both before and after surveys asked cyclist to rate different intersection features for the four intersections along the corridor of this study. Each feature has the same weight of five points where five means the respondent rated the feature very good and one means very poor. ("I don't know" answers were excluded from the analysis). The total number of responses for each feature in each intersection was then multiplied with its associated weight and divided by the total feature responses to find each feature weight out of 5 in both surveys. An example of this procedure for the safety feature of Lake Michigan and Seward Ave shown is shown below:

Table 12- Summary of responses for the safety feature of Lake Michigan and Seward Ave intersection

Responses for the bicyclist safety feature for lake Michigan and Seward Avenue intersection		
Rating value	Before	After
Very Good (5)	2	5
Good (4)	22	19
Fair (3)	8	9
Poor (2)	3	2
Very Poor (1)	3	1
Total (Excluded IDK)	38	28

Bicyclist safety rating (**Before case**): $\frac{(2*5)+(22*4)+(8*3)+(3*2)+(3*3)}{39} = 3.44$

Bicyclist safety rating (**After case**): $\frac{(5*5)+(11*4)+(8*3)+(2*2)+(1*3)}{28} = 3.69$

By following the same procedure, all features ratings were compared in before and after installing the bike box at the intersection of Lake Michigan and Seward Avenue. Figure 21 compares the different feature ratings before and after installing the bike boxes at Lake Michigan and Seward intersection. Notably, all features rating for the intersection of Lake Michigan and Seward Avenue increased. The bike box in another words, can have a positive impact on intersection features like safety, space of bicyclist, signal timing, and ease to navigate. More specifically, there was a meaningful increase in the space and ease to navigate feature ratings for this intersection from 3.34 to 3.69, and from 3.2 to 3.86 respectively. Among the other three intersections that did not have bike box installed, there was a slight or no obvious change that can be found for their features ratings. In fact, there was a negative change in the feature ratings in some of the intersections that did not have a bike box installed. For instance, at the intersection of Fulton and Seward which is the closest intersection to Lake Michigan and Seward, all feature ratings in the after case was slightly lower than in before case. This negative change is believed to be because survey respondents compared this intersection features with that of Lake Michigan and Seward intersection with bike boxes.

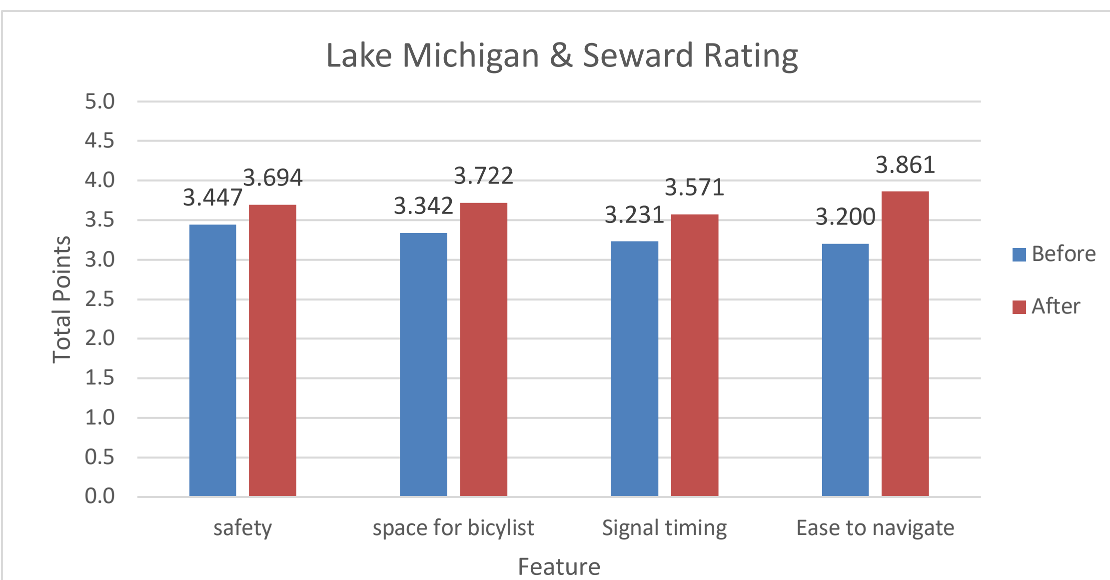


Figure 21- Features rating for Lake Michigan and Seward intersection

Bike box can promote bicycling and enhance safety (Question 13 and 14)?

To help measuring bicyclist perception of safety, all surveyed bicyclist were asked about their level of agreement that bike enhances safety and box promotes bicycling. Table 13 below compares respondent's level of agreement about these two features before and after installing the bike box. All positive and negative feedbacks were added simultaneously together, and then plotted in pie charts to get the total respondent's level of agreement of these features in before and after case. 49 % of the total respondents in the before case agreed that bike box can promote bicycling. This percentage increased to 65% in the after-case survey after installing bike boxes at Lake Michigan and Seward Avenue. A reduction of 11% in the proportion of respondents with negative feedback took a place in the after-case survey. Figure 22 below shows the proportion of positive and negative feedback that bike box promotes bicycling. Similarly, and as shown in figure 23, the vast majority of respondents (60 % in before case and 92% in after case) have a positive feedback that bike box can enhance the bicyclist's safety at intersection. Notably, the proportion of respondents with negative feedback about this feature dropped to 0% in the after-case survey.

Table 13- Bicyclist level of agreement that bike boxes can promote bicyclist and enhance safety

Bike box purpose	**Promote Bicycling**			**Enhance Safety**		
	Before	**After**	**% difference**	**Before**	**After**	**% difference**
Strongly Agree	8 18%	7 19%	1%	12 27%	9 24%	-2%
Agree	14 31%	17 46%	15%	15 33%	25 68%	34%
Neutral	8 18%	12 32%	15%	5 11%	2 5%	-6%
Disagree	5 11%	0 0%	-11%	4 9%	0 0%	-9%
Strongly Disagree	0 0%	0 0%	0%	0 0%	0 0%	0%
I don't know	10 22%	1 3%	-20%	9 20%	1 3%	-17%
Total	45	37		45	37	

in a different word, the bike box seems to have a positive impact on the bicyclist perception of safety and bike trip promotion. Meaning, the introduction of bike box will make bicyclist feel safer when cycling near or at intersections with a bike box, and bike box will encourage people to ride their bike more often in a way that can lead to more livable and sustainable communities.

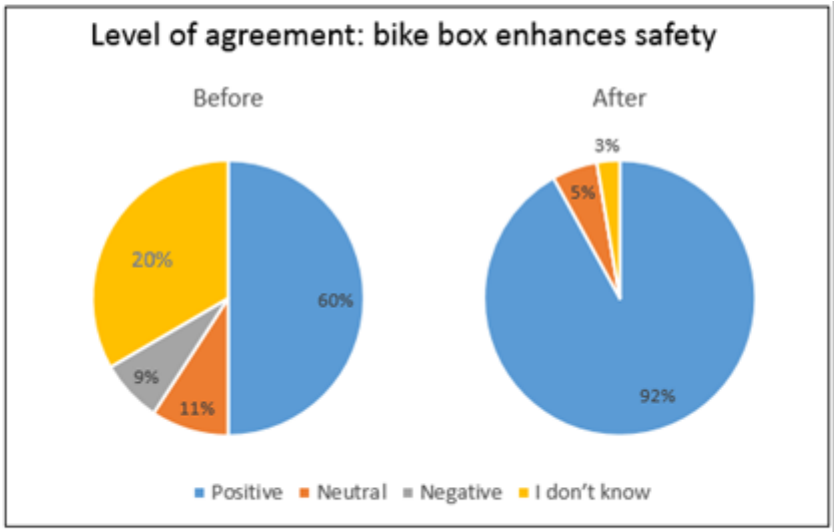


Figure 22- Before and after bicyclist level of agreement that bike box can enhance safety

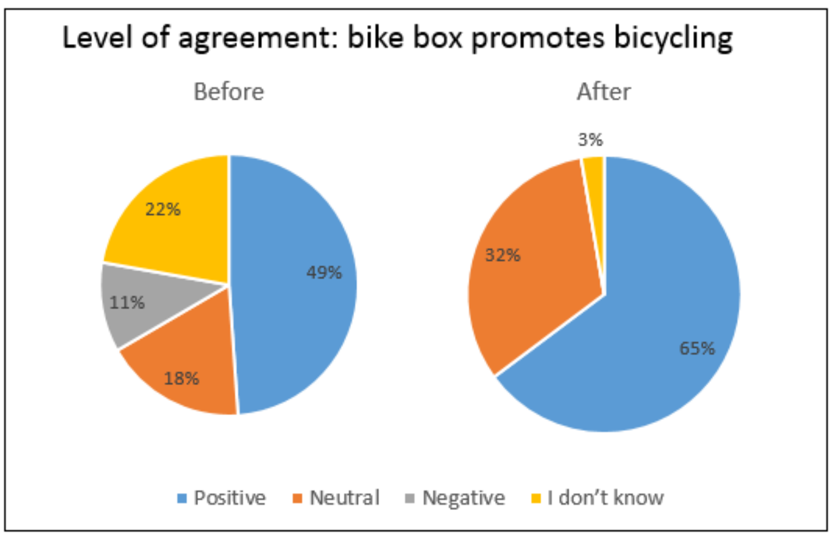


Figure 23- Before and after bicyclist level of agreement that bike box can promote bicycling

4.2 VISSIM SIMULATION

The primary purpose of the VISSIM simulation was to assess the impact of the studied treatments. The six simulation scenarios which are the base model, model 1, three variations of model 2, and model 3 were modeled in 15 runs in VISSIM. The base model was then compared to all other models to evaluate the operational and safety impact of each studied treatment. To do that, the average vehicle and bike delay were obtained from VISSIM node evaluation, and conflicts among users were obtained from SSAM. After that, economic analysis for each of the studied treatment was done by using the described methodology in chapter 3 of this paper to determine if actual implementation of these treatments will be beneficial or not. This section will show sample result of users delay at different traffic volume levels for demonstration purpose only and will exclusively focus on presenting vehicle-bike conflicts. Detailed information about users delay with different traffic volume levels, and conflicts among different intersection users are shown in Appendix G.

Base Vs. Model 1 (LBI)

Operation Performance

The first model examined adding 5 seconds of leading interval to all approaches of the intersection. Every cycle, bicyclist were shown a green light before auto vehicles were. Left turn vehicles including bicyclist, and vehicles in the shared through-right turn lanes were shown a red indication for the duration of the leading interval before being shown a green indication. Result of the operation analysis for vehicle and bicycle delay at 0.8 traffic volume level is shown in table 14 and 15 and depicted in figure 24 and 25 respectively. In terms of the average vehicle delay, there was a uniform increase in auto vehicle delay after adding the LBI treatment to the signal controller of this intersection. This increase in delay which is almost by the same amount of the leading interval (5 seconds) at this traffic volume level is expected and can be explained as followed: LBI prevents all auto vehicle movements for 5 seconds, so they have less green time to move through the intersection and that caused this increase in vehicle delay. Furthermore, prohibiting right turn on red in this model have an impact on this increase in delay.

Table 14- Vehicle delay results and comparison of base model and model 1 at 0.8 traffic volume level

Vehicle delay results at 0.80 traffic volume level					
Scenario	Bike volume level				
	46	92	184	276	368
Base	15.45	15.61	15.77	16	16.29
Model 1	20.84	20.95	21.32	21.81	22.19
% change					
from base to model 1	34.9%	34.3%	35.2%	36.3%	36.2%

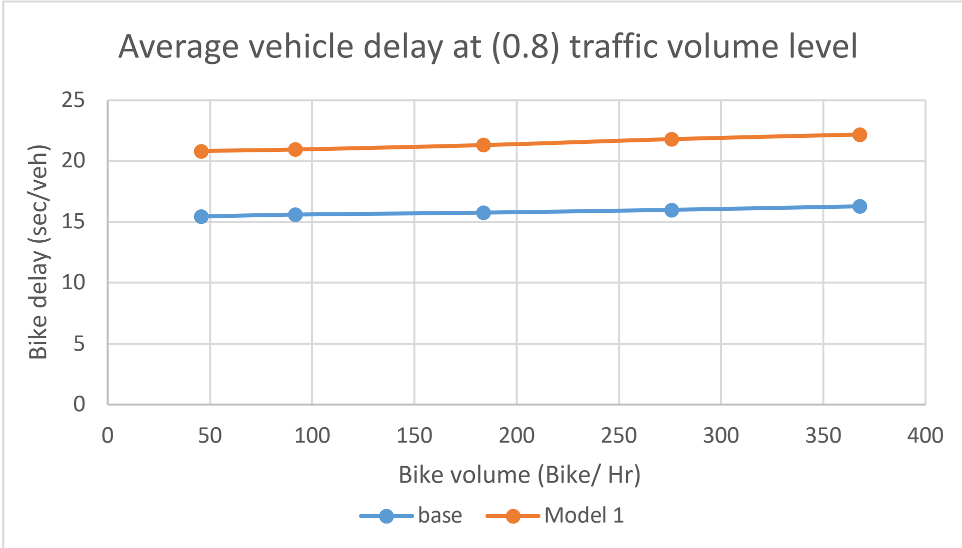


Figure 24- Average vehicle delay of the base model and model 1 at 0.8 traffic volume level

In regards of the average bicycle delay, there was a little overall change in bicyclist delay after implementing the LBI treatment. This little increase in bicyclist delay (< 1 second) at this traffic volume is believed to come from the increase in delay of left turn bicyclist since they are not benefiting from the leading interval in this model. Results of bicyclist delay are shown in table 15.

