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Addressing Bicycle-Vehicle Conflicts with Alternate Signal Control Strategies

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ADRESSING BICYCLE-VEHICLE CONFLICTS WITH ALTERNATE SIGNAL CONTROL STRATEGIES

Final Report

NITC-RR-897

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16. Abstract

There is nationwide interest in supporting sustainable and active transportation modes such as bicycling and walking due to the many benefits associated with them, including reduced congestion, lower emissions and improved health. Although the number of bicyclists is increasing, safety remains a top concern. In urban areas, a common crash type involving bicycles at intersections is the "right hook" where a right-turning vehicle collides with a through bicyclist. While geometric treatments and pavement markings have been studied, there is a lack of research on signal timing treatments to address right-hook bicycle-vehicle conflicts. This study analyzed the operational impacts of traditional concurrent phasing, leading bike intervals (LBI), split leading bike intervals, and exclusive bike phasing in a microsimulation environment, and explored the safety impacts of traditional concurrent phasing, leading bike intervals, split leading bike intervals, and mixing zones using video-based conflict analysis. The microsimulation analysis revealed increased delays due to LBI, split LBI and exclusive bike phasing for the affected motor vehicle phases compared to traditional concurrent phasing. Using post-encroachment time (PET), a surrogate safety measure, conflicts between turning vehicles and bicyclists were investigated. While the split LBI treatment was useful in mitigating conflicts during the lead interval, the risk for bicyclists is shifted to the stale green portion of the phase. No correlations were found between the frequency of conflicts and elapsed time since green. With the mixing zone treatment, significant confusion was exhibited by both cyclists and drivers, with respect to the correct action to be taken. Our observations also revealed that a significant percentage of the vehicles merged into the mixing zone at the very last second, thus adding to the confusion. This study provides broad-based recommendations on the appropriate treatment to be implemented to reduce right-hook conflicts.

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DISCLAIMER

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1.0 INTRODUCTION

There is nationwide interest in supporting sustainable and active transportation modes such as bicycling and walking due to the many benefits associated with them, including reduced congestion, lower emissions and improved health. Bicycle trips increased from 0.7% of total trips in 1995 to 1.0% in 2009 (*Pucher et al., 2011*). Although the number of bicyclists is increasing, safety remains a top concern and can be a limiting factor in engaging new cyclists (*Sanders, 2013*). According to the National Highway Traffic Safety Administration , there were 818 bicyclist fatalities in 2015, accounting for 2.3% of all motor vehicle-related fatalities. As a proportion of total crashes, bicyclist fatalities are increasing. Of these, 70% occurred in urban areas and 28% occurred at intersections (*NHTSA, 2015*). In Oregon alone, 42 bicyclists were involved in fatal crashes from 2009-2013 (*ODOT, 2014*).

In urban locations, intersections are areas where a variety of modes converge, thus leading to an increased potential for conflicts. A common crash type involving bicycles at intersections is the “right hook” where a right-turning vehicle collides with a through bicyclist. Right-hook crashes typically occur in one of two ways. First, they can occur during the onset of the green indication due to the failure of the motorist to notice and yield to the bicyclist . The second scenario occurs at least several seconds after the onset green indication (sometimes termed as “stale green”), and may happen when either a faster bicyclist overtakes a slower vehicle or a faster vehicle overtakes a slower cyclist. In either case, the vehicle executes a turn in front of the bicyclist (*Hurwitz et. al, 2015*). Various studies have investigated causal factors for right-hook crashes between bicycles and motor vehicles. Primary causal factors are a motorist’s failure to look for the bicyclist prior to turning, bicyclist inattention, especially on familiar routes, and a bicyclist’s inaccurate assumption regarding motorist yielding behavior (*Summala, 1988; Summala et al., 1996; Räsänen and Summala, 1998*). Recent work by Hurwitz and Monsere (*Hurwitz et. al, 2015*) confirmed a number of these factors using a driving simulator. Various mitigation treatments have been employed to reduce and/or eliminate the probability for a right-hook crash to occur. Geometric treatments including advance stop lines or bike boxes have been used in some cities as a treatment, and there is some evidence showing a reduction of right-hook conflicts at the onset of the green indication due to their use (Dill et al., 2012). Other treatments that have been used include signage (static or dynamic), colored pavement markings highlighting potential conflict areas, enhanced curb radii, mixing zones and the use of pocket bike lanes at intersections.

Signal timing treatments to improve safety and prevent right hook crashes include the provision of bicycle specific signals, exclusive bicycle phases and leading bike intervals (LBI). The city of Portland has also experimented with an active warning sign that lights up and reminds turning vehicles to yield to bicyclists (*Paulsen et al., 2014*). While exclusive phasing provides the potential to improve bicycle safety, the main drawback with this treatment is an increase in delay for all users at the intersection, which could lead to signal noncompliance. A leading bike interval is very similar to a leading pedestrian interval in that it allows bicycles to have a few seconds of head start while other traffic is restricted. An emerging treatment being used in New York City and other cities is a split LBI where during the first portion of the green phase, the through motor vehicle traffic, bicycles and pedestrians are allowed to continue through the intersection whereas the conflicting turns are restricted. This is followed by a permissive turning phase where the turning traffic is controlled by a flashing yellow arrow and is expected to yield to bicycles and pedestrians, while bicycles and pedestrians and through traffic continue to see a green or walk indication. While New York City has implemented split LBIs recently, the literature is void regarding the impacts of modified LBI on the safety and efficiency of all users at the intersection. This study aims to fill that gap by conducting research that will study various alternate signal timing control strategies to reduce conflicts between bicycles and turning vehicles. Providing guidance for improving bicycle safety at intersections could increase the attractiveness of this mode for potential new cyclists.

The goals of this research are twofold: a) assess efficiency impacts of signal timing strategies for mitigating bicycle-vehicle right-hook conflicts using a microsimulation platform and b) understand the safety implications of signal timing treatments and mixing zone using surrogate safety measures with video observations in multiple locations. A simulated intersection was developed in VISSIM and the efficiency impacts of the signal timing strategies were studied on all users using the ASC/3 software-in-the-loop signal controller software. Video observations were collected and analyzed at intersections in New York City, NY, Portland, OR, and Phoenix, AZ.

The remainder of this report is organized in the following manner. A detailed literature review of the existing control strategies is presented in Chapter 2. Also included in Chapter 2 are findings from a brief practitioner survey that was conducted to understand the state of practice with respect to use and deployment of signal control strategies for bicyclists. A description of the simulation model development for evaluating bicycle control strategies is presented in Chapter 3, followed by a description of data and methods used for conflict analysis in Chapter 4. The results of the video-based conflict analysis are presented in Chapter 5. A discussion of the results is presented in Chapter 6. The report wraps up with conclusions and recommendations in Chapter 7.

2.0 LITERATURE REVIEW

A common crash type between bicycles and motor vehicles at intersections is the "right hook," where a right-turning vehicle collides with a through bicyclist, as shown in Figure 2.1. Similar to right-hook crashes, left-hook crashes can also occur when a bike lane exists to the left of a left-turn lane on a one-way street. Various intersection design and signal timing treatments have been used to reduce and/or eliminate the probability for right-hook crashes to occur. A prior study explored intersection design treatments to reduce right hooks, including signage, colored pavement markings highlighting potential conflict areas, enhanced curb radii and protected intersections (*Hurwitz et al., 2015*). However, this study did not explore the potential for using signal timing treatments to reduce right-hook crashes.

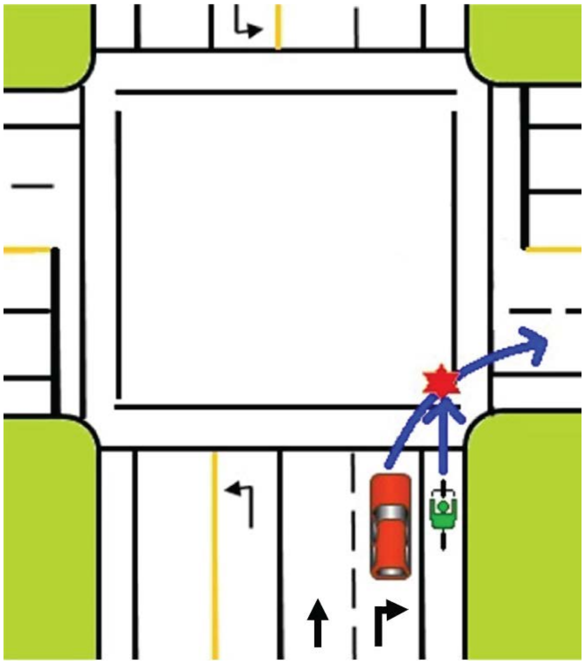


Figure 2.1: Right-hook Crash

(Source: Hurwitz et al., 2015)

Exclusive bicycle phases and leading bicycle intervals (LBI) are two types of signal timing treatments that are being implemented to minimize conflicts between bicycles and turning vehicles. With exclusive phases, bicyclists are provided with a separate signal phase. An LBI is similar in operation to a leading pedestrian interval (LPI). During an LBI, bicyclists are provided a green indication for a few seconds prior to the start of a concurrent vehicular green indication to allow the bicyclists to establish themselves in the intersection. An emerging treatment being implemented in New York City and other National Association of City Transportation Officials (NACTO) member cities is a split LBI. The split LBI consists of a green indication for through bicycles and a concurrent green indication for the through vehicles, while maintaining a red indication for the right-turning vehicles. After a fixed interval, the right-turning vehicles are released and expected to yield to the through bicyclists.

While exclusive bicycle phase and LBI strategies improve bicycle safety, the drawback to these treatments is an increase in delay for all users at the intersection, which could lead to signal noncompliance. Although the split LBI is being used in New York City, the impacts of this strategy on conflicts between bicycles and turning vehicles, as well as the efficiency of all users at the intersection, is not well known. This study aims to address that gap by conducting research on signal timing control strategies for mitigating right-hook crashes.

The objective of this chapter is to review the academic literature on existing signal timing strategies targeting right-hook crashes and the occurrence of right-hook crashes in the crash data, along with surrogate safety measures. Specific signal timing strategies reviewed are: traditional phasing with no priority for bicycles, LBI, split LBI and exclusive bicycle phases. In addition, this chapter reports on the results obtained from a nationwide survey of practitioners. The literature review and state-of-the-practice survey provide an overview of the current use of signal timing strategies to mitigate right-hook conflicts in the United States. Gaining an understanding of the various signal timing strategies will lead to better guidance and improve bicycle safety at intersections. This could increase the attractiveness and use of bicycling for transportation.

2.1 RIGHT-HOOK CRASH TYPES

Right-hook crashes typically occur in one of two ways as stated below. Figure 2.2 illustrates the various right-hook crash typologies.

a) **At start of movement through intersection:** A right hook at the onset of the green indication (Figure 2a) or at a STOP sign (Figure 2b) can occur when a bicyclist stops to the right of a vehicle that is waiting at a red indication or STOP sign and fails to notice the bicyclist, who may be occluded in the vehicle's blind spot. Immediately after the signal turns green, the bicyclist proceeds through the intersection and the motorist turns right simultaneously, leading to a conflict and possible collision (*Hurwitz et al., 2015*). Some literature has termed this a right hook during the start-up green (*City of Fort Collins, 2013*).
b) **During motion through intersection:** A right hook can also occur at an intersection several seconds after the signal turns green when there is relative motion between the right-turning motorist and the through-moving bicyclist (*Hurwitz et al., 2015*). Some literature has termed this a right hook during the "stale" green (*City of Fort Collins, 2013*). A right-hook crash in this condition can occur in two ways: a) when a bicyclist overtakes a slow-moving vehicle from the right and the vehicle unexpectedly makes a right turn (Figure 2c); and, b) when a fast-moving vehicle overtakes the bicyclist and then tries to make a right turn directly in front of the bicyclist, who is proceeding through the intersection (Figure 2d) (*Hurwitz et al., 2015*).

In either case, the vehicle executes a turn in front of the bicyclist (*Hurwitz et. al, 2015*). Various studies have investigated causal factors for right-hook crashes between bicycles and motor vehicles. Primary causal factors are a motorist's failure to look for the bicyclist prior to turning, bicyclist inattention, especially on familiar routes, and a bicyclist's inaccurate assumption regarding motorist yielding behavior (*Summala 1988, Summala et al., 1996, Räsänen and Summala 1998*). Recent work by Hurwitz and Monsere (*Hurwitz et. al, 2015*) confirmed a number of these factors using a driving simulator.

A) Right hook at start-up green

B) Right hook at STOP sign

C) Right hook when cyclist passes slow-moving car

D) Right hook when motorist passes cyclist

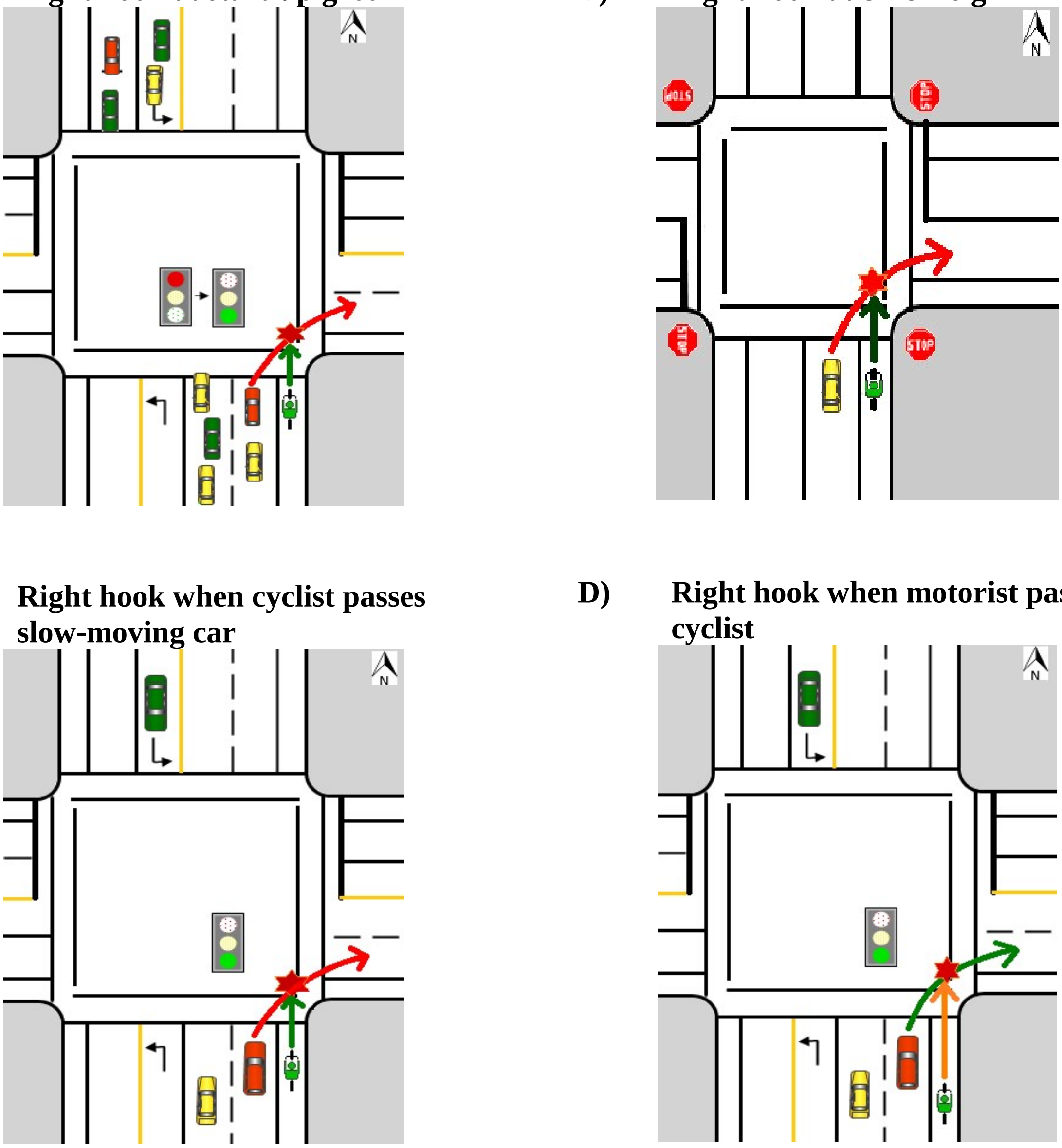


Figure 2.2: Right-hook Crash Typologies

(Source: Hurwitz et al., 2015)

2.2 CRASH DATA OVERVIEW

Statewide crash data from Oregon, Arizona and New York was examined to understand the extent of bicyclist fatalities. As field deployments of split LBI treatments were scheduled for Phoenix, AZ, as well as Portland, OR, crash data for these states was reviewed. In addition to deployment data from these states, the research team will also review video data from New York City where split LBI has already been implemented. In Oregon, 59 bicyclists were involved in fatal crashes from 2004-2008 (*ODOT, 2009*) and 42 bicyclists were involved in fatal crashes from 2009-2013 (*ODOT, 2014*), as shown in Table 2.1.

In Arizona, 131 bicyclists were involved in fatal crashes from 2004-2008 and 115 bicyclists were involved in fatal crashes from 2009-2013 (*ADOT*). In New York, 225 bicyclists were involved in fatal crashes from 2004-2008 and 207 bicyclists were involved in fatal crashes from 2009-2013 (*NYCDOT*). During this span of 10 years, all three states saw an overall decrease in total traffic fatalities and bicyclist fatalities.

Table 2.1: Total and Bicyclist Fatalities 2004-2013

	Oregon			Arizona			New York		
Year	**Total Fatalities**	**Bicyclist Fatalities**	**% of Total Fatalities**	**Total Fatalities**	**Bicyclist Fatalities**	**% of Total Fatalities**	**Total Fatalities**	**Bicyclist Fatalities**	**% of Total Fatalities**
2004	456	8	1.8	1151	27	2.3	1495	41	2.7
2005	487	11	2.3	1179	35	3.0	1410	47	3.3
2006	478	14	2.9	1299	29	2.2	1433	45	3.1
2007	455	15	3.3	1071	21	2.0	1317	50	3.8
2008	416	11	2.6	937	19	2.0	1224	42	3.4
2009	377	7	1.9	806	25	3.1	1148	29	2.5
2010	317	7	2.2	762	19	2.5	1192	36	3.0
2011	331	15	4.5	825	23	2.8	1153	57	4.9
2012	337	10	3.0	821	18	2.2	1163	45	3.9
2013	313	3	1.0	844	30	3.6	1188	40	3.4

2.2.1 Oregon Right-hook Crash Analysis

Hurwitz et al. further explored the bicycle-vehicle crashes reported in the ODOT data from 2007-2011 to identify the characteristics of intersections where right-hook crashes occurred. First, they identified all combinations of vehicle movements that could be typed as a potential right-hook crash (i.e., a through bicycle and a right-turning vehicle) and extracted these from the crash database. Second, at the locations where each of these crashes occurred, design and operational variables were collected (e.g., presence of bike lanes, right-turn lanes and traffic control devices), as well as injury levels. The findings are summarized below (*Hurwitz et al. 2015*).

In Oregon, the reported crash data indicates that the right-hook crash is a common bicycle-motor vehicle crash type at urban intersections. Many of these crashes result in severe injury to the bicyclist. The research reviewed 504 potential right-hook crashes identified from vehicle movement data out of the 4,072 total crashes identified in ODOT bicycle crash data (ODOT, 2011). Identified right-hook crashes accounted for 12.3% of all crashes during this time period. Though it is a frequent crash type, the majority of recorded crashes were moderate (62%) in severity. A further 28% were minor injury and 4% were no injury. Still, 7% of the crashes involved severe or fatal injuries and represent an opportunity to improve bicycle safety. Each right-hook crash was reviewed in detail to identify the type of intersection traffic control and lane configurations. Seventy-four percent of right-hook crashes occurred at intersections and the remaining 26% occurred at driveways. The most common intersection configuration for right-hook crashes was a bike lane to the right of a through motor vehicle lane with no exclusive right-turn lane. This configuration accounted for 59% of total crashes at signalized intersections and 64% of total crashes at minor stop intersections.

2.3 SURROGATE SAFETY MEASURES

Quantification of safety has traditionally been performed by using accident data, which is a reactive approach and has several limitations such as limited sample size, improper records, missing information about causal factors, and randomness associated with accidents. To replace the need for crash data, surrogate safety measures (SSM) have been developed as a more proactive approach based on an observable non-crash event that is related to crashes and can further be converted into a corresponding crash frequency or severity. A SSM identifies the less severe events that occur more frequently in a transportation system as compared to severe accidents, and the frequency of severe accidents is reduced by reducing these less-severe accidents. It is assumed that if an accident countermeasure affects the traffic safety, it should affect its surrogate as well (*van der Horst, 1990*). The following sections will describe common SSM and studies that have been done to test the SSM with bicycle-vehicle interactions.

2.3.1 Traffic Conflict Technique (TCT)

A traffic conflict technique (TCT) is a systematic method of observing and measuring accident potential, where conflicts are defined as the occurrence of evasive vehicular actions and characterized by braking and/or weaving measures. This technique was developed in 1967 by General Motors (GM) to answer the question of whether or not GM cars were relatively less involved in unsafe traffic situations than cars of other manufacturers. This method defined a traffic conflict as any potential accident situation, leading to the occurrence of evasive actions such as braking and swerving. The definition was operationalized by observing the onset of brake lights, lane changes, and traffic violations (*van der Horst, 1990*). Since then, the technique has been refined and observed in a variety of ways that quantify traffic conflicts on a more detailed level.

2.3.2 Swedish TCT

During the 1970s and 1980s at Lund University in Sweden, the Swedish TCT was developed. This method took the idea of TCT and made a distinction between non-serious and serious conflicts. It was determined that a collision course is a necessary condition for a conflict, meaning that at a certain moment, two road users were on their way to collide and an evasive action was required by one or both of them to prevent a collision. Two indicators determined the severity of the collision: Time-to-Accident and Conflicting Speed. Time-to-Accident is the time remaining to a collision when an evasive action is taken by a road user. Conflicting Speed is the speed of the road user when he or she takes the evasive action. The severity of the conflict is higher when the Time-to-Accident decreases and the Conflicting Speed increases. In this study, the serious conflicts had a strong correlation with the number of police-reported accidents (*Laureshyn et al., 2016*).

2.3.3 Time-to-Collision (TTC)

Related to the Time-to-Accident principle in the Swedish TCT, a focus on the Time-to-Collision (TTC) measure was deemed important by Hayward in 1971 to describe the danger of a conflict situation. The TTC is defined as the time required for two vehicles to collide if they continue at their present speed on the same path.

$$TTC = \frac{D}{\Delta V}$$

Where,
D = relative distance
ΔV = relative speed between the two vehicles

The study concluded that the lower the TTC, the higher the collision probability will be (*Laureshyn et. al., 2016*). A later study conducted by Van der Horst evaluated road design elements of bicycle routes, defining a minimum threshold of 1.5 seconds or less to be considered critical for a conflict between a car and a bicyclist (*Laureshyn et al., 2016*).

2.3.4 Post-Encroachment Time

To use TTC as a surrogate safety measure there needs to be a collision course for the road users. However, there can still be situations where a conflict may occur with no collision course, such as when two road users just miss each other at high speed without considerable path or speed change. The post-encroachment time measurement can account for these instances. The PET measure is defined as the time between the departure of the encroaching cyclist from the potential collision point (at the intersection of the two trajectories) and the arrival of the first vehicle at the potential collision point at the intersection, or vice versa (*Gettman et al., 2003*).

$$PET = t_v - t_b$$

Where,
t_v = arrival/departure time of the encroaching cyclist from potential collision point
t_b = arrival/departure time of the first vehicle at the potential collision point

This metric gives a measure of how closely a collision was avoided in the final stage of an encounter (van der Horst, 1990). The lower the PET, the more likely a collision would have been. In urban areas PET values lower than 1 s are considered critical for vehicle-vehicle conflict

(*Laureshyn et al., 2016*). For cyclists, PET values (for each cyclist) are separated into four categories:

- PET ≤ 1.5 s, considered as a *very dangerous interaction*
- 1.5 s < PET ≤ 3s, considered a *dangerous interaction*
- 3s < PET ≤ 5s, considered a *mild interaction*
- PET > 5s, considered as a *no interaction*

PET has often been measured through video analysis (*Zangenehpour et al., 2016*).