Table 15- Bicycle delay results and comparison of the base model and model 1at 0.8 traffic volume level

Bike delay results at 0.80 traffic volume level					
Scenario	Bike volume level				
	46	92	184	276	368
Base	12.49	12.99	13.27	13.45	13.09
Model 1	13.02	13.51	14.11	14.22	13.85
% change					
from base to model 1	4.2%	4.0%	6.3%	5.7%	5.8%

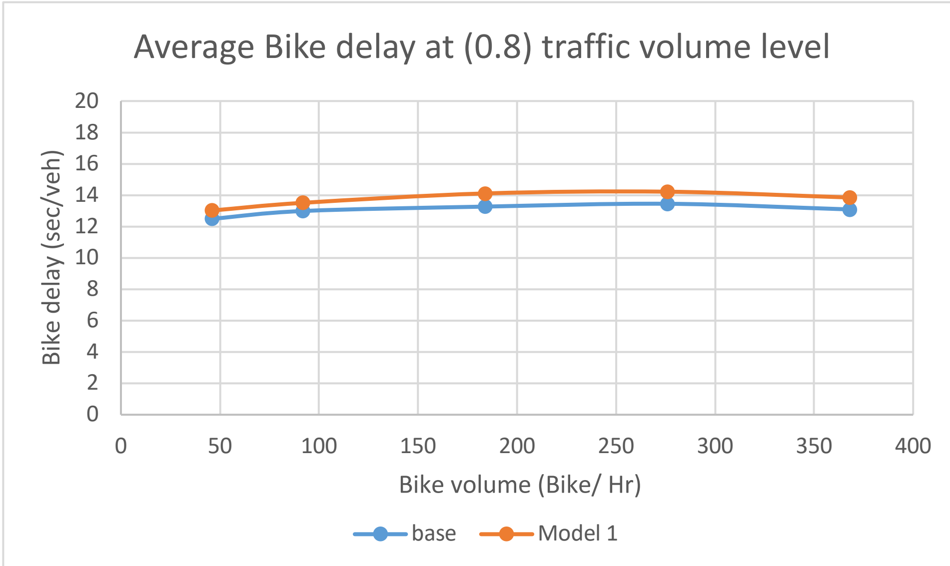
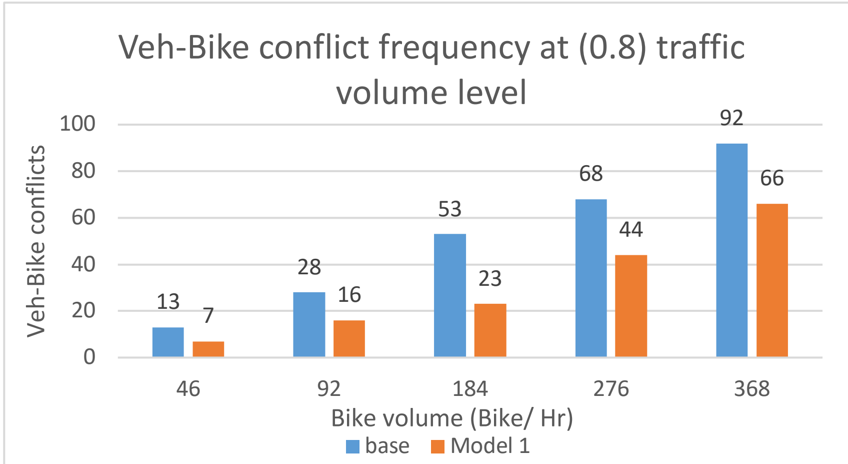


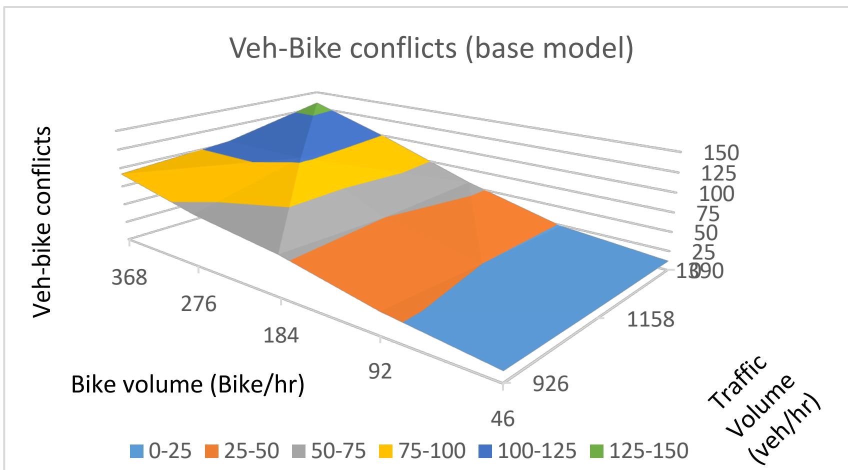
Figure 25- Average bicycle delay of the base model and model 1 at 0.8 traffic volume level

Safety Evaluation

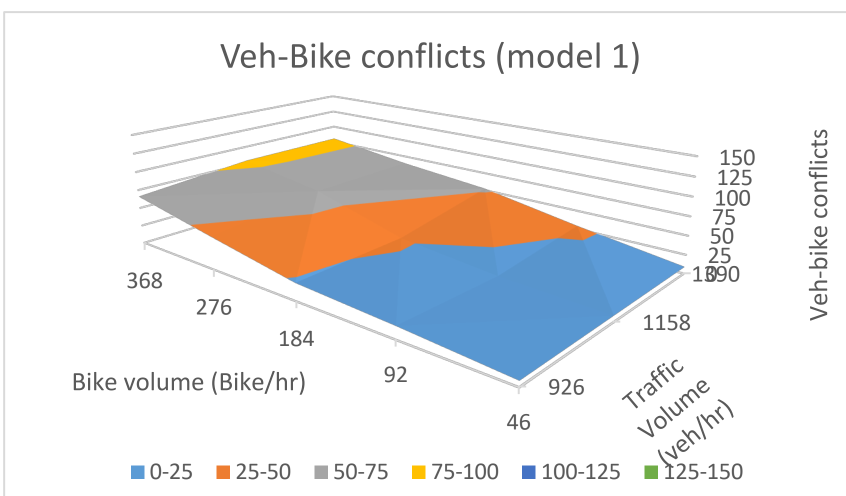
The base model and model 1 were run and then the number of conflicts among users were obtained and compared against each other. Result of safety analysis for this model is shown in figure 26 below. Part (a) of this figure compares the total number of vehicle-bike conflicts in the base model and model 1 at traffic volume level of 0.8 for demonstration purposes only. Clearly, it can be recognized that the base model results in a higher number of vehicle-bike conflicts and implementing the LBI treatment would result in a lower number of conflicts which is expected. For instance, at a volume of 276 bike/ hr., the number of conflicts dropped from 68 conflicts to 44 conflicts after adding the LBI treatment. This reduction in the vehicle-bike conflict is because LBI will give a head start for bicyclist to clear the conflict area before auto vehicles reach them. Part (b) and (c) of figure 26 shows a three-dimensional representation of the vehicle-bike conflicts in the base model and model 1 respectively. This representation will allow an intuitive comprehension of all traffic and bike volume combinations. We can see that the number of vehicle-bike conflict increases as auto traffic and bike volumes increases. It is noticeable that the higher number of vehicle-bike conflict frequency which are represented in the green and dark blue colors in part (b) were not shown after implementing the LBI treatment which is depicted in part (c) of figure 26. In another word, LBI implementation can lead to a safer environment for bicyclist as it can result in a reduction of vehicle-bike conflicts.



(a) Vehicle bike conflict comparison in the base and model 1



(b) 3D representation of vehicle-bike conflict in the base mode



(c) 3Drepresentation of vehicle-bike conflict in model 1

Figure 26- Vehicle bike conflicts in (a) base model Vs. model 1, (b) in base model, (c) in model 1

Economic Analysis

Now we have seen the operation and safety impact of adding LBI treatment to the selected intersection. However, understanding the operational cost and safety benefit is critical before considering actual implementation. By following the economic analysis methodology shown in chapter 3 earlier, a benefit-cost analysis was done for this model. A summary of the associated benefits (crash saved) and costs (delay cost, infrastructure cost) with different traffic and bike volumes are shown in table 16 below. The estimated number of crashes in the base model and model 1 was obtained by converting the total number of conflicts to crashes by using the equation shown in section 3.2.5 in chapter 3. The saved crashes were then found by finding the difference in number of crashes between these two models. The increased delay caused by implementing the LBI treatment found by finding the difference in vehicle delay. Saved crashes and delay increase were then converted to a monetary value for comparison purposes. Benefit-cost analysis shown in table 17 revealed (B/C <1) for all 15 traffic and bike volumes combinations. Indicating that the associated dis-benefits that come from delay increases outweigh all benefits that come from saved crashes of implementing the LBI treatment.

Table 16- Summary of all benefits and costs associated with base model and model 1

Summary of all benefits and cost associated with the base model and Model 1 (LBI)						
	traffic volume	Bike volume				
		46	92	184	276	368
Saved crashes (Crash)	926	1.23	1.26	2.19	0.73	1.23
	1158	1.56	1.06	1.39	1.96	1.06
	1390	2.55	2.58	0.51	2.52	0.53
Saved crashes benefits ($)	926	43811.97	44611.15	77887.24	26000.24	43811.97
	1158	55376.50	37575.49	49494.39	69524.66	37575.49
	1390	90447.42	91436.28	18201.25	89461.74	18819.25
Delay increase (Sec/veh)	926	5.39	5.35	5.55	5.81	5.90
	1158	6.87	7.15	7.36	8.32	9.12
	1390	8.79	9.14	10.30	11.36	12.65
delay disbenefits ($)	926	108739.64	107862.42	111967.54	117212.86	119028.55
	1158	173247.07	180308.08	185603.85	209813.04	229987.37
	1390	265998.56	276590.08	311693.42	343770.60	382807.93
Infrastructure cost		$29,500				

Table 17- Benefit/cost ratio associated with base model and model 1

B/C ratio for switching from the base model to model 1						
Bike Volume (Bike/hr)		46	92	184	276	368
Traffic volume (veh/hr)	926	0.317	0.325	0.551	0.177	0.295
	1158	0.273	0.179	0.230	0.291	0.145
	1390	0.306	0.299	0.053	0.240	0.046

Base Vs. Model 2 (Bike box)

Operation Performance

Model 2 tested the effect of adding bike boxes to all approaches of the selected intersection. This model consists of 3 different scenarios. The first scenario includes adding bike boxes only. No operational changes took place when adding the bike boxes except for prohibiting right turn on red. Second scenario includes the addition of 5 seconds of leading interval to the first scenario. Unlike model 1 shown earlier, left turn bicyclist in this case can procced during the leading interval due to the existence of the bike box. The third scenario includes the addition of 11 seconds of EBP to the first scenario. This would give bicyclist protected and unrestricted access to the intersection. Results of the operation analysis for vehicle and bicycle delay at 1.0 traffic volume level are shown in table 18 and 19 and depicted in figure 27 and 28 respectively. As far as auto vehicle delay is concerned, it can be noted that as we are implementing safer treatments in this model, vehicle delay increases as a result. Vehicle delay increased once we added the bike boxes as a result of prohibiting right turn on red. This delay would increase further once we add the LBI treatment since auto vehicles will have a shorter green time to move through the intersection. Implementing the EBP will only allow bicyclist to proceed during the phase, a substantial increase in auto vehicle delay would be expected and the results shown below seems to demonstrate this increase in auto vehicle delay.

Table 18- Vehicle delay results and comparison of base model and model 2 at 1.0 traffic volume level

Vehicle delay results at 1.0 traffic volume level					
Scenario	Bike volume level				
	46	92	184	276	368
Base	17.25	17.33	17.58	18.08	18.31
Bike box only	19	19.09	19.51	20.48	21.16
Bike box +LBI	24.56	24.57	25.06	25.95	26.92
Bike box + EBP	36.4	36.72	37.29	38.21	38.09
% change					
from base to bike box	10.1%	10.2%	11.0%	13.3%	15.6%
from base to bike box + LBI	42%	42%	43%	44%	47%
from base to bike box + EBP	111%	112%	112%	111%	108%

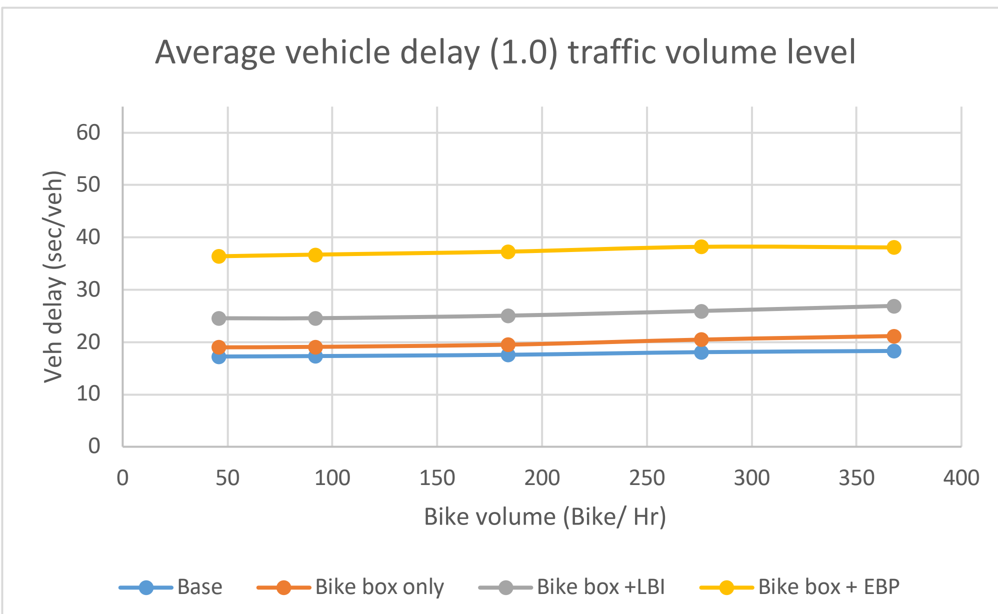


Figure 27- Average vehicle delay of the base model and model 2 at 1.0 traffic volume level

The average bicycles delay in this model saw slight to no change after adding either bike boxes or the leading interval. In fact, there was a slight decrease in bicyclist delay due to these treatments. Bicycle delay showed an excessive increase in delay after the addition of the EBP in this model. This result is expected since only bicyclist are allowed to move during this exclusive phase.

Table 19- Bicycle delay results and comparison of the base model and model 2 at 1.0 traffic volume level

Bicycle delay results at 1.0 traffic volume level					
Scenario	Bike volume level				
	46	92	184	276	368
Base	12.68	12.8	13.6	13.86	13.47
Bike box only	12.75	12.79	13.63	13.73	13.38
Bike box +LBI	12.47	12.74	13.44	13.8	13.54
Bike box + EBP	31.63	32.88	34.39	35.3	38.31
% change					
from base to bike box	1%	0%	0%	-1%	-1%
from base to bike box + LBI	-2%	0%	-1%	0%	1%
from base to bike box + EBP	149%	157%	153%	155%	184%

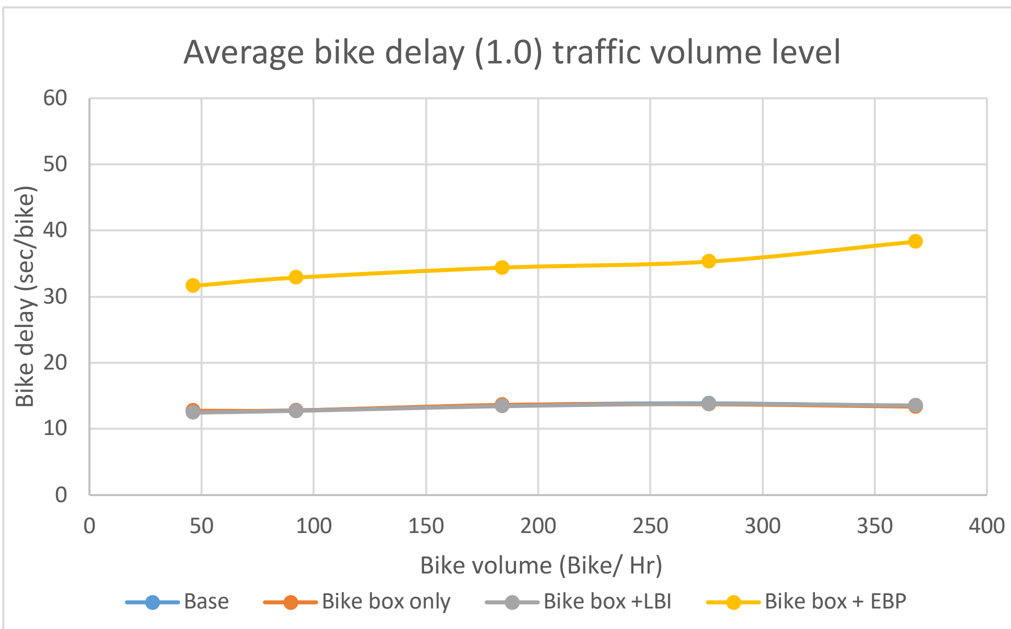
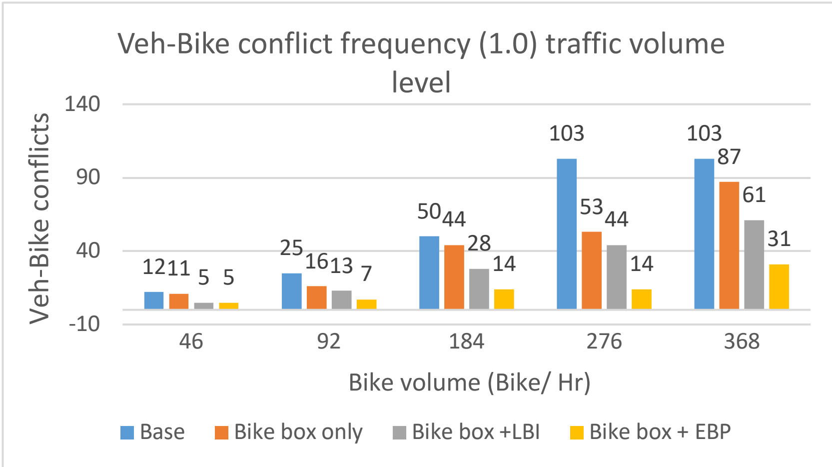


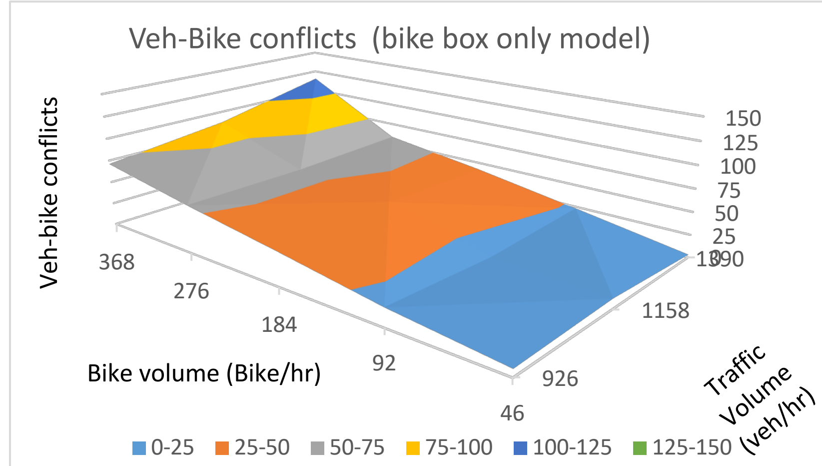
Figure 28- Average bicycle delay of the base model and model 2 at 1.0 traffic volume level

Safety Evaluation

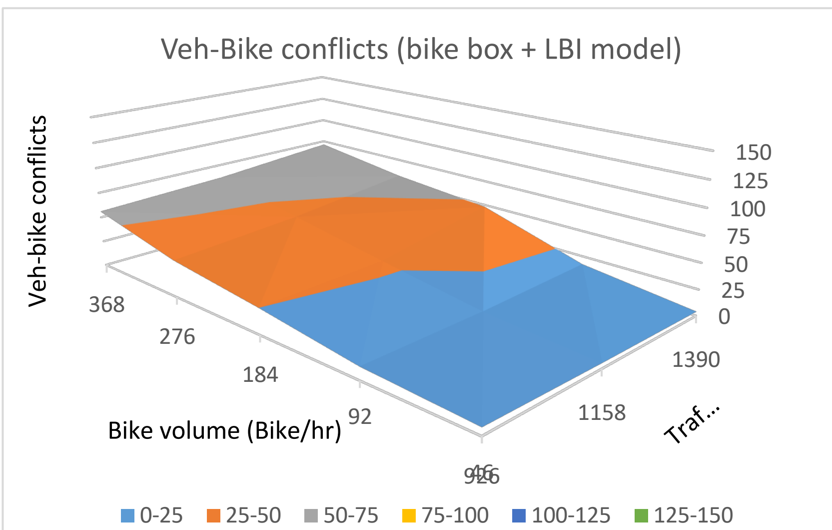
The number of vehicle-bike conflicts in all three scenarios of model 2 were obtained and compared against each other and against that of the base model. Result of safety analysis for this model is shown in figure 29 below. Part (a) of this figure compares the total number of vehicle-bike conflicts in the base model and all three scenarios of model 2 at traffic volume level of 1.0 for demonstration purposes only. Results demonstrate how the number of vehicle-bike conflicts would get reduced as we are implementing safer treatments. Implementing bike boxes only results in a lower number of conflicts than that of the base because bicyclist are benefiting from the physical separation of the bike box whether it is space or time. For example, the number of conflicts drop from 103 to 87 conflict after adding the bike box at bike volume of 368 bike/hr. Adding LBI to the bike box further reduced the conflicts to 61 since bicyclist have a head start to clear the conflict areas in the intersection. Adding EBP would result in the lowest number of vehicle-bike conflicts as expected, and the results seems to demonstrate that (31 conflicts only). This is because EBP will give bicyclist protected access to the intersection and will prevent all conflicts with auto vehicles during this period. A three-dimensional representation of the vehicle-bike conflicts of all three scenarios of model 2 can be seen in part (b), (c), and (d) of figure 29 below. These graphs demonstrates that the number of vehicle-bike conflicts will get reduced as we are implementing bicycle signal treatments with the bike box. Implementing bike boxes with EBP is classified as the safest treatment in terms of bicyclist safety in this model.



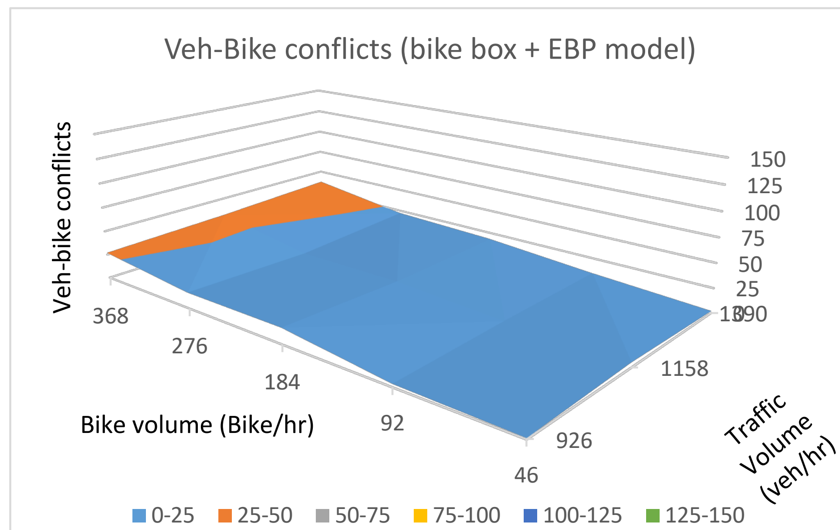
(a) vehicle-bike conflicts comparison in the base model and model 2



(b) 3D representation of vehicle-bike conflict in scenario 1 of model 2



(c) 3D representation of vehicle-bike conflict in scenario 2 of model 2



(d) 3D representation of vehicle-bike conflict in scenario 3 of model 2

Figure 29- Vehicle bike conflicts in (a) base model Vs. model 2, (b) in scenario 1, (c) in scenario 2, (d) in scenario 3

Economic Analysis

The three scenarios of model 2 were evaluated and the impact on intersection users delay and safety were shown earlier in this section. However, understanding the operational cost and safety benefit is critical before considering actual implementation. By following the economic analysis methodology demonstrated in chapter 3 earlier, a benefit-cost analysis was done for this model. A summary of the associated benefits (crash saved) and costs (delay cost, infrastructure cost) with different traffic and bike volumes for the base model and for the first scenario of model 2 is shown in table 20 below. The estimated number of crashes in these models were obtained by converting the total number of conflicts to crashes by using the equation shown in section 3.2.5 in chapter 3. The saved crashes were then found by finding the difference in number of crashes between these two models. The associated increase in delay of adding the bike box treatment found by finding the difference in vehicle delay in these models. Saved crashes and increase in delay were then converted to a monetary value for comparison purposes.