2.3.5 Dutch Conflict Technique (DOCTOR)

A technique developed in the Netherlands by the Institute of Road Safety Research and the Institute of Perception determines the probability of a collision by a combination of TTC and PET (*Laureshyn et al., 2016*). This technique is called the Dutch Conflict Technique (DOCTOR). A critical situation in this study is defined as a situation in which the available space for maneuver is less than the space needed for normal reaction. If at least one of the parties involved needs to take action to avoid a collision, the situation is labeled as a conflict. The severity of a conflict is scored on a scale from 1 (least severe) to 5 (collision), taking into account the probability of a collision and the extent of the consequences if a collision had occurred. The extent of the consequences is defined by the type of road and users involved in the conflict, their speeds, as well as the type of maneuvers performed. For example, a conflict between a car and a cyclist may produce much more serious consequences than a conflict between two cyclists. This technique does contain a subjective component because the observer has to determine the behavior of the road users as controlled or uncontrolled, and what the extent of the consequences would have been if a collision had taken place.

2.3.6 Probabilistic Surrogate Measures of Safety (PSMS)

A second technique that combines the TTC and PET measures is the Probabilistic Surrogate Measures of Safety (PSMS). Unlike traditional TCTs that rely on motion prediction along a vaguely defined "planned" course, this technique considers all possible paths that may lead two road users to collide. To predict the motion of the road users, it is important in this technique to select a motion prediction method. There are two categories that can be distinguished: context-free kinematic methods and methods based on observed motion patterns. Once a motion prediction method is chosen, a road user's future positions with respective probabilities can be estimated. Potential collision points and crossing zones are identified with their respective probabilities, as well as TTC for a collision point (i) at the instant in time (t) and predicted PET. Road users are said to be on a collision course at the instant in time (t) if the set of potential collision points is not empty, and therefore a traffic conflict can be computed (*Laureshyn et. al., 2016*). Another important component in this approach is the automation, as road user trajectories must be extracted automatically from video data to make the application feasible. For this particular study, only a subset of the large video dataset collected was processed due to the computational time of video analysis and motion prediction.

Table 2.2 summarizes the key studies that focus on surrogate safety measures, and Table 2.3 summarizes the advantages and disadvantages of each surrogate measure.

Table 2.2: Key Studies of Surrogate Safety Measures

Surrogate Type / Author	Location	Objective	Type of Analysis	Data Collected	Research Findings
Traffic Conflict Technique (TCT)					
General Motors TCT, *Perkins and Harris (1967)*	Warren, MI	Answer the question of whether or not GM vehicles were less involved in unsafe traffic situations than other car manufacturers	Observation	Observations of a traffic conflict as any potential accident situation, leading to the occurrence of evasive actions, such as braking and swerving	A generally applicable observation technique
Swedish TCT, *Laureshyn et al., (2016)*	Norway	Comparing traditional methods for surrogate safety analysis	Semi-automated video analysis	Manual detection and counting of critical events	Show similarities and are "compatible" with accident records, agrees well with DOCTOR for number, type, and location of conflicts
TTC, *Hayward, (1971)*	Washington, D.C.	Searching for a more objective way to describe the danger of a conflict situation	Quantitative analysis of film pictures	Minimum TTC values during the approach of two vehicles on a collision course	A minimum TTC value of 1.5 seconds for defining a conflict between a car and a bicyclist
Post-Encroachment Time					
PET, *Zangenehpour, (2015)*	Montreal, Canada	Determine if signalized intersections with cycle tracks are safer using surrogate safety analysis	Video analysis	Cyclist and motor-vehicle interactions defined from video, then ordered logit models with random effects were developed to evaluate the safety effects of cycle tracks	Intersection approaches with cycle tracks on the right are safer than intersections with no cycle tracks. Intersections with cycle tracks on the left compared to no cycle tracks were significantly safer.
Combination of TTC and PET					
DOCTOR, *Laureshyn et al., (2016)*	Norway	Comparing traditional methods for	Semi-automated video analysis	Manual detection and	Show similarities and are

		surrogate safety analysis		counting of critical events	"compatible" with accident records, agrees well with DOCTOR for number, type, and location of conflicts
PSMS, *Laureshyn et al., (2016)*	Norway	Comparing traditional methods for surrogate safety analysis	Automated video analysis	Automated tracking of road users in videos, considers the probabilities of multiple trajectories for each interaction – delivers a density map	Show similarities and are "compatible" with accident records, reported many more safety-relevant interactions including less severe events

Table 2.3: Advantages and Disadvantages of Surrogate Safety Measures

Crash Surrogates	Advantage	Disadvantage
General Motors TCT	• Simplicity of application	• Set of conflicts is too large to guarantee a close relationship with crashes
Swedish TCT	• Compatible with accident records	• Contains a subjective component
TTC	• Can be calculated for every scenario	• All road users will have a TTC value, whether there is a probability of collision or not
PET	• Used commonly at intersections	• Not useful on a segment
DOCTOR	• Compatible with accident records	• Contains a subjective component
PSMS	• Tracks all possible trajectories	• May include a significant share of false alarms

The technique used in this paper was post-encroachment time (PET). This is because the PET measurement is most useful at intersections where all interactions of interest involve the road users' paths crossing one another, and therefore could always be calculated in this study. PET can also be measured through video analysis, which was most appropriate for the technological resources available to the research team.

2.4 SIGNAL TIMING TREATMENTS

From a traffic operations perspective (signal timing), there are several options available to mitigate right-hook crashes at signalized intersections. Treatments at traffic signals, such as leading bicycle intervals (LBI), exclusive bicycle intervals (EBP), and a newer treatment called the split LBI are all used today. These treatments are designed to reduce conflicts with bicyclists and turning vehicles. Outside of the realm of safety improvements, there is little research on the efficiency impacts of these treatments. Each treatment will be explained in the following sections.

2.4.1 Traditional Phasing

The Manual on Uniform Traffic Control Devices (MUTCD) defines a signal phase as the right of way, yellow change, and red clearance intervals in a cycle that are assigned to an independent traffic movement or combination of traffic movements (*FHWA, 2015*). The movements served at an intersection can be categorized by the various users: vehicles, pedestrians, bicyclists, and transit. Traditional phasing allows non-conflicting movements to be served simultaneously. Traditional phasing typically doesn’t provide separate phasing for bicyclists, instead the signal phasing for bikes is provided concurrently with through vehicle traffic, as shown in Figure 2.3. Therefore, the right-hook crash potential is not addressed with traditional phasing.

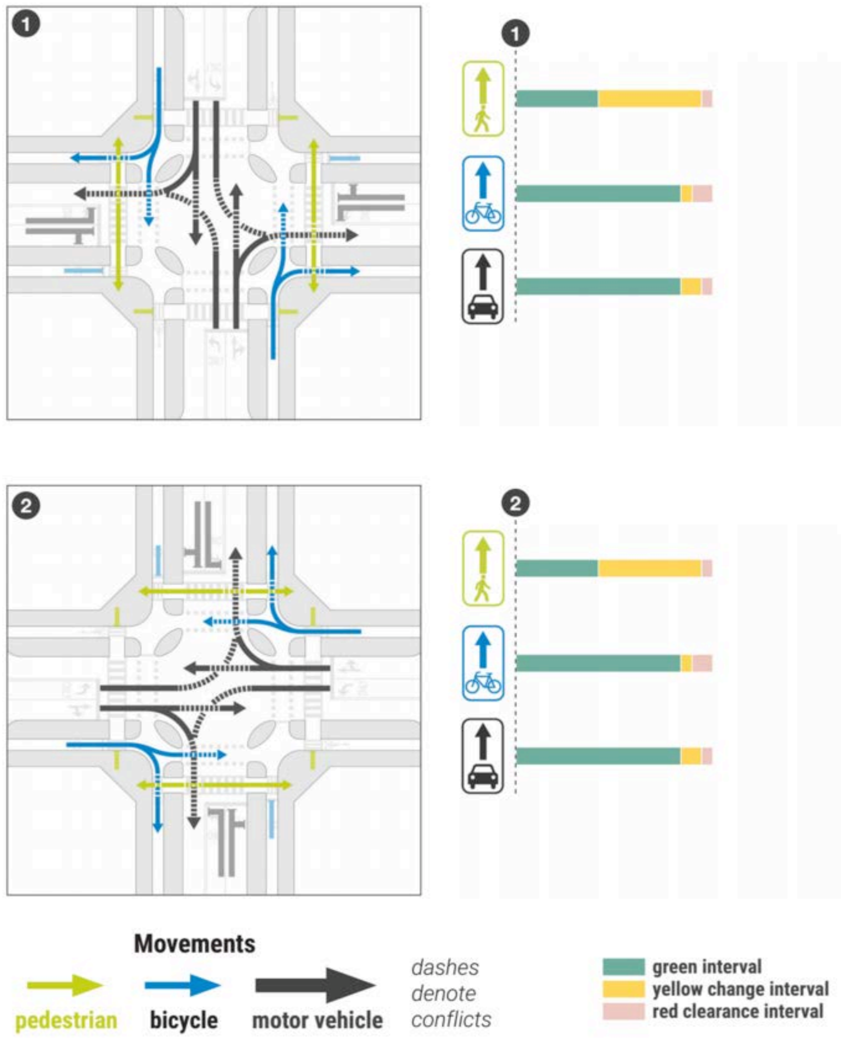


Figure 2.3: Traditional Concurrent Phasing

(Source: MassDOT, 2015)

2.4.2 Leading Bike Interval (LBI)

A leading bicycle interval (LBI) is a scenario where bicyclists are given a head start (usually around five seconds) at a signalized intersection in order to mitigate the conflicts associated with right-hook type crashes. The greatest advantage of this treatment is that the bicyclists are able to establish themselves in the intersection (and in the driver's visual field), thereby reducing the probability of a collision. In order to achieve this head start, the bicyclist is given a green indication before the vehicles in the corresponding approach. A lead interval may provide three to seven seconds of green time for bicycles prior to the green phase for the concurrent vehicle traffic (*MassDOT, 2015*). Figure 2.4 shows an example of the LBI.

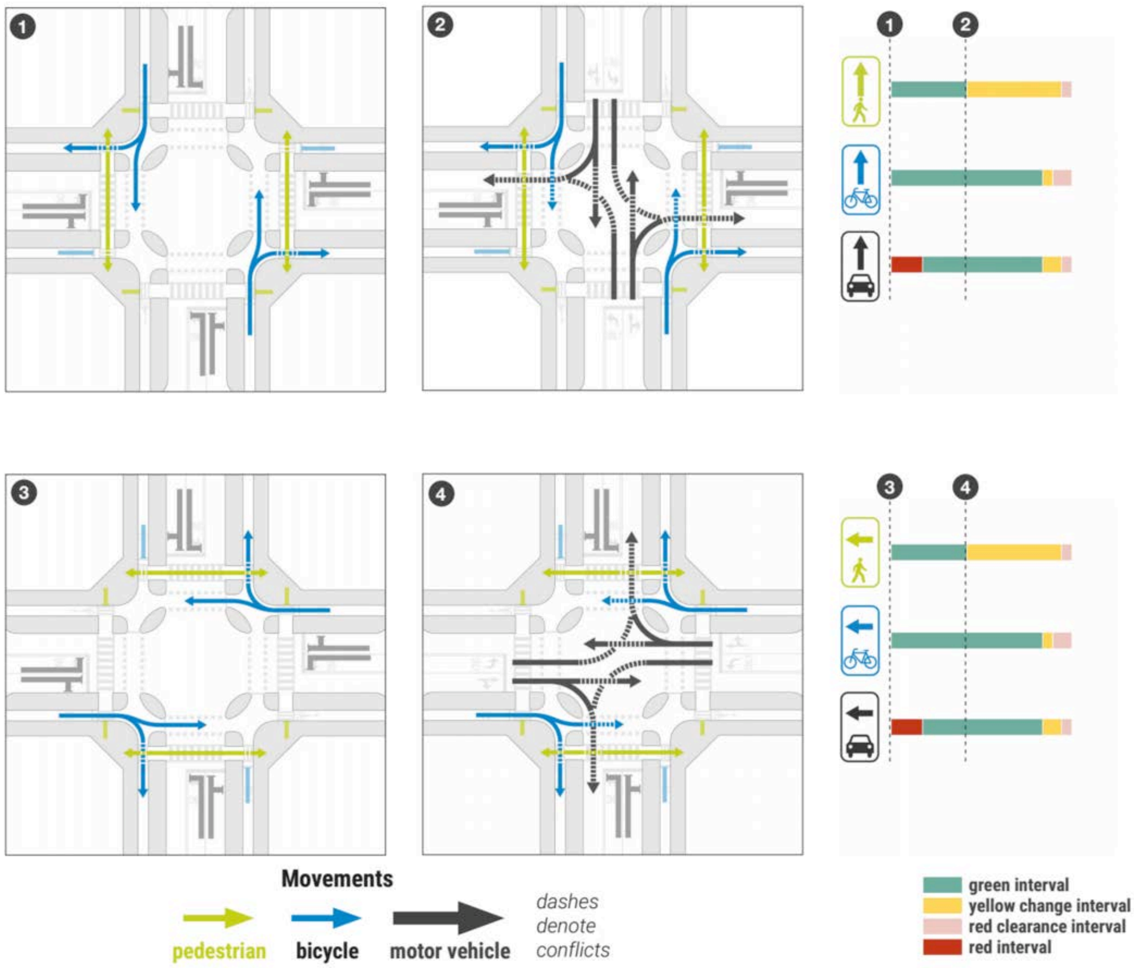


Figure 2.4: Leading Bicycle Interval

(Source: MassDOT, 2015)