Table 20- Summary of all benefits and costs associated with base model and scenario 1 of model 2

Summary of all benefits and cost associated with the base model and scenario 1 of model 2						
	traffic volume	Bike volume				
		46	92	184	276	368
Saved crashes (Crash)	926	0.71	1.06	0.89	1.12	1.19
	1158	2.25	1.15	1.04	1.58	0.53
	1390	1.12	1.81	2.49	1.68	0.38
Saved crashes benefits ($)	926	25319.67	37575.49	31631.11	39880.97	42226.50
	1158	79783.25	40658.41	36816.07	56232.56	18819.25
	1390	39880.97	64108.29	88479.27	59695.23	13485.88
Delay increase (Sec/veh)	926	1.73	1.74	1.86	2.25	2.39
	1158	1.75	1.76	1.93	2.4	2.85
	1390	2.16	2.21	2.81	3.34	3.96
delay dis-benefits ($)	926	34901.59	35103.34	37524.26	45392.24	48216.65
	1158	44131.35	44383.53	48670.57	60522.99	71871.05
	1390	65364.83	66877.91	85034.81	101073.40	119835.53
Infrastructure cost		$20,000				

The benefit-cost ratio for all 15 traffic volume combinations is shown in table 21 below. It can be noted that some cells have B/C ratio of > 1 indicating that the bike box treatment is desired at that traffic and bike volumes. Other cells with B/C ratio of < 1 indicates that bike box treatment The benefit-cost ratio for all 15 traffic volume combinations is shown in table 21 below. It can be noted that only one cell have B/C ratio of > 1 indicating that the bike box treatment is desired at that specific traffic and bike volume. Other cells with B/C ratio of < 1 indicates that bike box treatment is not desired at that traffic and bike volumes. This table gives an estimate traffic and bike volumes where the bike box can be beneficial. In order to find the exact traffic and bike volume thresholds in which the bike box treatment would be beneficial, a linear interpolation between the results was done. Then, the exact traffic and bike volumes threshold were found and presented in table 22 below. Finally, a graph was plotted (see figure 30) with these values to help visualize how the B/C is changing as a function of traffic and bike volumes. The bike box seems to be effective only at traffic volume range of 1086-1231 veh/hr and bike volume of 46 bike/hr. This bike volume can increase to 92 bike/hr at 1158 traffic volume per hour. This graph will help decision makers and city engineers to determine if the bike box treatment option is cost effective at different traffic and bike volume levels.

Table 21- Benefit/cost ratio associated with base model and scenario 1 of model 2

B/C ratio for switching from the base model to scenario 1 of model 2						
Bike Volume (Bike/hr.)		46	92	184	276	368
Traffic volume (veh/hr.)	926	0.461	0.682	0.550	0.610	0.619
	1158	1.244	0.632	0.536	0.698	0.205
	1390	0.467	0.738	0.842	0.493	0.096

Benefit-cost analysis of scenario 2 and 3 of model 2 revealed (B/C <1) for all 15 traffic and bike volumes combinations in both scenarios. Meaning that the associated dis-benefits that comes from delay increase and from high infrastructure costs outweigh all benefits that comes from saved crashes. Hint: see appendix G for Economic analysis results of scenario 2 and scenario 3 of model 2.

Table 22- Benefit/cost ratio associated with base model and scenario 1 of model 2 with volume cut off value

B/C ratio for switching from the base model to scenario 1 of model 2							
Bike Volume (Bike/hr)		46	64	92	184	276	368
Traffic volume (veh/hr)	926	0.461	0.5491	0.682	0.550	0.610	0.619
	1086	1	0.8594	0.64758	0.54036	0.6705	0.334
	1158	1.244	1	0.632	0.536	0.698	0.205
	1231	1	0.8665	0.6652	0.632	0.63362	0.17077
	1390	0.467	0.5738	0.738	0.842	0.493	0.096

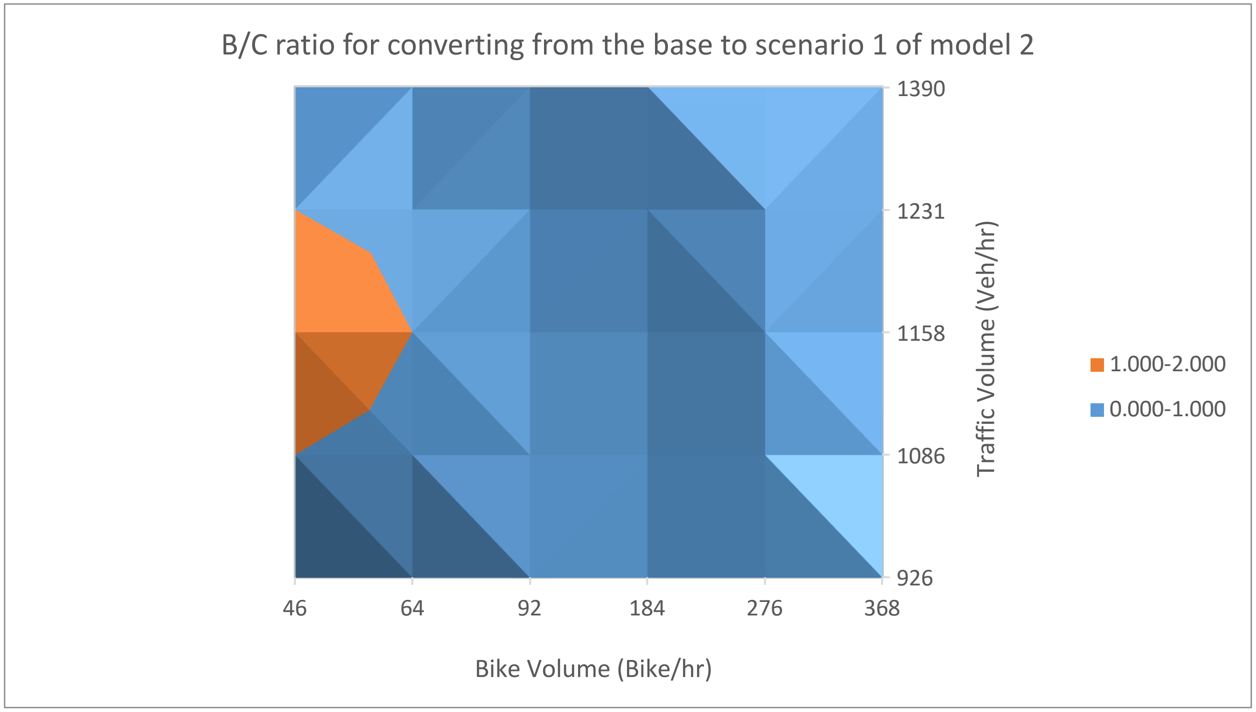


Figure 30- Benefit/cost ratio associated with the base model and scenario 1 of model 2

<u>Base Vs. Model 3 (Protected intersection)</u>

Operation Performance

The last treatment examined was the protected intersection design. Results of operation analysis for vehicle and bicycle delay at 1.2 traffic volume level is shown in table 23 and 24 and depicted in figure 31 and 32 respectively. In terms of the average vehicle delay, the protected intersection revealed a surprising result in which the delay for motor vehicle is lower than that of the conventional intersection design. This reduction in motor vehicle delay is due to two factors. First, all bicyclist making a left turn are removed from the auto vehicle lane to the bike lane so they can perform a protected two-stage left turn, so auto vehicles are no longer slowed down by their lower speed, specifically for left turn movements. Second, vehicle time spend yielding to bicyclist and pedestrian is lower since the advanced stop line for bicyclist and pedestrian would give them an automatic head start to clear the conflict areas of the intersection before auto vehicles reach them.

Table 23- Vehicle delay results and comparison of base model and model 3 at 1.2 traffic volume level

vehicle delay results at 1.2 traffic volume level					
Scenario	Bike volume level				
	46	92	184	276	368
Base	21.48	21.69	21.96	23	23.36
Protected intersection	20.63	20.69	20.82	20.91	21.12
% change					
from base to protected intersection	-4.0%	-4.6%	-5.2%	-9.1%	-9.6%

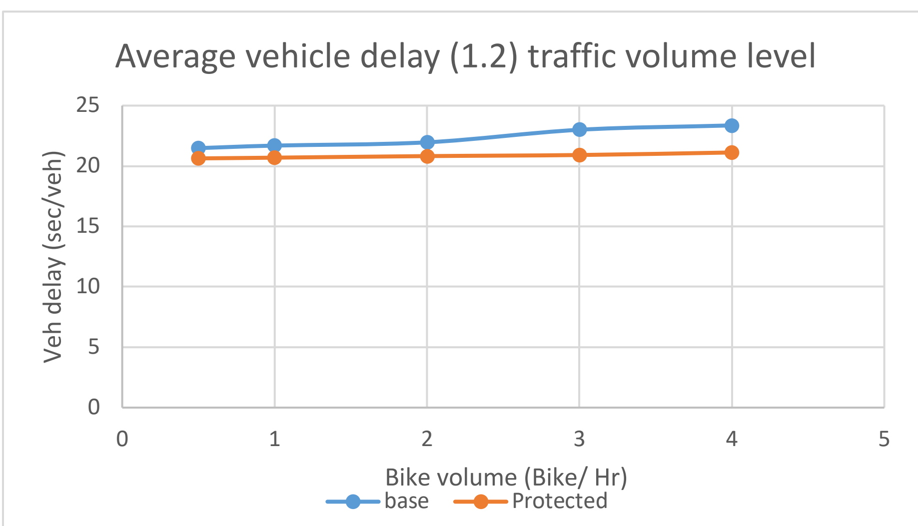


Figure 31- Average vehicle delay of the base model and model 3 at 1.2 traffic volume level

Regarding the average bicycle delay, it can be noted from table 24 that bicyclist will encounter a higher delay in the protected intersection model than that of the base model. This increase in bicyclist delay is expected since bicyclist in the protected intersection are required to make left turn in two stages. In this case, bicyclist have to wait for two green time phases; one to pass the crossing street and another one to complete the two-stage left turn.

Table 24- Bicycle delay results and comparison of the base model and model 3 at 1.2 traffic volume level

Bike delay results at 1.2 traffic volume level					
Scenario	Bike volume level				
	46	92	184	276	368
Base	15.88	16.03	15.91	16.06	16.57
Protected intersection	17.14	17.69	18.56	18.81	19.31
% change from base to protected intersection	7.9%	10.4%	16.7%	17.1%	16.5%

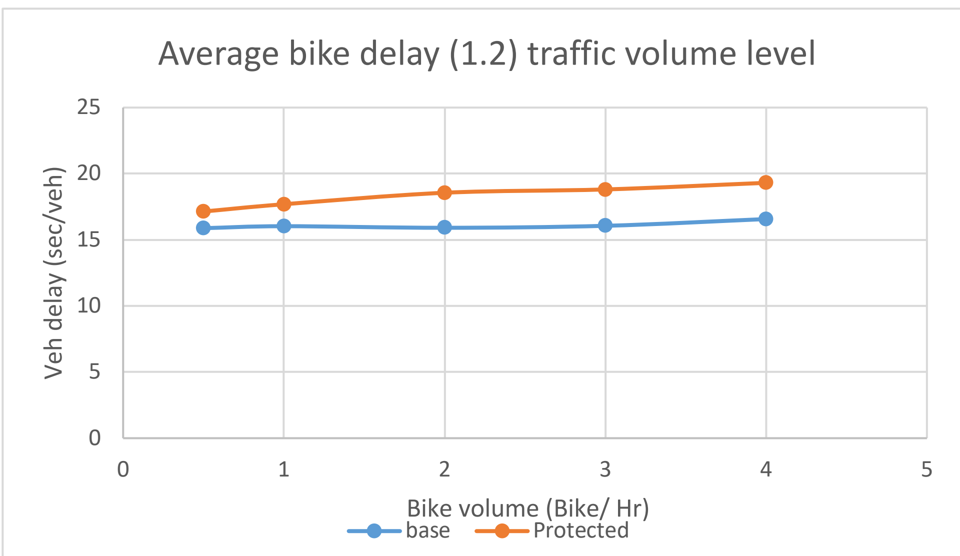
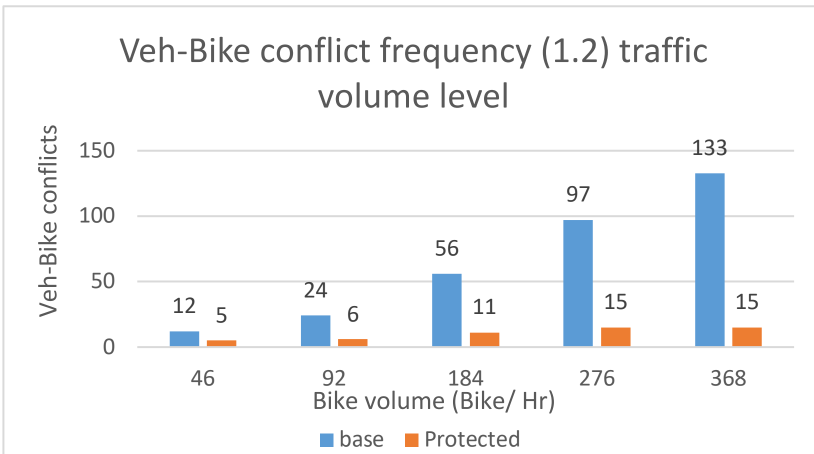


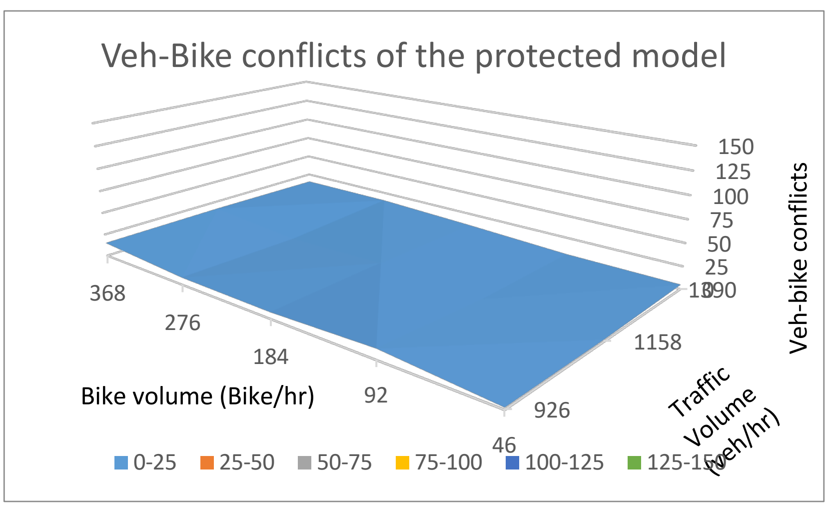
Figure 32- Average bicycle delay of the base model and model 3 at 1.2 traffic volume level

Safety Evaluation

Result of safety analysis for the base model and model 3 is shown in figure 33 below. Part (a) of this figure compares the total number of vehicle-bike conflicts in the base and model 3 at traffic volume level of 1.2 for demonstration purposes only. The similar trend seen in the previous two models can be seen in this model, that the number of vehicle-bike conflicts got reduced once we change from a conventional intersection design (base model) to the protected intersection design (model 3). However, this model revealed a substantial reduction in the number of vehicle-bike conflicts among all models. In fact, the protected intersection showed the lowest number of vehicle-bike conflicts among all models as can be seen in part (b) of figure 33 below. This result is likely, because bicyclist have a protected two-stage left turn, and they have an automatic head start due to the advanced stop line that allows bicyclist to clear the conflict area before auto vehicles reach them.



(a) vehicle-bike conflicts comparison in the base model and model 3



(b) 3D representation of vehicle-bike conflict in model 3

Figure 33- Vehicle bike conflicts in (a) base model Vs. model 3, (b) in model 3

Economic Analysis

Now, we have seen the operation and safety impact of changing from a conventional intersection design to protected intersection design. However, understanding the operational cost and safety benefits is critical before considering actual implementation. By following the economic analysis methodology shown in chapter 3 earlier, a benefit-cost analysis was done for this model. A summary of the associated benefits (crash saved, decrease in delay) and costs (infrastructure cost) with different traffic and bike volumes is shown in table 25 below. The estimated number of crashes in the base model and model 3 were obtained by converting the total number of conflicts to crashes by using the equation shown in section 3.2.5 in chapter 3. The saved crashes were then found by finding the difference in number of crashes between these two models. The decreased delay caused by implementing the protected intersection design found by finding the difference in vehicle delay. Saved crashes and delay savings were then converted to a monetary value for comparison purposes. The benefit-cost ratio for all 15 traffic volume combinations is shown in table 26 below. It can be noted that most cells of this table have B/C ratio of > 1 indicating that the protected intersection is desired at that traffic and bike volumes. Other cells with B/C ratio of < 1 indicates that protected intersection is not desired at that traffic and bike volumes. This table gives an estimate traffic and bike volumes where the protected intersection design can be beneficial. In order to find the exact traffic and bike volume thresholds in which the protected intersection would be beneficial, a linear interpolation between the results was done. Then, the exact traffic and bike volumes threshold were found and presented in table 27 below. Finally, a graph was plotted (see figure 34) with these values to help visualize how the B/C is changing as a function of traffic and bike volumes. The minimum hourly traffic and bike volume needed to justify the protected intersection design is 965 veh/hr and 368 bike/hr respectively. This required high level of bicycles starts to decrease in volume as the traffic volume increases. This graph will help the decision makers and city engineers to determine if the protected intersection is cost-effective at different traffic and bike volume levels. Model 3 came up with a higher B/C ratio than scenario 1 of model 2 shown earlier. This is because of two reasons; first, the protected intersection revealed a lower vehicle delay than the base model as explained earlier. Second, the protected intersection has a higher number of crash savings than that of scenario 1 of model 2. In fact, the only dis-benefit associated with the protected intersection is its relatively high infrastructure cost.

Table 25- Summary of all benefits and costs associated with base model and model 3

Summary of all benefits and cost associated with the base model and model 3 (protected)						
	traffic volume	Bike volume				
		46	92	184	276	368
Saved crashes (Crash)	926	0.87	1.12	1.28	1.61	2.09
	1158	3.64	3.03	4.17	6.63	4.97
	1390	5.48	6.63	7.30	10.14	10.39
Saved crashes benefits ($)	926	30909.62	39880.97	45414.58	57092.49	74135.95
	1158	129046.20	107679.71	148076.81	235283.29	176214.82
	1390	194515.93	235283.29	259194.25	359821.40	368759.42
Delay decrease (Sec/veh)	926	-0.03	0.11	0.23	0.42	0.63
	1158	0.66	0.67	0.86	1.23	1.37
	1390	0.85	1.00	1.14	2.09	2.24
delay benefits ($)	926	-605.23	2219.18	4640.10	8473.22	12709.83
	1158	16643.82	16896.00	21687.41	31018.03	34548.54
	1390	25722.27	30261.50	34498.11	63246.53	67785.75
Infrastructure cost		$107,900				

Table 26- Benefit/cost ratio associated with base model and model 3

B/C ratio for switching from the base model to the protected intersection model						
Bike Volume (Bike/hr.)		46	92	184	276	368
Traffic volume (veh/hr.)	926	0.285	0.390	0.464	0.608	0.805
	1158	1.350	1.155	1.573	2.468	1.953
	1390	2.041	2.461	2.722	3.921	4.046

Table 27- Benefit/cost ratio associated with base model and model 3 with volume cut off value

B/C ratio for switching from the base model to the protected intersection model							
Bike Volume (Bike/hr.)		46	92	121	184	276	368
Traffic volume (veh/hr.)	926	0.285	0.390	0.413	0.464	0.608	0.805
	965	0.466	0.520	0.562	0.652	0.923	1.000
	975	0.509	0.551	0.598	0.698	1.000	1.047
	1038	0.800	0.760	0.836	1.000	1.507	1.360
	1082	1.000	0.904	1.000	1.208	1.857	1.575
	1111	1.134	1.000	1.110	1.348	2.091	1.720
	1158	1.350	1.155	1.287	1.573	2.468	1.953
	1390	2.041	2.461	2.544	2.722	3.921	4.046

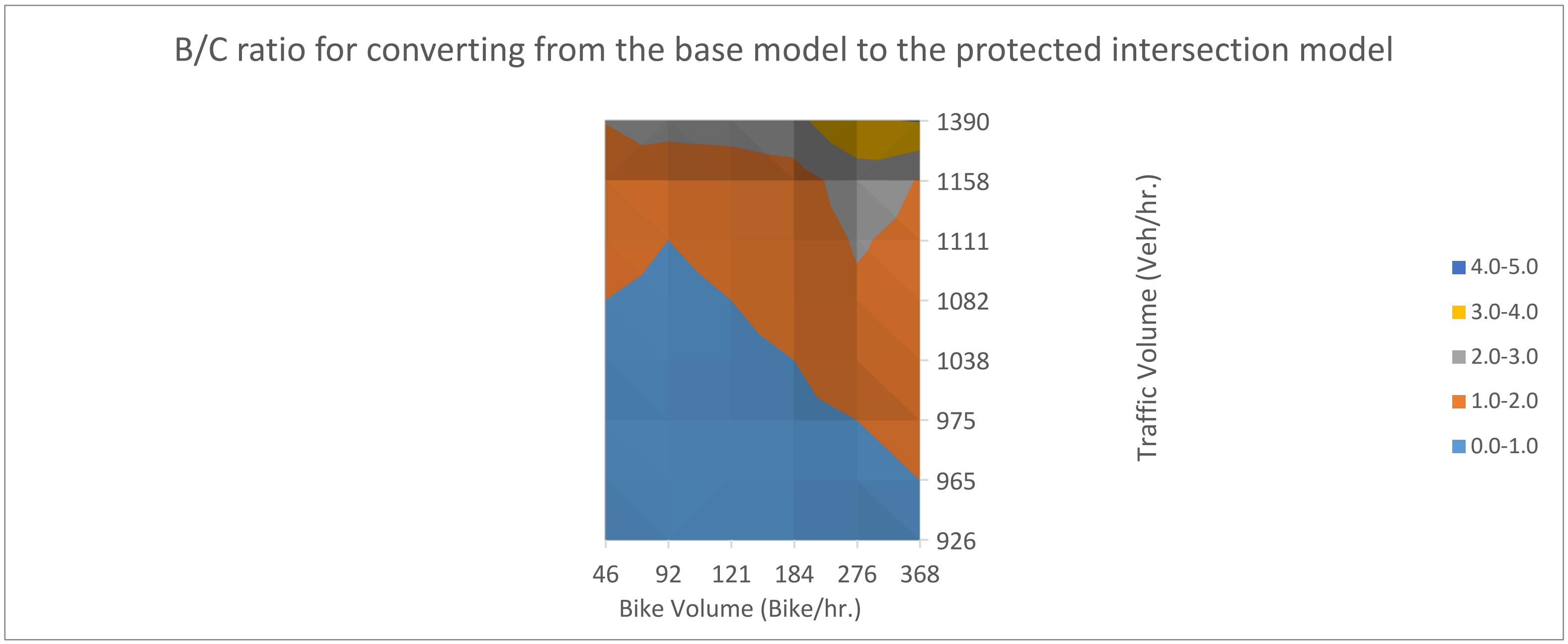


Figure 34- Benefit/cost ratio associated with the base model and model 3

4.3 GENERAL GUIDELINE TO FACILITIES BICYCLIST LEFT-TURN MOVEMENTS

One of the objectives of this research was to develop a general guideline to facilitate bicyclist left turn movements at intersection. Intersection design must take into account all bicyclist movements including right, through movement, and left turn movements. One of the most challenging turning movements for bicyclist at intersection is left turn movement. In fact, left turn movement from a right-side bike lane creates the most potential for conflict with auto vehicles. This problem led to an increasing interest in finding innovative facilities or even different intersection design that can provide a safer and more convenient way for bicyclist to make a left turn. This research has developed a general guideline (see table 28 below) that contains three different facility types that can be used to facilitate bicyclist left turn movements. These facilities are; bike box, protected intersection, and two-stage left turn boxes. The first two treatments were studied and evaluated in this research. However, the two-stage turn boxes were not assessed due to the limitation of VISSIM in presenting the real behavior of bicyclist with such treatment. This guideline shows the major pros and cons of each treatment and talks about different phasing and gives recommendation of the phasing scheme. It also helps in determining whether these treatments are compatible with bicycle signal faces and gives an estimate cost for each treatment. The author recommend the use of this guild side by side with the developed graphs shown earlier in section 4.2. The guideline along with the developed graphs will help the decision makers and city engineers in determining which treatment to implement and at what traffic and bike volume levels.

Table 28- General guideline to facilitate bicycle left turn movements

Treatment type	Pros	Cons	Phasing options			Compatibility with bike faces		Estimated treatment C\cost
			Lead-Lag Phasing (all approaches) / Recommended phasing	Split Phasing (all approaches) / Recommended phasing	Combination of lead-lag and splits / recommended phasing	LBI	EBP	
Bike Box	Facilitates one stage left turn for bicyclist	Effective only on red (bicyclist arriving on green will not be able to use it)	No / N. A	Yes / N. A	Yes / Split phasing on approaches with high bike volume	Yes [24]	Yes [24]	$ 5,000/ box; green thermoplastic pavement, signage, and installation [20]
Protected intersection	Suitable for areas with high bike and pedestrian volume	May increase bicyclist delay due two stages left turn. Need a major geometric change.	Yes / N. A	Yes / N. A	Yes / Splits phasing on approaches with low bike volume	Yes	Yes	High; ≃ $110,000/ Intersection [20]
Two-stage left turn box	Reduce conflicts between bicycles and pedestrian. Facilitate left turn bicyclist arriving on green.	May increase delay for bicyclist as they will need two green phases to make a left turn [24]	Yes / lead-lead-- lag-lag (To minimize bicyclist delay)	Yes / N. A	Yes / Split phasing on approaches with low bike volume	Yes [24]	Not preferred (will increase bicycle delay)	$1,000/ box; green thermoplastic pavement, signage, and installation [20]