Signal indications for a LBI are shown in Figure 2.5. During the first portion of the green phase, bicycles and pedestrians are allowed to enter the intersection while the through vehicle traffic and turning vehicles are restricted by red. The second portion follows with a permissive turning phase where the turning vehicles are controlled by a green arrow but are still expected to yield to bicycles and pedestrians. The bicycles, pedestrians and through traffic continue to have the green or walk indication.

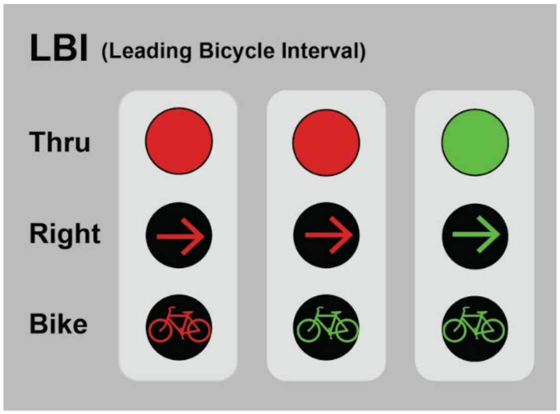


Figure 2.5: Leading Bicycle Interval Signal Phases

2.4.3 Split Leading Bike Interval (Split LBI)

A variation on the LBI is the split LBI, which is the same basic scheme but instead of stopping all the vehicles, only the conflicting right-turn movements are stopped. This has the same advantages as the LBI, with the addition of allowing the through movements to proceed without an increased delay from the treatment. An example can be seen in Figure 2.6.

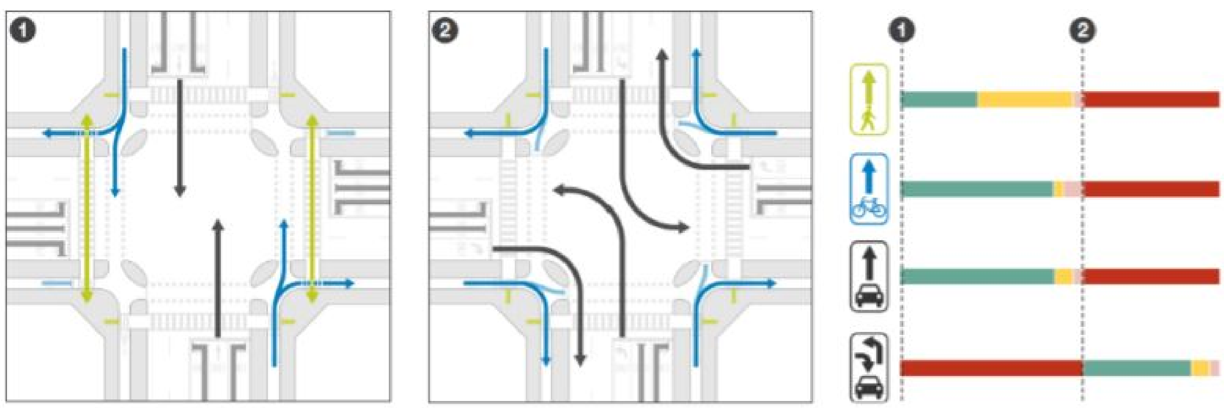


Figure 2.6: Split Leading Bicycle Interval

The typical operation of a split LBI is shown in Figure 2.7. During the first portion of the green phase, the through vehicle traffic, bicycles and pedestrians are allowed to continue through the intersection whereas the turning vehicles are restricted by a red indication. The second portion follows with a permissive turning phase where the turning vehicles are controlled by a flashing yellow arrow and required to yield to bicycles and pedestrians. The bicycles, pedestrians and through traffic continue to have the green or walk indication.

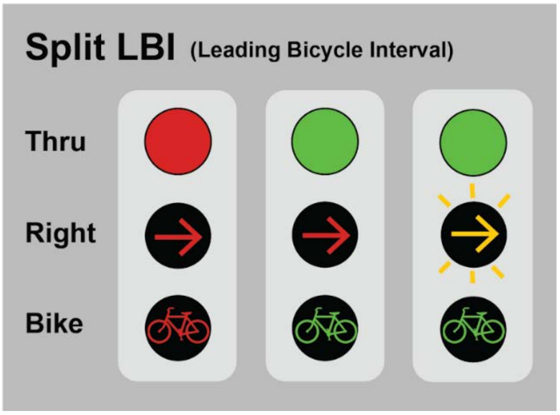


Figure 2.7: Split Leading Bicycle Interval Signal Phases

It is important to note that both the LBI and split LBI require that motor vehicles comply with right-turn-on-red restrictions. Unfortunately, motor vehicle operators have demonstrated a low level of compliance for obeying right-turn-on-red restrictions (*Preusser et al.*, 1981). Advances in regulatory signage have helped reduce these conflicts (*Paulsen et al., 2016*), but the need for the LBI and split LBI treatments remain.

2.4.4 Exclusive Bicycle Phasing (EBP)

The final treatment is an exclusive bicycle phase (EBP), which is a type of phasing where all traffic is stopped and bicycles are allowed unrestricted access to the intersection (similar to an exclusive pedestrian phase, also called a Barnes dance or pedestrian scramble). This signal timing treatment reduces potential for conflicts between bicyclists and vehicles; however, it does increase delay within the intersection. The EBP is often used when safety concerns dictate the need for complete separation of bicycles and vehicles, and to improve bicycle operations. An example can be seen in Figure 2.8 below.

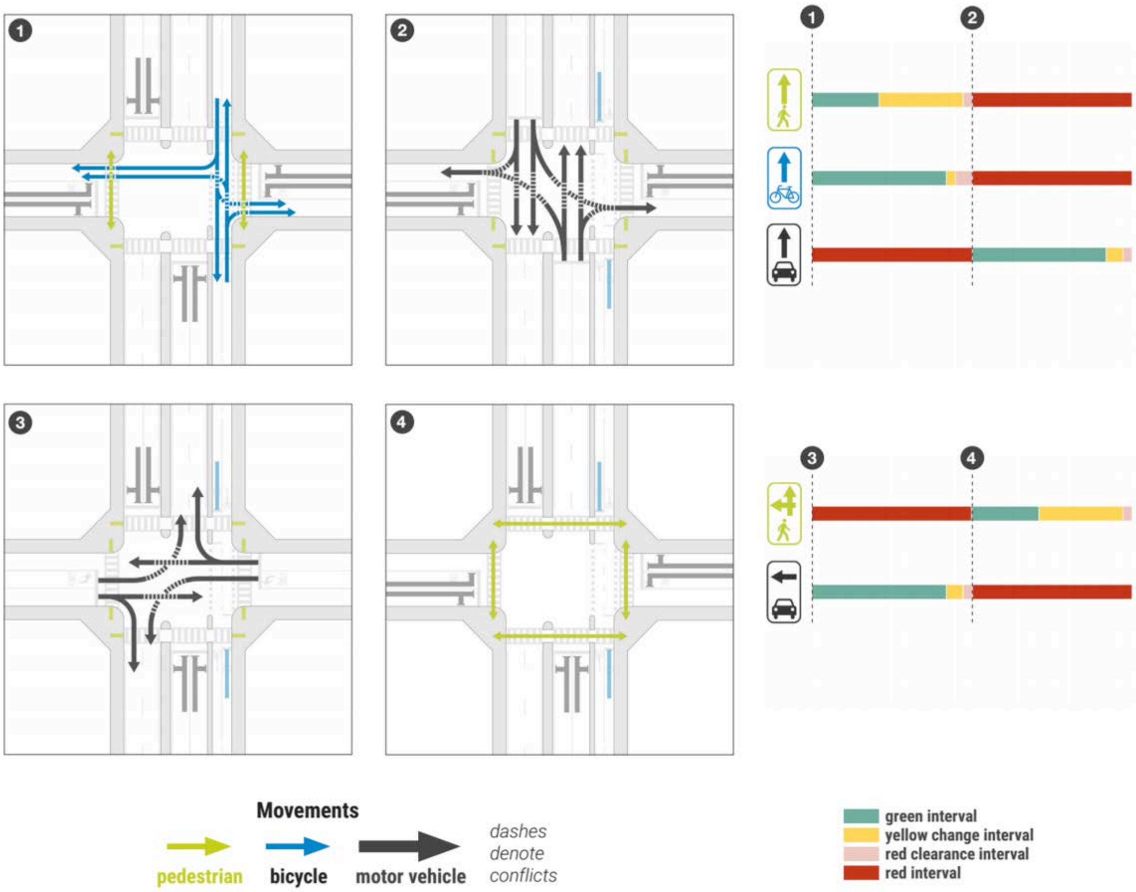


Figure 2.8: Exclusive Bicycle Phasing

(Source: MassDOT, 2015)

2.5 MIXING ZONES

A mixing zone is an area where the turning vehicles are expected to yield and cross paths with a bicyclist in advance of an intersection (*MassDOT, 2015*). This treatment is intended to minimize conflicts with turning vehicles at intersections and can be considered as an alternative to an exclusive bike signal phase (*NACTO, 2014*). This treatment can reduce motor vehicle speed in the turn lane and reduce the risk of right-hook conflicts at intersections. This treatment is typically used in locations where there is not enough space to include a right-turn lane and a bicycle lane at the intersection, or at locations where a right-turn lane is not present but there is risk of conflicts between turning vehicles and bicyclists. The merge point is recommended to be located as close to the intersection as possible, so that vehicular speeds are lower in that area (*MassDOT, 2015*). Figure 2.9 shows a graphic of two types of mixing zones. The figure on the left is a design where drivers and bicyclists cross paths to reach a right-turn lane and a bike lane, respectively. The figure on the right allows the motor vehicles and bicycles to share the same lane.