CHAPTER 5

CONCLUSION

CONCLUSION AND STUDY CONTRIBUTION

The objective of this study was to evaluate two bicycle crash countermeasures with bicycle signal treatments at urban intersections. The two countermeasures are: bike boxes and the protected intersections. The bicycle signal treatments that were tested simultaneously with these countermeasures are the leading bicycle interval and the exclusive bicycle phase. This research also aimed to identify when these countermeasures are needed, and to develop and provide general guideline to facilitate bicycle left turn movements. A before and after bicyclist survey was conducted in the selected site. The main purpose of the survey was to measure bicyclist perception of safety of the bike box and bicycle signal, and to assess knowledge, understanding, and other reactions to the new treatments. A chi-squared test/ Fisher exact test was used to test for statistical significance among the results of both cases of the survey. Through data driven analysis, it was found that bike box seems to have a positive impact of bicyclist perception of safety and bike trip promotion. Put differently, the introduction of the bike box will make bicyclist feel safer when cycling at or near intersections with bike box and will encourage people to ride their bikes more often in a way that can lead to more livable and suitable communities. Furthermore, it was found that bike box can facilitate bicyclist one-way left turn movement, and capable to encourage bicyclist to stop in front of auto vehicles and will help bicyclist to switch their stopping position from the most right-hand side to the most left-hand side of the street when making a left turn. Further data analysis revealed that bike box can have a positive impact on intersection features such as safety, space for bicyclist, signal timing, and ease to navigate. Through VISSIM simulation, this research investigated engineering countermeasures from both traffic operation (e.g., impact on intersection users delay), and traffic safety prospective (e.g., conflicts among users as a surrogate safety measure). Results of operation analysis indicate that adding a bike box may increase vehicle delay due to prohibiting the right turn on red. Analysis also showed that bicycle signal treatments can lead to a higher vehicle delay, specifically with an exclusive bicycle signal phase. In fact, implementing exclusive bicycle phase would result in excessive increase in delay for all intersection users. Results of safety evaluation revealed that the bike box can enhance bicyclist safety by reducing the number of vehicle-bike conflicts. Additionally, bike box can further reduce vehicle-bike conflicts if combined with bicycle signal treatments such as the LBI or

EBP. This research also showed that the protected intersection design can be effective in reducing the number of vehicle-bike conflicts and can result in a lower vehicle delay. However, protected intersection design revealed a higher bicycle delay due to the two-stage left turn required for bicyclist to make a left turn. This study also evaluated the cost-effectiveness of these treatment through performing economic analysis. The resulted increase/decrease in delay and saved crashes were converted to monetary values under different traffic and bike volumes combinations to determine if such treatments are cost-effective before actual implementation take place. This revealed the threshold values for traffic and bike volumes that would justify the addition of bike box and the protected intersection treatments. The bike box treatment was found to be effective at traffic volume range of 1086-1231 veh/hr and bike volume of 46 bike/hr. This bike volume level can increase to 92 bike/hr at 1158 traffic volume per hour and the bike box can still be considered advantageous. On the other side, the protected intersection showed a wider range of both traffic and bike volumes where it would be beneficial. It also can be noted that the protected intersection treatment has a higher benefit to cost ratio than that of the bike box. In fact, if we compare these two treatments against each other, the protected intersection design will be more favorable option than the bike box design. Further economic analysis showed that the associated dis-benefits that come from delay increases of implementing bicycle signal treatments such as the LBI and EBP outweigh all benefits that come from saved crashes. Finally, this research created and developed a general guild line with three different facility types that can be used at urban intersection to facilitate bicyclist left turn movements. The developed guideline with the found threshold values of traffic and bike volumes will help the decision makers determine what treatment should be used and when this treatment is most desirable.

LIMITATION

There are few limitations that are associated with this study. Bicyclist survey non-response limited increasing the sample size of the survey data. Catching bicyclist attention in the field was not easy, especially since no incentives were available due to limited resources. Increasing survey sample size would remove any potential bias in the results. Also, this study evaluated the proposed countermeasure in a virtual environment under one intersection geometry design, and under one signal control type which was a fixed time signal. This may limit the transferability of results to different intersection geometries or different signaling systems. Additionally, due to the lack of safety performance measures, this research was limited to the use of a surrogate safety measures "conflicts "which is defined as a possibility of a crash. Finally, this study evaluated countermeasures with different traffic and bike volumes, but under a fixed pedestrian volume.

FUTURE RESEARCH

Moving forward, there are several potential extensions for this work. First, future survey research could include surveys of the motorist and pedestrians. This would allow for a wider understanding of road users perception of safety of the studied treatments. Secondly, more experimentation should be conducted with different intersection geometries, and with different type of signaling system. Thirdly, evaluation of the installed bike boxes should be revisited when an actual crash data is available from the site. Another space that was left for future work is related to VISSIM simulation and SSAM software. More effort is needed to improve bicyclist behavior in VISSIM, specifically, overtaking and queuing. Also, more validation effort is needed to improve SSAM accuracy and capabilities to represent the real world conflicts. And more effort is needed to improve SSAM efficiency. This can be done by creating a code that can run parallel with SSAM to speed up the time needed for data processing and filtration. Finally, the recommendation for the use of the bike box and the protected intersection in this research was purely based on economic analysis that considered the safety of intersection users and their delay to have the same weight. It could be interesting to consider different weighting scheme for these features.

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APPENDICES

Appendix A

Survey postcard

Appendix B

Bicyclist survey (before)

Hello!

Western Michigan University and the City of Grand Rapids would like to thank you for your interests in completing the survey of *Effectiveness of Bicycle Signal at Urban Intersections*. We are seeking bicyclists' feedback on two potential bicycle safety improvements: (1) bicycle signal and (2) bicycle box. This survey will take no more than 10 minutes to complete. Your participation in this study is completely voluntary. There are no foreseeable risks associated with this project. However, if you feel uncomfortable answering any question(s), you can withdraw from the survey at any point. It is very important for us to learn your opinions.

Your survey responses will be strictly confidential and data from this research will be reported only in the aggregate basis. If you have questions at any time about the survey or the procedures, you may contact the principle investigator, Dr. Jun-Seok Oh at 269 276 3216, or via email at jun.oh@wmich.edu.

Thank you so much for your time and support. You can now start answering the survey questions.

1. What is your age group?

- ☐ Less than 16 years
- ☐ 16-24 years
- ☐ 25-34 years
- ☐ 35-49 years
- ☐ 50-64 years
- ☐ 65+

2. What is your gender?

☐ Male ☐ Female ☐ Prefer not to say

3. Education attainment

- ☐ High school or less
- ☐ Associate degree/ some college courses but not degree
- ☐ Bachelor's degree
- ☐ Graduate degree or more
- ☐ Prefer not to say

4. How frequent do you bike?

- ☐ Everyday
- ☐ Several times a week
- ☐ Several times a month
- ☐ Very rarely

5. What is the primary purpose of bike trips?

- ☐ Exercise and health
- ☐ Recreation
- ☐ Commuting (Work/School)
- ☐ Errands/Shopping
- ☐ Other (Please specify)

____

6. How would you classify yourself as a biker?

- ☐ Beginner
- ☐ Intermediate
- ☐ Experienced

7. **How would you make a <u>left turn</u> at this intersection? Pick the best option that you will follow.**

- A

- B

- C

- D

8. **Why do you prefer to follow that path you picked in the previous question (question 7)? Select all that apply.**

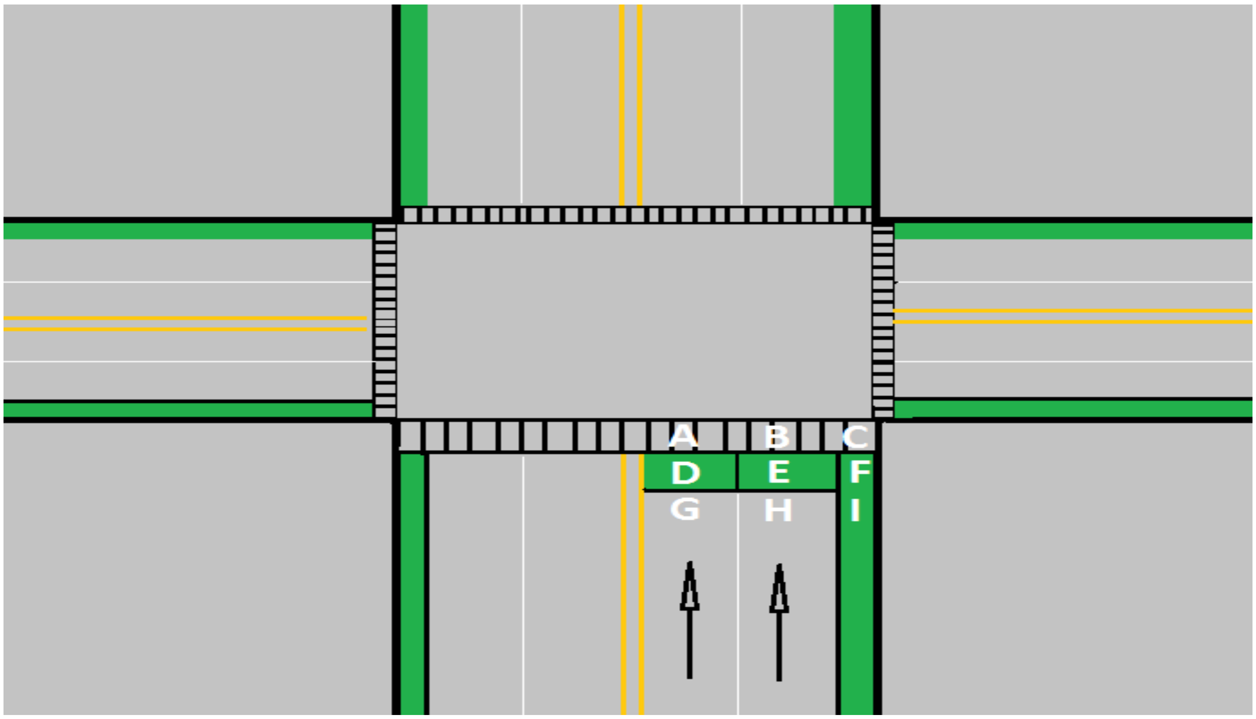
☐ Safer
☐ Faster
☐ Shorter
☐ Other (please specify)

____

____

9. If you want to make a <u>left turn movement</u> at a red signal in the shown intersection, where will you stop your bike? Select all that apply.

▢ A	▢ B	▢ C
▢ D	▢ E	▢ F
▢ G	▢ H	▢ I



10. Check the rating scale of following features for the identified intersections shown in the below maps.

Feature	Very good	Good	Fair	Poor	Very poor	I don't know
#1	Fulton with Seward Avenue					
Bicyclists' Safety						
Space for bicyclists						
Signal timing for bicyclists						
Ease to navigate						

Feature	Very good	Good	Fair	Poor	Very poor	I don't know
#2	Lake Michigan with Seward					
Bicyclists' Safety						
Space for bicyclists						
Signal timing for bicyclists						
Ease to navigate						

Feature	Very good	Good	Fair	Poor	Very poor	I don't know
#3	Bridge Street with Seward Avenue					
Bicyclists' Safety						
Space for bicyclists						
Signal timing for bicyclists						
Ease to navigate						

Feature	Very good	Good	Fair	Poor	Very poor	I don't know
#4	Leonard Street with Seward					
Bicyclists' Safety						
Space for bicyclists						
Signal timing for bicyclists						
Ease to navigate						

11. How much do you agree that bicyclists need dedicated traffic signal? If you are not familiar with such signals, select "*I don't know*"

- ▢ Strongly Agree
- ▢ Agree
- ▢ Neutral
- ▢ Disagree
- ▢ Strongly Disagree
- ▢ I don't know

12. What do you think is the purpose of the pavement markings in the red box? Select all that apply.

- ▢ Room for bicyclists to stop
- ▢ Room for bicyclists to make left turn
- ▢ To give bicyclists a head start at the beginning of green signal indication
- ▢ To keep cars away from crosswalk
- ▢ I don't know

13. How much do you agree that bike box will promote bicycling and enhance safety? If you are not familiar with such signals, select "*I don't know*"

Features	Strongly Agree	Agree	Neutral	Disagree	Strongly disagree	I don't know
Promote bicycling						
Enhance safety						

There will be another follow up survey in the future if one or both improvements are installed in the area. Would you be willing to participate in the follow up survey? If yes, please provide your preferred contact information.

Name:___________________________________

Address:__________________________________

Telephone:________________________________

Email: ___________________________________

Appendix C

Bicyclist survey (after)

Hello!

Western Michigan University and the City of Grand Rapids would like to thank you for your interests in completing the survey of *Effectiveness of Bicycle Signal at Urban Intersections*. We are seeking bicyclists' feedback on two potential bicycle safety improvements: (1) bicycle signal and (2) bicycle box. This survey will take no more than 10 minutes to complete. Your participation in this study is completely voluntary. There are no foreseeable risks associated with this project. However, if you feel uncomfortable answering any question(s), you can withdraw from the survey at any point. It is very important for us to learn your opinions.

Your survey responses will be strictly confidential and data from this research will be reported only in the aggregate basis. If you have questions at any time about the survey or the procedures, you may contact the principle investigator, Dr. Jun-Seok Oh at 269 276 3216, or via email at jun.oh@wmich.edu.

Thank you so much for your time and support. You can now start answering the survey questions.