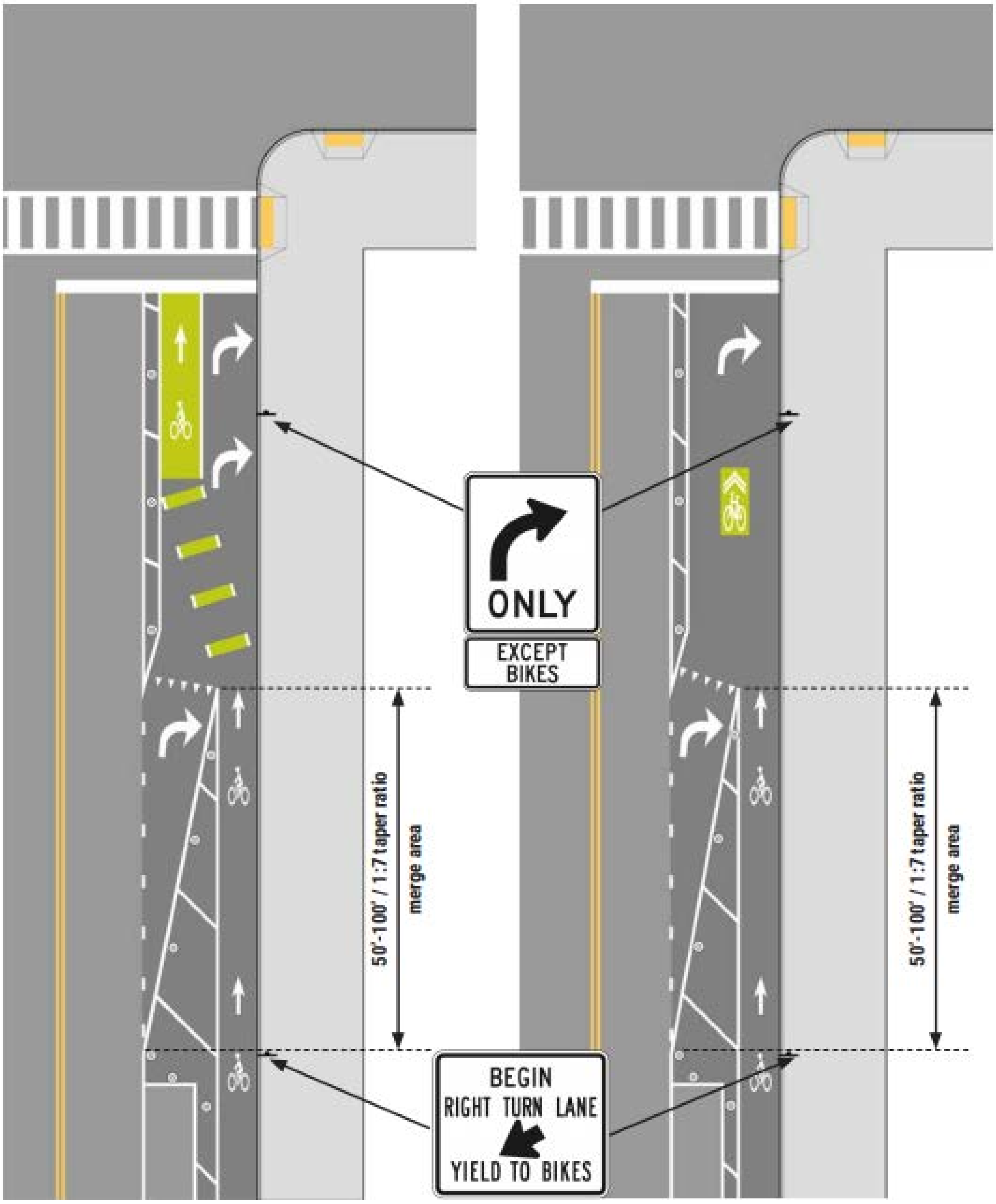


Figure 2.9: Mixing Zones

(Source: MassDOT, 2015)

Monsere et al. studied five designs for protected bike lanes at intersections, which included mixing zones(*Monsere et al., 2015*). Video analysis for the mixing zones with yield markings revealed that while 93% of the turning vehicles used the lane as intended, only 63% of the observed bicycles correctly used the mixing zone. Additionally, their findings also revealed that 1% to 18% of vehicles at mixing zones also turned from the wrong lane. Monsere et al. also found that the perception of safety for cyclists appeared to be influenced by the volume of turning motor vehicle traffic (*Monsere et al., 2015).*

2.6 PRACTITIONERS SURVEY

A survey was developed for practitioners by the research team to understand the awareness of bicycle-specific signal control strategies and their implementation across various jurisdictions around the country. This survey was administered online and was designed to gather information on three types of bicycle control treatments – protected bicycle phases, LBIs, split LBIs and one pedestrian control treatment – LPI. The questions asked for specific locations where these treatments were implemented; reasons for their implementation; geometry of approach; average vehicle and bicycle (or pedestrian) traffic at the location(s) where it was implemented; seconds of leading interval provided; and evidence of reduction in crashes/conflicts. Participants were solicited from the Transportation Research Board's Traffic Signal Systems Committee (AHB25), the Association of Pedestrian and Bicycle Professionals and the Institute of Transportation Engineers listserv.

The survey garnered 69 complete responses as shown in Figure 2.10. Sixty-five percent of the survey respondents reported themselves as engineers, 18% as planners, 4% as researchers and 13% were categorized as other.

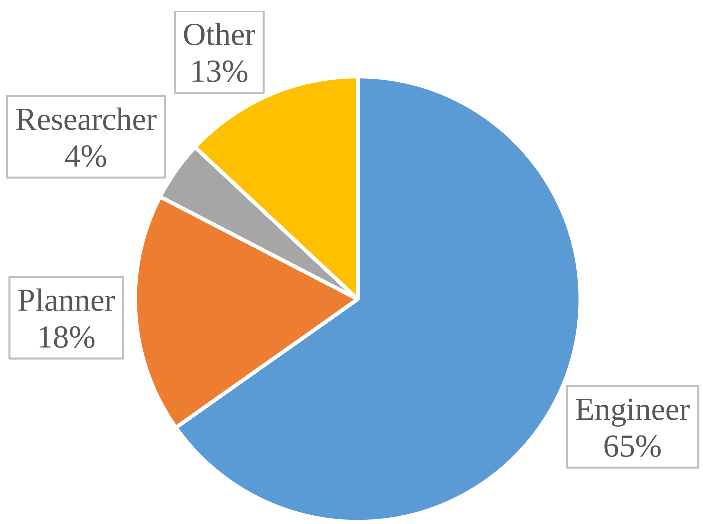


Figure 2.10: Distribution of Practitioner Survey Respondents

Figure 2.11 shows the distribution of control strategies. Twenty-eight respondents indicated that they had not implemented any of the signal timing strategies. While 27 respondents indicated that they had implemented a protected bike phase, they did not provide any detailed information regarding that phase.

Twenty-eight respondents had implemented a LPI with 3-8 seconds of leading interval. At the locations where the LPI was implemented, pedestrian traffic ranged from less than 400 to 15,000 pedestrians per day. Two intersections had vehicle volumes below 10,000 ADT. The remaining 17 intersections saw vehicle volumes ranging from 10,000 to 70,000 ADT. All respondents either had no data on efficacy, had only anecdotal evidence or relied upon short periods of observation by a qualified person. Two concerns were expressed by one respondent with the LPI at two intersections. One was that their LPI placed pedestrians directly in the path of left-turning vehicles once a green was given to the vehicles. Another complaint was from drivers who mistakenly assumed pedestrians would not be crossing because their signal was red, only to have the pedestrian step out possibly after a right turn on red was initiated by the vehicle.

Ten respondents indicated that they were aware of LBI implementation by their agency. Respondents stated that LBIs were implemented with 3-6 seconds of leading interval at intersections with high bicycle volumes. Two stated reasons for implementing a LBI were an intersection with offset geometry and a bicycle lane positioned to the right of a shared right/through travel lane. One respondent provided volume data for their installation: 10,000 vehicular ADT and 1,000 bicycles per day. No respondents had data on the efficacy of the treatment.

Approximately half of all respondents (52%) were aware of the split LBI strategy. Only one respondent had implemented a split LBI. The split LBI implementation used five seconds of leading interval at an intersection with a high volume of vehicular turning movements opposing through bicycle traffic. No information was available on bicycle or vehicular traffic volumes. No data was available on the efficacy of the treatment.

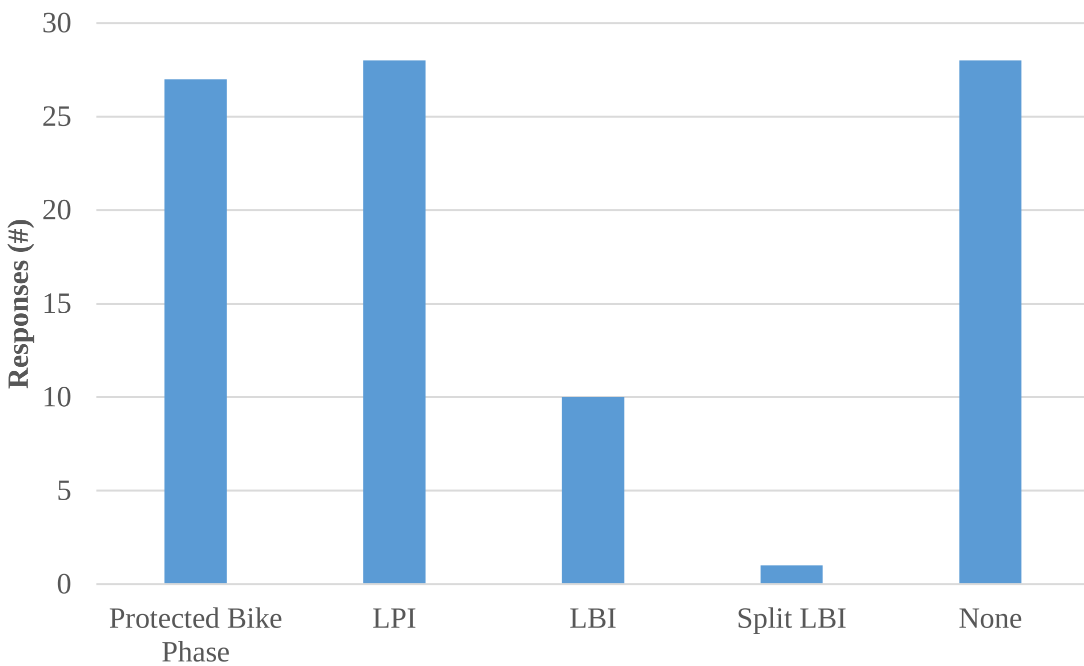


Figure 2.11: Distribution of Control Strategies

2.7 SUMMARY

This chapter presented a review of the right-hook crash types, followed by a brief analysis of the bicycle crashes in Oregon, New York and Arizona. The review revealed that bicyclist fatalities in all three states accounted for 2-4% of the total fatalities. Previously conducted reviews of the Oregon crash data revealed that right-hook crashes were a common type of bicycle-vehicle crashes at intersections. Commonly used surrogate safety measures including TTC and PET were reviewed, followed by signal timing strategies to mitigate right-hook crashes. Concurrent phasing, LBIs, split LBIs, and exclusive bicycle phasing are signal timing strategies that are commonly used in practice. The chapter ends with findings from a practitioner survey that was conducted to assess the state of the practice with respect to signal timing strategies for bicyclists. The survey revealed that while LPI is a well-known strategy and implemented for improving pedestrian safety, bicycle safety strategies such as LBI and split LBI are less popular for implementation.

3.0 SIMULATION

A number of tools have been developed for analyzing traffic. Traffic analysis tools are typically grouped into analytical and simulation models. Analytical models use mathematical formulations to determine traffic states (capacity, density, speed, delay and queuing) on facilities (*Akcelik, 2007*). These tools are specifically suited for analyzing small-scale facilities. Simulation models are often used to model traffic flows in a network. These models can be multimodal in nature and are used to model the interactions between different modes on a transportation network. These tools are useful in evaluating design alternatives and for decision-making purposes. There are three categories of simulation models – macroscopic, mesoscopic and microscopic models. In macroscopic models, the simulation takes place on a section basis, without explicitly considering individual vehicles. Some well-known examples of macroscopic simulation models are PASSER, SYNCHRO, TRANSYT and TRANSYT7F. Mesoscopic models are a blend of macroscopic and microscopic models. Microsimulation models model the movement of individual vehicles in the traffic stream based on car-following and lane-changing models. The most popular among these are PARAMICS, AIMSUN, VISSIM, SIMTRAFFIC and CORSIM.

Microsimulation models are being increasingly used as an analysis tool worldwide. The advantages of microsimulation models are their ability to model systemwide impacts of alternatives and various geometric configurations. While these models can provide detailed statistics, there are a few issues worth noting. These models often require large amounts of data and the accuracy of data inputs into the simulation model affects the precision of results. These models also need to be properly calibrated and validated to yield accurate results. Some degree of user skill is also required to build a representative model.

In this research, VISSIM microsimulation software is used to model the interactions between vehicles and bicycles on an urban street network to evaluate the impacts of various signal timing strategies on user delays for all modes. The following sections describe the steps taken in model development, calibration and validation.