1. What is your age group?

- ☐ Less than 16 years
- ☐ 16-24 years
- ☐ 25-34 years
- ☐ 35-49 years
- ☐ 50-64 years
- ☐ 65+

2. What is your gender?

- ☐ Male
- ☐ Female
- ☐ Prefer not to say

3. Education attainment

- ☐ High school or less
- ☐ Associate degree/ some college courses but not degree
- ☐ Bachelor's degree
- ☐ Graduate degree or more
- ☐ Prefer not to say

4. How frequent do you bike?

- ☐ Everyday
- ☐ Several times a week
- ☐ Several times a month
- ☐ Very rarely

5. What is the primary purpose of bike trips?

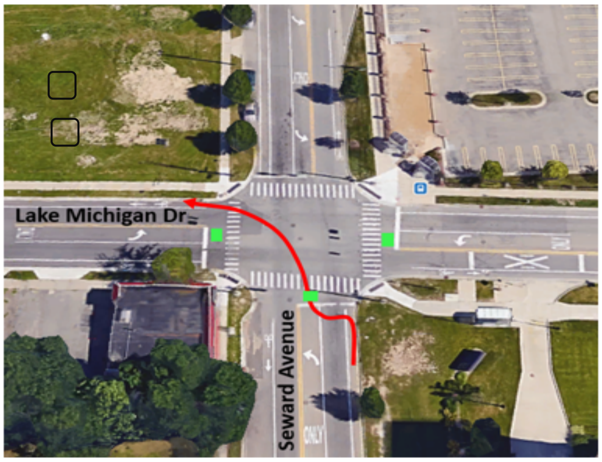
- ☐ Exercise and health
- ☐ Recreation
- ☐ Commuting (Work/School)
- ☐ Errands/Shopping
- ☐ Other (Please specify)

____

6. How would you classify yourself as a biker?

- ☐ Beginner
- ☐ Intermediate
- ☐ Experienced

7. How would you make a left turn at this intersection? Pick the best option that you will follow



- A
- B

- C
- D

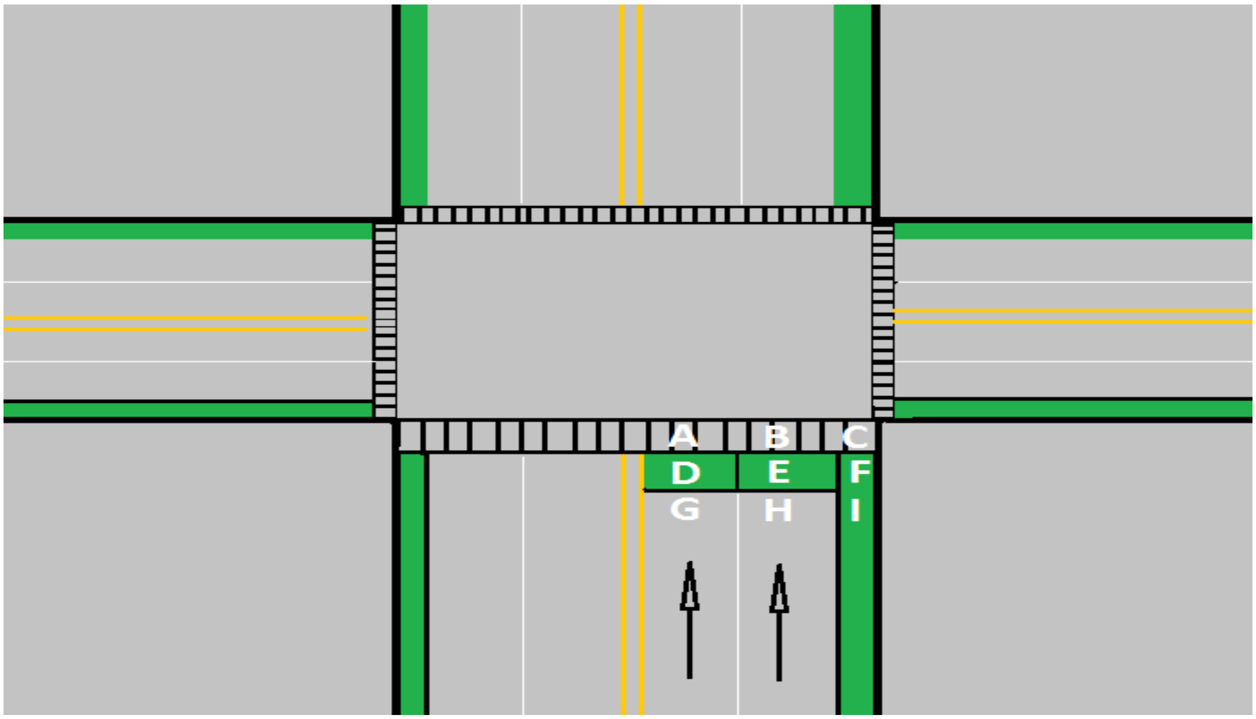
8. Why do you prefer to follow that path you picked in the previous question (question 7)? Select all that apply.

- ☐ Safer
- ☐ Shorter
- ☐ Faster
- ☐ Other (please specify)

____

9. If you want to make a <u>left turn movement</u> at a red signal in the shown intersection, where will you stop your bike? Select all that apply.

▢ A	▢ B	▢ C
▢ D	▢ E	▢ F
▢ G	▢ H	▢ I



10. Check the rating scale of following features for the identified intersections shown in the below maps.

Feature	Very good	Good	Fair	Poor	Very poor	I don't know
#1	Fulton with Seward Avenue					
Bicyclists' Safety						
Space for bicyclists						
Signal timing for bicyclists						
Ease to navigate						

Feature	Very good	Good	Fair	Poor	Very poor	I don't know
#2	Lake Michigan with Seward					
Bicyclists' Safety						
Space for bicyclists						
Signal timing for bicyclists						
Ease to navigate						

Feature	Very good	Good	Fair	Poor	Very poor	I don't know
#3	Bridge Street with Seward Avenue					
Bicyclists' Safety						
Space for bicyclists						
Signal timing for bicyclists						
Ease to navigate						

Feature	Very good	Good	Fair	Poor	Very poor	I don't know
#4	Leonard Street with Seward					
Bicyclists' Safety						
Space for bicyclists						
Signal timing for bicyclists						
Ease to navigate						

11. How much do you agree that bicyclists need dedicated traffic signal? If you are not familiar with such signals, select "*I don't know*"

- ▢ Strongly Agree
- ▢ Agree
- ▢ Neutral
- ▢ Disagree
- ▢ Strongly Disagree

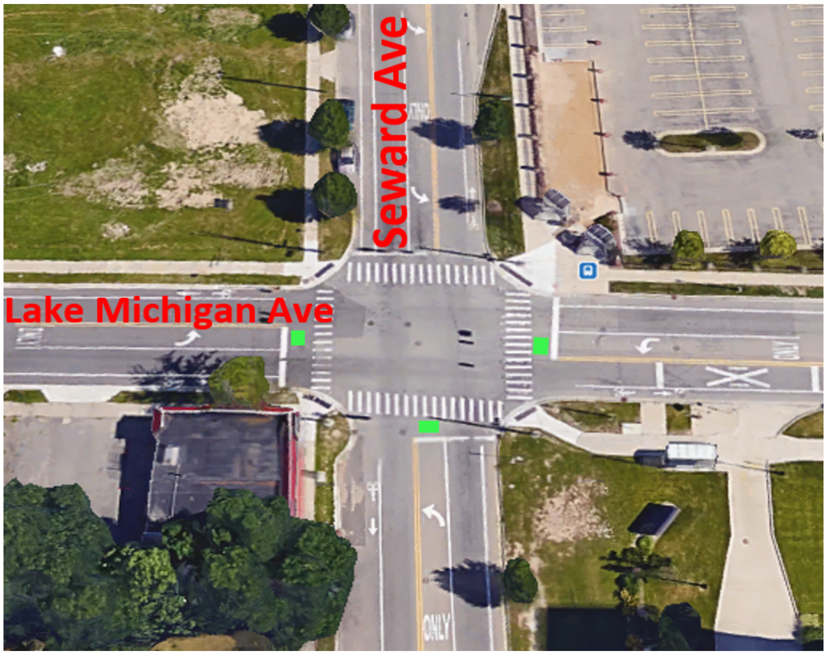
- ▢ I don't know

12. What do you think is the purpose of the pavement markings in the red box? Select all that apply.

- ▢ Room for bicyclists to stop
- ▢ Room for bicyclists to make left turn
- ▢ To give bicyclists a head start at the beginning of green signal indication
- ▢ To keep cars away from crosswalk
- ▢ I don't know

13. **The city of Grand Rapids recently installed a bike boxes at the three approaches of Lake Michigan & Seward Avenue as shown. Do you remember if you had ride through the bike box after it was installed?**

▢Yes
▢No
▢I don't know



14. **How much do you agree that the installed bike box will promote bicycling and enhance safety? If you are not familiar with such signals, select "*I don't know*"**

Features	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly disagree**	**I don't know**
Promote bicycling						
Enhance safety						

Appendix D

Consent Form

Western Michigan University

Civil and Construction Engineering

Principal Investigator: Jun-Seok Oh, Civil and Construction Engineering

Co- Principle Investigator: Valerian Kwigizile, Civil and Construction Engineering

Student Investigator: Odai Alhouz, Civil and Construction Engineering

Ahmad Feizi, Civil and Construction Engineering

Title of Study: Effectiveness of Bicycle Signals for Improving Safety and Multimodal Mobility at Urban Intersections

You have been invited to participate in research project titled "Effectiveness of Bicycle Signals for Improving Safety and Multimodal Mobility at Urban Intersections." This project will serve as Odai Al houz thesis for the requirements of master in Civil and Construction Engineering. This consent document will explain the purpose of this research project and will go over all of the time commitments, the procedures used in the study, and the risks and benefits of participating in this research project. Please read this consent form carefully and completely and please ask any questions if you need more clarification.

What are we trying to find out in this study?

The main objective of this study is to investigate the effectiveness of a bicycle signal and bike box on a different road users at urban intersections. The study focuses on increasing the bicyclists' safety by providing a specific signal and by making bicyclists more visible by placing them on front of the vehicles in a bike box. By doing so, the bicyclists will have a head start before vehicles, and will help them make a left turn at an intersection safer and more easily.

Who can participate in this study?

Both bicyclists and motorists from both gender and age ranges between 16-80 years can participate in this study, with emphasize on bicyclists regardless the level of biking experience.

Where will this study take place?

This study will take a place at the following four intersection in the city of Grand Rapids: the intersection of Fulton with Seward Ave, the intersection of Lake Michigan Ave with Seward Ave, the intersection of Bridge St with Seward Ave, and the intersection of Leonard St with Seward Ave.

What is the time commitment for participating in this study?

The study should take the participant no more than 15 minutes to complete the survey which is all what he/she has to do. This time includes a brief introduction, participant's agreement, and filling the survey.

What will you be asked to do if you choose to participate in this study?

A subject will be asked to fill in the survey that consist of a 15 questions to investigate their perception of the bike signal and bike box improvements that will be installed at the four mentioned above intersections.

What information is being measured during the study?
Completion of the survey will provide the project team with several important information, such information are; demographic information of the intersection's users, and user perception of bike signal and bike box before being installed. No personal information will be collected from participants.

What are the risks of participating in this study and how will these risks be minimized?
The survey will be totally anonymous and hazard free, and participation of the survey is voluntary. Since there will be no personal data collected from the subject, a risk free experience is expected.

What are the benefits of participating in this study?
There is no direct benefit to you as a participant in this study. However, your participation and feedback will help us provide a safer bicycle facility's improvements in Grand Rapids and other cities in the near future. Potential benefits associated with this study are: increase the safety of bicyclists, increase the visibility of bicyclists to other road users, and provide a head start for bicyclists at intersection.

Are there any costs associated with participating in this study?

As a participant, there is no direct costs associated with your participation in this study other than your time commitment. Your participation is completely voluntary.

Is there any compensation for participating in this study?

As a participant, there is no compensation for your participation in this study

Who will have access to the information collected during this study?

The collected data will be used and analyzed to help in completion of this project by the research team members only. No other personnel will have access to the collected data. The results of this research study will be disseminated as a research report to the city of Grand Rapids, and very possibly as a thesis for one of the participant students, also through journal publications.

What if you want to stop participating in this study?

You can choose to stop participating in the study at any time for any reason. You will not suffer any prejudice or penalty by your decision to stop your participation. You will experience NO consequences either academically or personally if you choose to withdraw from this study.

The investigator can also decide to stop your participation in the study without your consent

Should you have any questions prior to or during the study, you can contact the primary investigator, *Jun-Seok Oh* at *269-276-3216* or at *jun.oh@wmich.edu*. You may also contact the Chair, Human Subjects Institutional Review Board at *269-387-8293* or the Vice President for Research at *269-387-8298* if questions arise during the course of the study.

This consent document has been approved for use for one year by the Human Subjects Institutional Review Board (HSIRB) as indicated by the stamped date and signature of the board chair in the upper right corner. Do not participate in this study if the stamped date is older than one year.

I have read this informed consent document. The risks and benefits have been explained to me. I agree to take part in this study.