3.1 MODEL DEVELOPMENT

In order to assess the impacts of treatments (LBI, split LBI and EBP) on all users at a signalized intersection, microsimulation was utilized. PTV's VISSIM was chosen because of its flexibility with modeling bicyclists and pedestrians, in addition to passenger vehicles and heavy goods vehicles (HGV), and for its ability to perform software-in-the-loop (SITL) simulation. The Econolite ASC/3 was chosen as the signal controller in the SITL environment for its programmable logic controller.

3.1.1 Site Selection

The study location was chosen with input from project partners and included three intersections along the major east-west arterial of SE Division Street in Portland, OR. Three intersections along the corridor, 119th Avenue, 122nd Avenue and 130th Avenue, were modeled. Figure 3.1 shows the study location within the broader Portland area.

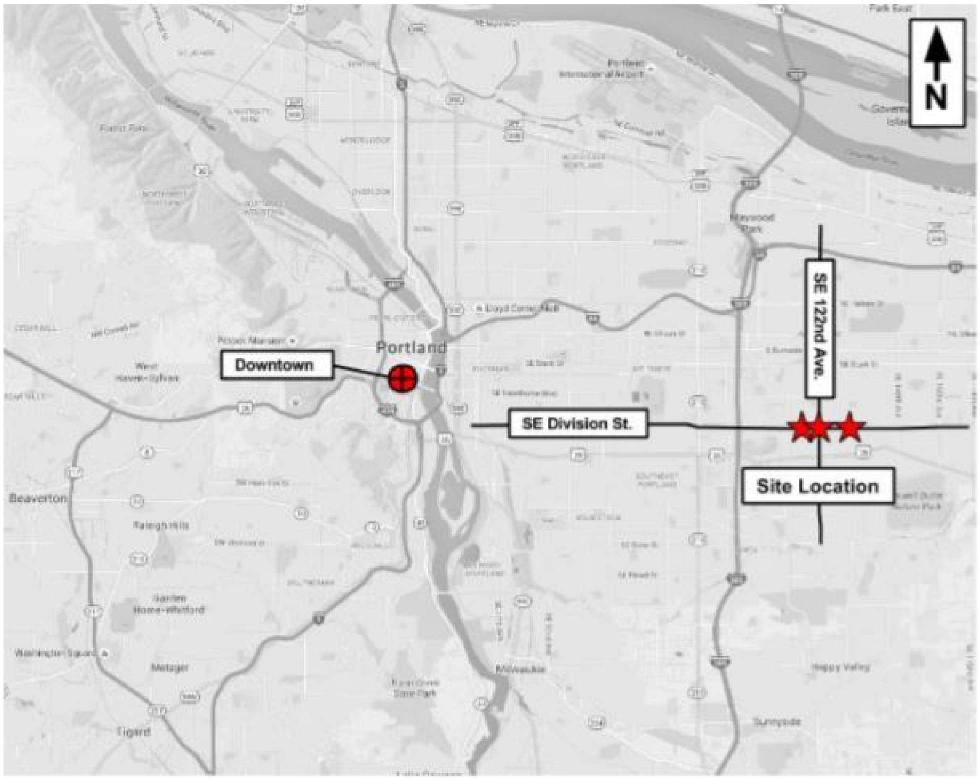


Figure 3.1: Study Location in Portland, OR

These three intersections were chosen for their geometric characteristics, the ability to perform actual field implementation, and for the intersections' location within a high crash corridor (*Portland Bureau of Transportation*, *2014*). Figure 3.2 shows the study corridor and the intersections as they currently exist. This study focused on 122nd and Division exclusively, but retained the broader network in order to increase the realism of the simulation.

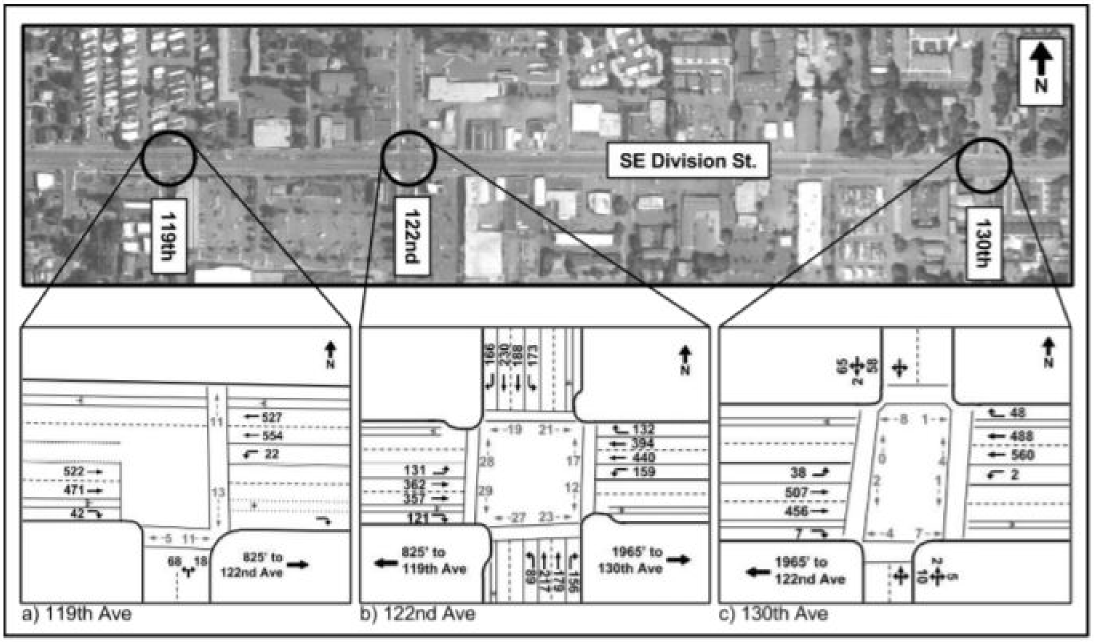


Figure 3.2: Realworld Intersection Geometry and Traffic Volumes

3.1.2 Inputs to the Model

3.1.2.1 Geometry

The geometric information used to build the model was obtained from several sources. Street and intersection locations, as well as placement of lanes and crosswalks, were developed using the background mapping (Bing Maps) option that is part of the VISSIM software. Lane widths were found using the measuring tool in Google Maps, and were between 10-12 feet for all vehicle lanes, 5 feet for bicycle lanes, and 10 feet for crosswalk widths, which were coded as two 5-foot parallel lanes each running in the opposite direction (north and south, for example).

In order to model the conflicts between right-turning vehicles and bicycles, the geometry of SE Division and 122nd was modified from its actual state. First, the eastbound approach was changed from an alignment where the bicycle lane was in-between the through lane and the right-turn lane, to one where the bicycle lane was to the right of the right-turn lane. This was done to simulate the split LBI treatments. In normal practice, the bike lane is typically to the left of the right-turn lane, in the absence of a bike signal. The westbound approach was also changed from a dedicated right-turn lane (which was a shared lane with bicycles and vehicles) to a version where the dedicated right-turn lane was eliminated. In its place the bicycle lane was extended to the stop bar, and the right-most through lane was converted to a shared through/right-turn lane for vehicles. Figure 3.3 shows these modifications.

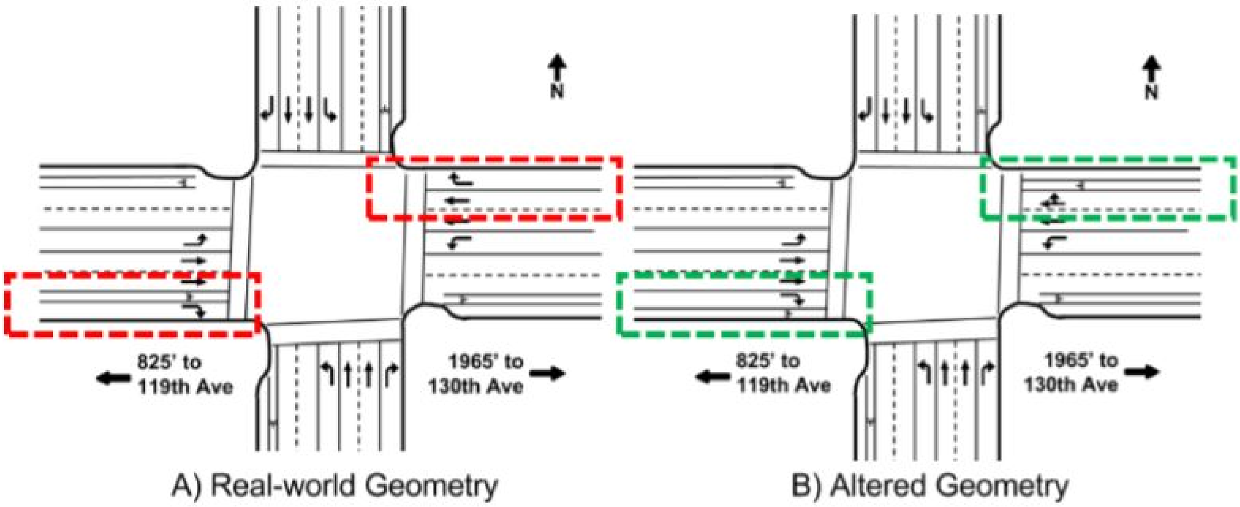


Figure 3.3: Modified Intersection Geometry

3.1.2.2 Vehicle Volumes

In order to simulate the treatments of the coordinated base case, LBI, split LBI and EBP, VISSIM required the user to input traffic volumes, vehicle types and speeds. Traffic volumes and vehicle compositions were obtained from Quality Counts, a traffic data collection firm. The data collection was performed on Tuesday Sept. 22, 2015, and included 24-hour tube counts (including vehicle classification and volumes) as well as turning movement counts from 11 a.m. to 1 p.m. (which included bicycle and pedestrian counts) at all three intersections.

The results of this data collection showed a total average daily vehicle count of ±18,000 veh/day. Figure 3.2 shows the volumes during the study time interval (with the volumes remaining the same despite the geometric changes). HGVs varied between 3-10% for the corridor. Pedestrian volumes were 184 at the peak 15-minute period from 12:45 p.m. to 1 p.m. at 122nd, while bicycle counts totaled three for the same period.

The Quality Counts data had two aspects that required modification for modeling: Many bicycle movements were unused during the count (listed as zeros in the tally), and the pedestrian data was recorded only for the crosswalk used but not the pedestrian's direction of travel. The bicycle volumes in the Quality Counts data were so low that many of the movements had zero bicyclists, while the others had as little as one bicyclist. To remedy this a sensitivity analysis was devised (see Section 3.2.5 below).

Pedestrians used in VISSIM microsimulation require detailed information on their movements for proper coding, and this includes not only the crosswalk used but also the direction of crossing. The pedestrian movement data collected by Quality Counts only coded the number of pedestrians using each crosswalk (for example, the north side had 37 crossing, but no directional data), meaning that counts in each direction were not available. To resolve this discrepancy, video data from a prior traffic count at the intersection that was done in June 2015 was used. In the previous traffic count, video data was recorded for a 24-hour period and the pedestrians' crossing movements were observed and tallied. These results included the direction of the pedestrian movement; for example, crossing from east to west or from west to east. Those directional ratios from the previous pedestrian movement study were then applied to the Quality Counts pedestrian count data, thereby giving a reasonable estimate for the number of pedestrians crossing in a given direction.

3.1.2.3 Speeds

VISSIM uses mathematical distributions for speed as defined by the user. Table 3.1 shows the posted speeds for the streets in the model, the distribution used for each of those streets, and the speed distribution for each mode type. It was also assumed that right-turning vehicles make the turn at 9 mph, while left-turning vehicles went 15 mph.

Table 3.1: Speeds in Model

	SE Division	***SE 119th***	***SE 122nd***	***SE 130th***
Posted Speed (mph)	35	25	35	25
VISSIM Speed Distribution Range (mph)	33-37	33-37	23-27	23-27
	Car	***HGV***	***Bicycle***	***Pedestrian***
Speed Distribution by Mode (mph)	*By Speed Limit*	*By Speed Limit*	*8-12*	*3-5*

Transit operations, though present in the field, were excluded from the models in order to simplify the total number of variables that would influence the study. In addition, no vehicle occupancy data was obtained and, therefore, vehicle occupancy was assumed to be one person per vehicle.

3.1.2.4 Driver Behavior

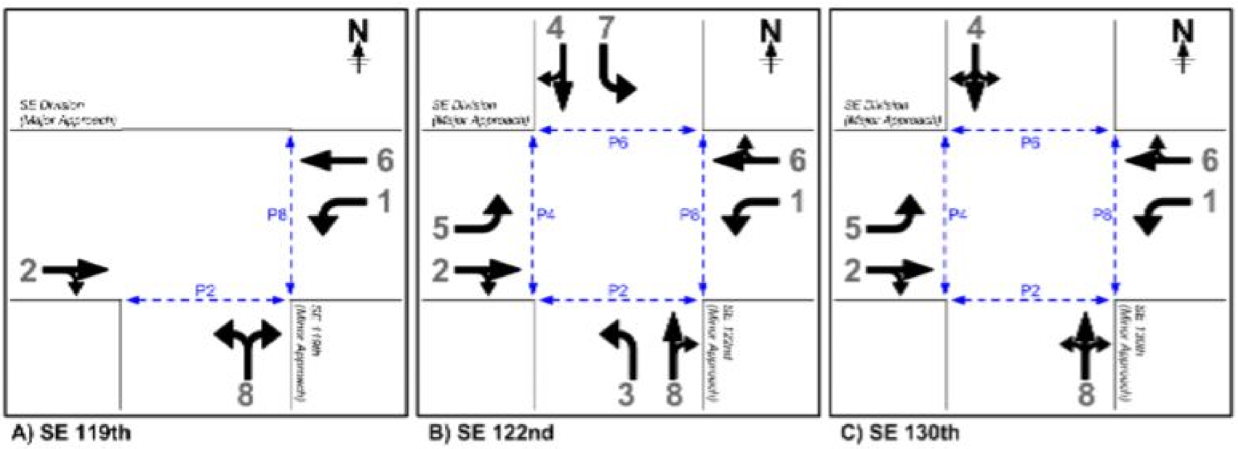
VISSIM utilizes mathematical functions to model the behavior of users (pedestrian, bicycle, vehicle) in the simulation (PTV Group, 2014). These include behavioral factors such as lane changing, lateral motions and actions related to traffic signals, including the way a vehicle behaves at an amber indication (called "Behavior at Amber"). Default settings in VISSIM were used for all behaviors with the exception of Behavior at Amber (see Section 3.1.2.6.1 below).

3.1.2.5 Signal Control

All three of the intersections in the study were signalized. Timing plans, detector plans, and other pertinent information were provided by the Portland Bureau of Transportation (PBOT). For each of the treatments Synchro Traffic Modeling software was used to develop the coordination specifics, including the timing splits and offsets. An additional alteration was the use of the Econolite ASC/3 controller in place of the Type 2070s and

170s with Voyage and Wapiti software that were present at the intersections. This was done to take advantage of a native programmable logic controller (PLC) present in the ASC/3, which was used for the implementation of the bicycle-specific treatments.

The intersection at SE 119th is a T-intersection and used phases 1, 2, 6, and 8. It has no north-side approach (Figure 3.4A); as such it also lacked the eastbound left-turn lane (Phase 5), the westbound right-turn lane (Phase 6 right turn), the northbound through lane (Phase 8 through), and lacked two of the pedestrian crossings. Figure 3.4B shows the phase diagram for the intersection of SE Division and 122nd, which was as standard 8-phase intersection where phases 2 (eastbound) and 6 (westbound) were the major phases, while phases 4 (southbound) and 8 (northbound) were the minor phases. As shown in Figure 3.4C, 130th used a 6-phase configuration, lacking the dedicated left-turn phases on the minor approaches and the right-turn lanes on the major approaches compared to 122nd.



(A) SE Division and 119th (B) SE Division and 122nd (C) SE Division and 130th

Figure 3.4: Intersection Phase Diagrams

All right-turn movements at the intersection allowed a right turn on red (RTOR), except during the time the LBI and split LBI treatments were active (see 3.1.2.6.1). Another notable change to the signalization along the study corridor was the development of a coordination scheme. The study corridor is not normally run in coordination where all three intersections, 119th, 122nd and 130th, would be coordinated with each other. In practice the intersection of 119th and Division is coordinated with the intersection of 112th (which was not included in the study corridor), the intersection of 122nd is set to free, and the intersection of 130th is coordinated with 136th (which was not included in the study corridor). The intersection of Division and 122nd is operated in a free mode, as the volumes on both streets are fairly similar.

The change was made to compare the impacts of the treatments against the coordinated base case, which is why all three intersections were placed in coordination with each other.

For the coordination scheme a cycle length of 110 seconds was chosen. The cycle length varies at 122nd and Division throughout the day, allowing for responsive operation during peak hours. A 110-second cycle length was used to correlate with the common cycle length during the pedestrian peak hour of ±12 p.m., which at that time of day runs at roughly 110 seconds.

3.1.2.6 Modifications for Specific Treatments

3.1.2.6.1 Leading Bicycle Interval and Split Leading Bicycle Interval

The LBI and split LBI required the use of a special setup in VISSIM. Several elements were added to the model or changed to accommodate the treatments. These include: an additional set of signal heads to control traffic during the LBI (termed "Delay Gates"); the use of a PLC; an alteration to the way vehicles interact with an amber indication; and the alteration of the bicycle volumes present at the intersection of 122nd. Each of these will be explored in depth below, beginning with the Delay Gates.

3.1.2.6.2 Delay Gates

In practice, LBI and split LBI treatments require a method to control right-turning traffic during the treatment itself. Often this is achieved by using signage, such as "No Turn on Red" signs, or by using dynamic regulatory signage (Figure 3.5). Since VISSIM does not offer a conditional RTOR setting, a separate system was devised to enforce the LBI and split LBI treatments. This system involved the creation of a second set of signal heads that, in effect, mimicked a dynamic regulatory right-turn sign.

Figure 3.5: Dynamic Regulatory Signage (U.S. Department of Transportation: Federal Highway Administration, n.d)

These new signal heads were termed "Delay Gates" and their setup in VISSIM can be seen in Figure 3.6 below. The system used the PLC present in the ASC/3 to change the indication of the Delay Gate from a rest state of green to red during the five seconds of LBI or split LBI.

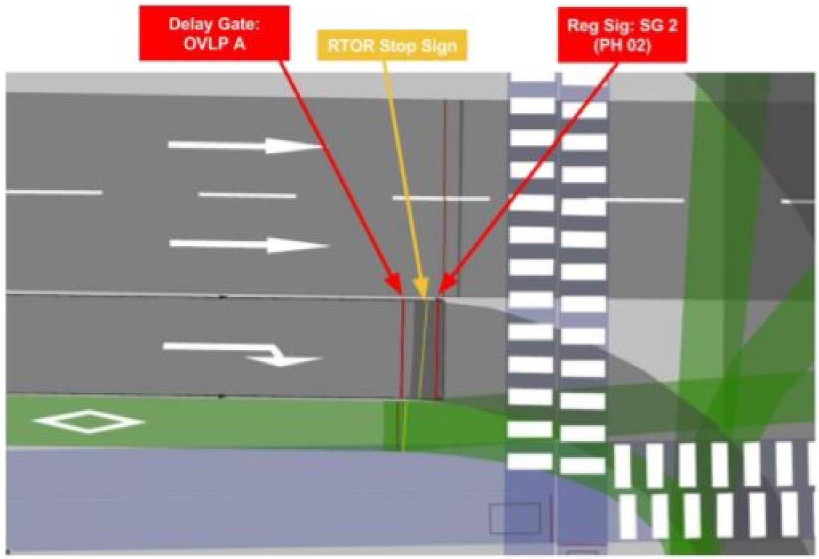


Figure 3.6: Delay Gate Setup in VISSIM

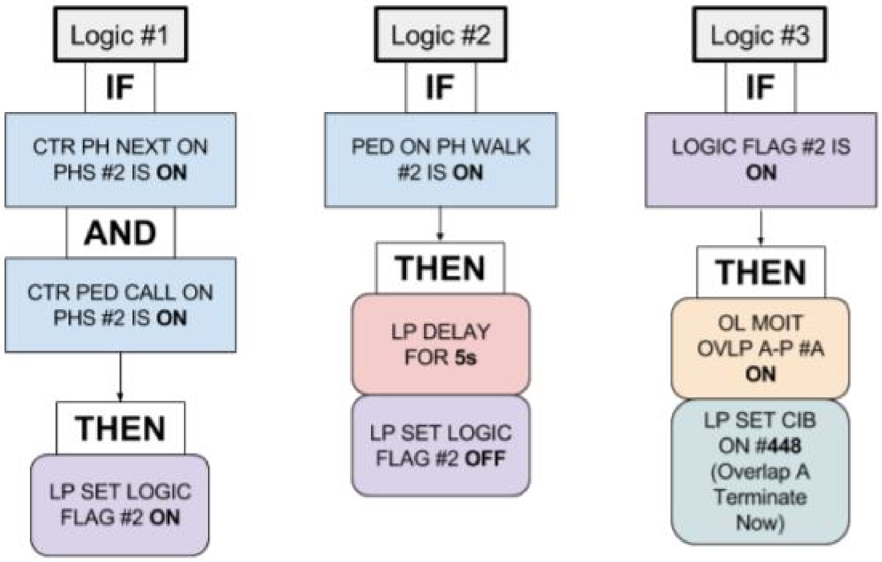
These Delay Gates effectively simulated dynamic regulatory right-turn signage. Both eastbound and westbound used the same basic scheme but applied to different lanes as appropriate to the LBI or split LBI. The Delay Gate was placed in the eastbound right-turn lane for the split LBI, and the westbound through and shared through/right-turn lanes for the LBI. They were located slightly upstream of the main vehicle signal head and the RTOR stop sign. They operated by turning red only during the LBI, thereby restricting the vehicle movements from proceeding in their regular path, especially from making right turns (i.e., potential right hooks). The gates were assigned to Overlaps A (phase 2) and C (phase 6).

The LBI operated in the following sequence (See Figure 3.8): First the regular signal heads turn from green to amber to red at the end of their phase. Just before the start of the vehicle phase, the Delay Gates turns from green to amber to red (thus beginning the LBI/split LBI). Quickly thereafter the regular signal heads turn green (starting the vehicle phase); however, the vehicles are restricted by a red Delay Gate. After five seconds, the Delay Gate turns green and the vehicles are no longer delayed. This marks the completion of the LBI/split LBI cycle.

3.1.2.6.3 LBI and Split LBI Algorithm

An algorithm was developed that worked in tandem with the Delay Gates (i.e., additional signal heads) to create the LBI treatments. The algorithm took advantage of Overlaps and the PLC capabilities within the ASC/3 controller.

Overlaps A and C were used to control the LBI. Both were set such that all phases were turned on; Overlap A included phases 1, 2, 3, 4, 5, 6, 7, and 8. Overlap C was the same. This allowed the signal state to remain green at all times, and then be “Terminated” in logic step #3 (See Figure 3.7), causing the indication to



change from green to red for the duration of the LBI or split LBI.

Figure 3.7: LBI/Split LBI Algorithm

The logic statements in Figure 3.7 can be explained further as follows: When the walk signal illuminates, the Overlap turns red (the always-green Delay Gate turning to red is the Overlap being “Omitted”), and then delays that for five seconds. After the five seconds, the Delay Gate turns green again and the cycle repeats itself.

The PLC uses the pedestrian timing in logic #1 and #2 because the LBI and split LBI phases are set to “Pedestrian Recall,” meaning that the pedestrian movements will be served every cycle. This provides an easy marker to tie the logic functions to.

3.1.2.6.4 Behavior at Amber

VISSIM allows the user to pick between two options for the behavior at amber: “Continuous Check” and “One Decision” (PTV Group, 2014). Continuous Check allows the vehicle in the model to continuously check (checks every two seconds) the status of the signal state and then decide whether to go or not. One Decision uses a probabilistic function to decide whether or not to stop at the amber, and when a decision is made it is not re-examined. The main difference between the two is that Continuous Check gives more opportunity to pass through the signal during the amber illumination.