Please Print Your Name

______________________________________ _________________________________

Participant's signature Date

Appendix E

HSIRB Approval Letter

WESTERN MICHIGAN UNIVERSITY

Human Subjects Institutional Review Board

Date: May 23, 2017

To: Jun-Seok Oh, Principal Investigator
Valerian Kwigzile, Co- Principal Investigator
Odai Alhouz, Student Investigator for thesis
Ahmad Feizi, Student Investigator

From: Amy Naugle, Ph.D., Chair

Re: HSIRB Project Number 17-05-17

This letter will serve as confirmation that your research project titled "Effectiveness of Bicycle Signals for Improving Safety and Multimodal Mobility at Urban Intersections" has been **approved** under the **exempt** category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note: This research may **only** be conducted exactly in the form it was approved. You must seek specific board approval for any changes in this project (e.g., ***you must request a post approval change to enroll subjects beyond the number stated in your application under "Number of subjects you want to complete the study***)." Failure to obtain approval for changes will result in a protocol deviation. In addition, if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

Reapproval of the project is required if it extends beyond the termination date stated below.

The Board wishes you success in the pursuit of your research goals.

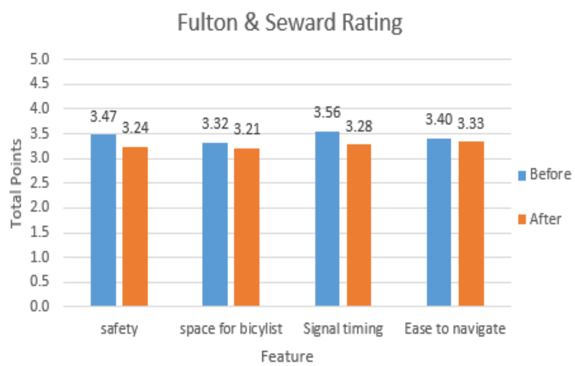
Approval Termination: **May 22, 2018**

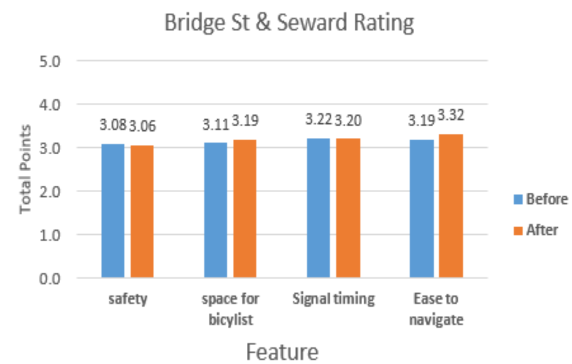
1903 W. Michigan Ave., Kalamazoo, MI 49008-5456
PHONE: (269) 387-8293 FAX: (269) 387-8276
CAMPUS SITE: 251 W. Walwood Hall

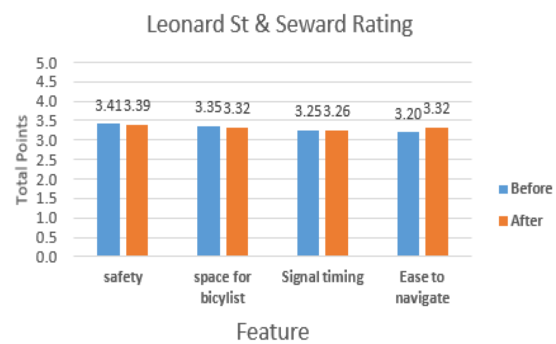
Appendix F

Other survey responses

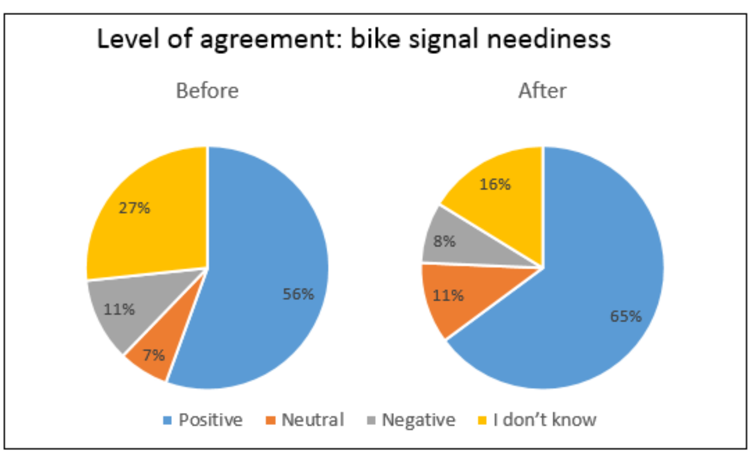
Check the rating scale of following features for the identified intersections shown in the below maps (question 10)







How much do you agree that bicyclists need dedicated traffic signal? If you are not familiar with such signals, select "*I don't know*" (question 11)



Bicycle signal neediness	Before	After	% difference
Strongly Agree	8 18%	9 24%	+7%
Agree	17 38%	15 41%	+3%
Neutral	3 7%	4 11%	+4%
Disagree	5 11%	3 8%	-3%
Strongly Disagree	0 0%	0 0%	0%
I don’t know	12 27%	6 16%	-10%
Total	45	37	

What do you think is the purpose of the pavement markings in the red box? Select all that apply (question12)?

Bike box purpose	Before	After	% difference
Room for bicyclist to stop	18 23%	23 29%	+6%
Room for bicyclist to make a left turn	31 39%	30 38%	+1%
To give bicyclist a head starts at the beginning of green indication	16 20%	15 19%	-1%
To keep cars away from crosswalk	8 10%	8 10%	+0%
I don’t know	6 8%	2 3%	-5%
Number of Responses	79	78	
Total	45	37	

Appendix G

Simulation results

Summary of all benefits and cost associated with the base model and scenario 2 of model 2						
	traffic volume	Bike volume				
		46	92	184	276	368
Saved crashes (Crash)	926	1.02	1.66	2.12	1.49	1.91
	1158	1.99	1.54	2.30	3.15	1.28
	1390	1.71	1.21	1.02	1.00	1.42
Saved crashes benefits ($)	926	36061.24	58823.85	75068.64	52831.75	67704.82
	1158	70439.91	54524.33	81692.65	111861.04	45414.58
	1390	60570.39	43017.08	36061.24	35311.06	50322.69
Delay increase (Sec/veh)	926	5.65	5.52	5.54	5.85	6.03
	1158	7.31	7.24	7.48	7.87	8.61
	1390	9.34	9.41	10.76	11.38	13.41
delay disbenefits ($)	926	113984.97	111362.31	111765.79	118019.84	121651.22
	1158	184342.95	182577.70	188630.00	198464.98	217126.24
	1390	282642.38	284760.68	325613.70	344375.83	405806.67
Infrastructure cost		$49,500				

B/C ratio for switching from the base model to scenario 2 of model 2						
Bike Volume (Bike/hr.)		46	92	184	276	368
Traffic volume (veh/hr.)	926	0.221	0.366	0.465	0.315	0.396
	1158	0.301	0.235	0.343	0.451	0.170
	1390	0.182	0.129	0.096	0.090	0.111

Summary of all benefits and cost associated with the base model and scenario 3 of model 2						
	traffic volume	Bike volume				
		46	92	184	276	368
Saved crashes (Crash)	926	0.89	1.47	1.78	1.71	2.41
	1158	0.26	0.22	0.62	2.75	1.73
	1390	0	0	0.02	1.15	1.78
Saved crashes benefits ($)	926	31631.11	51991.40	63218.27	60570.39	85551.15
	1158	9216.32	7744.66	21998.44	97435.46	61449.30
	1390	0.00	0.00	647.19	40658.41	63218.27
Delay increase (Sec/veh)	926	12.64	12.50	12.47	12.26	12.00
	1158	19.15	19.39	19.71	20.13	19.78
	1390	33.84	33.86	33.97	34.43	34.66
delay disbenefits ($)	926	255003.55	252179.14	251573.91	247337.30	242091.97
	1158	482923.05	488975.35	497045.08	507636.61	498810.34
	1390	1024049.05	1024654.28	1027983.04	1041903.33	1048863.47
Infrastructure cost		$49,500				

B/C ratio for switching from the base model to scenario 3 of model 2						
Bike Volume (Bike/hr.)		46	92	184	276	368
Traffic volume (veh/hr.)	926	0.104	0.172	0.210	0.204	0.293
	1158	0.017	0.014	0.040	0.175	0.112
	1390	0.008	0.013	0.001	0.037	0.058

At 0.8 (926 Veh/ hr.) traffic volume level																															
Model		Base model					Model 1 (LBI)					Model 2 scenario 1 (Bike box)					Model 2 scenario 2 (Bike box+ LBI)					Model 2 scenario 3 (Bike box+ EBP)					Model 3(Protected intersection)				
Bike volume (bike/hr.)		46	92	184	276	368	46	92	184	276	368	46	92	184	276	368	46	92	184	276	368	46	92	184	276	368	46	92	184	276	368
Delay	veh	15.5	15.6	15.8	16.0	16.3	20.8	21.0	21.3	21.8	22.2	17.2	17.4	17.6	18.3	18.7	21.1	21.1	21.3	21.9	22.3	28.1	28.1	28.2	28.3	28.3	15.5	15.5	15.5	15.6	15.7
	Bike	12.5	13.0	13.3	13.5	13.1	13.0	13.5	14.1	14.2	13.9	12.5	12.7	13.3	13.5	13.2	12.2	12.5	13.1	13.3	13.1	31.3	32.0	32.4	33.9	36.9	14.1	14.5	16.1	16.3	16.3
conflicts	veh-bike	13	28	53	68	92	7	16	23	44	66	8	20	37	53	71	7	12	25	36	56	1	3	16	16	27	2	11	7	8	15
	veh-ped	16	19	17	11	13	4	6	7	3	4	16	10	14	6	9	0	2	4	3	3	1	2	1	1	1	31	29	29	30	28
	veh-veh	334	341	338	350	372	274	287	261	328	329	286	288	295	297	321	288	278	265	301	312	299	295	290	314	324	269	275	292	297	321
	total	363	388	408	429	477	285	309	291	375	399	310	318	346	356	401	295	292	294	340	371	301	300	307	331	352	302	315	328	335	364

At 1.0 (1158 Veh/ hr.) traffic volume level																															
Model		Base model					Model 1 (LBI)					Model 2 scenario 1 (Bike box)					Model 2 scenario 2 (Bike box+ LBI)					Model 2 scenario 3 (Bike box+ EBP)					Model 3(Protected intersection)				
Bike volume (bike/hr.)		46	92	184	276	368	46	92	184	276	368	46	92	184	276	368	46	92	184	276	368	46	92	184	276	368	46	92	184	276	368
Delay	veh	17.3	17.3	17.6	18.1	18.3	24.1	24.5	24.9	26.4	27.4	19.0	19.1	19.5	20.5	21.2	24.6	24.6	25.1	26.0	26.9	36.4	36.7	37.3	38.2	38.1	16.6	16.7	16.7	16.9	16.9
	Bike	12.7	12.8	13.6	13.9	13.5	14.0	13.9	14.5	15.0	14.5	12.8	12.8	13.6	13.7	13.4	12.5	12.7	13.4	13.8	13.5	31.6	32.9	34.4	35.3	38.3	14.0	14.6	15.9	16.3	16.2
conflicts	veh-bike	12	25	50	103	103	8	14	27	61	79	11	16	44	53	87	5	13	28	44	61	5	7	14	14	31	2	5	10	7	16
	veh-ped	23	20	18	18	8	4	4	4	5	7	22	11	17	16	9	7	5	5	4	3	2	2	1	0	0	23	21	23	21	24
	veh-veh	528	502	537	571	583	459	459	489	518	538	411	446	475	530	555	442	438	451	493	550	530	515	542	541	564	371	374	388	409	446
	total	563	547	605	692	694	471	477	520	584	624	444	473	536	599	651	454	456	484	541	614	537	524	557	555	595	396	400	421	437	486

At 1.2 (1390 Veh/ hr.) traffic volume level																															
Model		Base model					Model 1 (LBI)					Model 2 scenario 1 (Bike box)					Model 2 scenario 2 (Bike box+ LBI)					Model 2 scenario 3 (Bike box+ EBP)					Model 3(Protected intersection)				
Bike volume (bike/hr.)		46	92	184	276	368	46	92	184	276	368	46	92	184	276	368	46	92	184	276	368	46	92	184	276	368	46	92	184	276	368
Delay	veh	21.5	21.7	22.0	23.0	23.4	30.3	30.8	32.3	34.4	36.0	23.6	23.9	24.8	26.3	27.3	30.8	31.1	32.7	34.4	36.8	55.3	55.6	55.9	57.4	58.0	20.6	20.7	20.8	20.9	21.1
	Bike	15.9	16.0	15.9	16.1	16.6	17.9	17.2	17.6	17.2	18.2	15.3	15.9	15.7	16.1	16.3	15.4	15.9	16.0	16.2	16.7	39.3	41.1	42.1	46.8	51.6	17.1	17.7	18.6	18.8	19.3
conflicts	veh-bike	12	24	56	97	133	9	29	52	64	80	3	23	42	58	115	4	17	48	57	71	2	9	18	22	37	5	6	11	15	15
	veh-ped	16	18	13	14	8	8	8	7	8	3	12	11	11	12	9	6	5	4	4	3	1	3	2	0	4	24	23	23	21	17
	veh-veh	739	768	775	823	826	620	642	743	733	841	679	674	663	767	809	659	711	724	806	807	789	833	820	838	825	515	526	537	554	585
	total	767	810	844	934	967	637	679	802	805	924	694	708	716	837	933	669	733	776	867	881	792	845	840	860	866	544	555	571	590	617