A quirk in the operation of the LBI and split LBI treatments compelled an alteration of the behavior at amber. During testing it was observed that vehicles could “sneak” through the LBI treatments. Figure 3.8 shows the following sequence:

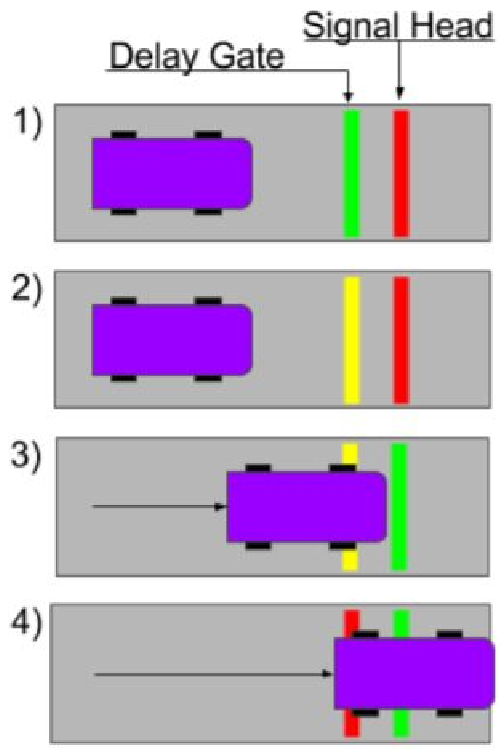


Figure 3.8: Behavior at Amber Error

1. The stopped vehicle observes the red indication and does not advance.
2. Delay Gate turns amber, vehicle makes first decision at amber. Vehicle does not proceed because the signal head is still red.
3. Just over two seconds later, the Delay Gate is still amber and the signal head turns green; since two seconds has elapsed the decision at amber rechecks and, finding a green indication on the signal head rather than a red indication as before, proceeds.
4. A split second later the Delay Gate turns red, but the decision at amber has been made and the vehicle is already advancing, negating any benefit from the LBI.

Changing the decision at amber from Continuous Check to One Decision remedied the problem. In the scenario above, the vehicle completes step one by making One Decision, but then remains stopped and does not advance during the potential operation flaw in step 3.4.

Since the behavior at amber was changed from its default Continuous Check to One Decision, the change was examined to see what occurred as a result. Results indicated that delay increased slightly, which is expected. The amber time at 122nd is 3.9 seconds for the through phases. The Continuous Check checks every two seconds (thereby allowing at least two checks for each amber), while the One Decision option only checks the signal state once. During One Decision the vehicle has fewer opportunities to evaluate the signal state, and in turn will be more likely to stop at the amber, which increases delay.

The changes associated with altering the behavior to amber can be seen in Table 3.2, which shows the percentage difference in user delay (% Diff) when comparing the Continuous Check and 16 One Decision options, where "LBI: RT" (westbound right turn; the highest change at 4.3%) represented a 1.4-second increase in total user delay. Other values differ by tenths of a second. This suggests that changing the behavior at amber had little overall impact on user delay. It is therefore assumed that the changing of the behavior of amber was an appropriate alteration for the circumstances.

Table 3.2: Decision at Amber Change Analysis

Movement	***Continuous Check (sec)***	***One Decision (sec)***	***% Difference***	***Delay Difference (sec)***
Split LBI: TH	16.83	16.93	0.6%	0.1%
Split LBI: RT	5.31	5.32	0.2%	0.1
EB LT	62.57	63.24	1.1%	0.67
LBI: TH	28.15	28.63	1.7%	0.48
LBI: RT	24.13	25.17	4.3%	1.4
WB LT	52.45	53.17	1.4%	0.72
NB TH	37.32	37.42	0.3%	0.1
NB RT	7.21	7.23	0.3%	0.2
NB LT	55.53	56.1	0.9%	0.48
SB TH	34.55	34.47	-0.2%	-0.8
SB RT	6.17	6.15	-0.3%	-0.2
SB LT	55.09	55.92	1.5%	0.83
122nd: All	29.89	30.17	0.9%	0.28

3.1.2.6.5 Exclusive Bicycle Phase

Another treatment studied was an exclusive bicycle phase (EBP), which is a scheme where all traffic is stopped except for the bicycle traffic. From an operational standpoint the EBP was implemented by adding Phase 9 (which corresponded to Bike Phase 2) and Phase 10 (corresponded to Bike Phase 6) at the end of rings I and II (See Figure 3.9). This allowed the EBP to time as a separate phase pair.

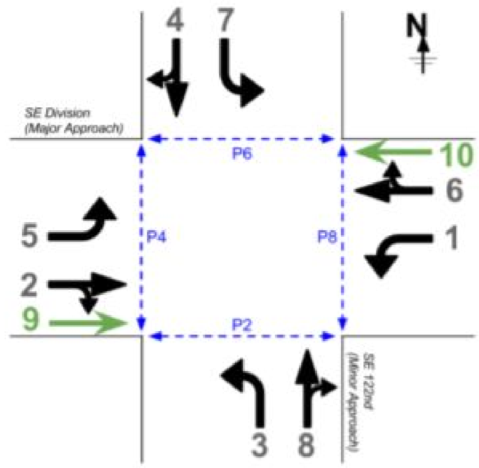


Figure 3.9: EBP Phase Diagram of SE 122nd and Division

In addition, the following were programmed: five-second amber (needed to clear 10 mph bicycles from the intersection); a one-second red clearance; a 10-second green time (splits); and (since the bicycle approaches had detection) a two-second vehicle extension time.

In order to ensure an “apples-to-apples” comparison between the base case and the EBP the cycle length remained at 110 seconds, thereby eliminating the effects of differing cycle lengths from complicating the analysis. This EBP effectively caused an approximately 15-second shortening of the overall cycle length; this reduction in cycle length took away green time from the other phases and gave it to the EBP. At 10 seconds of EBP green time, only three bicyclists were able to pass through the signal head.

One notable challenge that was encountered was the development of the timing scheme for EBP implementation. Synchro was used to develop the timing plans, but the software does not have the ability to model bicyclists as active users of the roadway; they are instead coded in the program as an interference for vehicles. In order to resolve this, the EBP was modeled as an exclusive pedestrian phase (which is a setting that Synchro does have) with a value of 10 seconds. Figure 3.10 shows the Synchro splits, with the EBP seen as the pedestrian Phase 09 at the end of the cycle. From this model offsets and splits were obtained, which were used in the EBP VISSIM model.

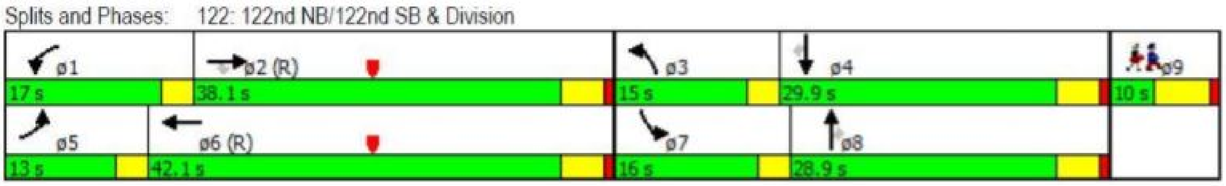


Figure 3.10: Sychro Splits for EBP

The simulation of the EBP did not include the sensitivity analysis like the LBI treatments did. This was due to the single-file bicycle lane setup, which severely limited the realism of the EBP. Bicyclists, because of the nature of their vehicle, do not queue up like motorized vehicles do and they tend to "pack in" much tighter. The model retained the same vehicle queueing behavior for bicycles, passenger cars and HGVs.

With regards to EBP performance, this means that the way VISSIM models the bicyclists during the 10 seconds of EBP only allows for three to pass through the light. This is probably lower than what could be expected for a real-life intersection, which would imply that the delay values seen in the results could be improved with modifications to the queuing-at-stop behavior of the bicyclists (see Section 3.4.1 below).

The inability to move more than three bicyclists through the intersection during the EBP limited the upper bounds of the bicycle volumes, which is why the sensitivity analysis was not completed for this treatment. However, the Quality Counts volumes from September were too low to produce meaningful data results. In order to remedy this conundrum a bicycle volume of 1% of vehicle traffic was used, which was compared to the base case 1% scenario.

3.2 METHODS

In order to test the proposed treatment types at the intersection of 122nd and Division, the VISSIM model was coded for specifics such as number of runs and randomization of the vehicles. Additionally, a base case model was developed and validated using a state DOT protocol. Bicycle volumes were also altered to accommodate shortcoming in the traffic data, and the model results were tested for statistical accuracy using t-tests. Specifics of these will be explored in depth below.

3.2.1 Model Calibration

Simulation models are often calibrated to real-world data in order to make estimates on their accuracy. The Oregon Department of Transportation (*ODOT*) uses the GEH formula to compare the real-world input volumes and model output volumes. The GEH formula is an empirical formula that was established by Geoffrey E. Havers in 1970, and is commonly used in traffic engineering, forecasting and modeling to compare two sets of traffic volumes.

The formula is given by:

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

where,
m = output traffic volume from simulation model (vph)
c = input traffic volume (vph)

The ODOT VISSIM protocol report provides guidance on acceptable values for GEH statistic (ODOT, 2011). ODOT recommends that GEH statistics should be calculated for all intersection turns and mainline links and for traffic volumes at all entry and exit locations for each model, with the criteria presented in Table 3.3 used to assess the validity of the model results.

Table 3.3: ODOT GEH Criteria

Value of Statistic	***Criteria***
GEH < 5.0	Acceptable Fit
5.0 <= GEH <= 10.0	Caution: possible model error on bad data
GEH > 10.0	Unacceptable

(Source: ODOT, Protocol for VISSIM Simulation, June 2011)

The model was validated using the base case volume outputs for vehicles and pedestrians (bicycles were not validated because of the bicycle volume sensitivity analysis) and the input volumes from the Quality Counts data. The GEH analysis revealed GEH < 5.0 for all vehicle and pedestrian links, meaning all data was considered to have an “Acceptable Fit.”

3.2.2 Number of Runs

VISSIM allows users to define the model’s parameters for simulation (number of runs, randomizer information, and total time interval of the runs), and how the model will vary those parameters. In order to obtain meaningful statistical information from the treatments, each model (base case, LBI, split LBI, EBP) was run 10 times. A randomizer inherent in the program varies aspects like vehicle arrivals and volumes, and does so by user defined “seed” intervals. A random seed interval was used, starting at random seed number 56, and increasing the seed value by one each run. The duration of each run was 4,500 seconds (one hour and 15 min), but was only recorded for the last 3,600 seconds (one hour). This allowed the model time to populate with traffic.

3.2.3 Metrics

VISSIM allows for the gathering of a number of traffic performance metrics, including: queueing, delay, travel times, as well as logging capabilities for signal changes, detector calls, and many other features. For this study delay per user, number of users, queue length, and several other metrics were recorded. These were gathered from "nodes," which are data gathering boundaries set by the user in VISSIM. The nodes were drawn by the modeler as squares that surrounded the intersection, thereby limiting data collection to just the intersection itself. VISSIM sorts all metrics by the movement and vehicle type.

3.2.4 Statistics

In order to determine the validity of the results a standard paired, two-tailed, t-test was performed using Microsoft Excel. The two-sample t-test statistically examines if the means of two populations are different. The test assumes a normal distribution and is performed when the sample size is small. The formula is listed below:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

Where,
$\overline{x_1}$ = Mean 1
$\overline{x_2}$ = Mean 2
s_1 = Standard Deviation 1
s_2 = Standard Deviation 2
n_1 = Total Sample Size 1
n_2 = Total Sample Size 2

All results from the statistical analysis were incorporated into the data tables in the Results section. The results were tested for significance at the 95% confidence interval using the Microsoft Excel =t.test() function.

3.2.5 Bicycle Volumes

Bicycle volumes at the intersection were low, eight total for the study hour of 12 p.m. to 1 p.m. This caused two issues with the model: there were not enough bikes to fully test the 21 treatments, and the results for bicyclists were suspect due to small sample size errors. In order to remedy this, a sensitivity analysis was performed where bicycle volumes were varied as a function of vehicle volume, from 1-10%, in 1% increments. These ranges of bicycle volumes were tested to account for a variety of locations with low and high bicycle volumes. For example, high bicycle volumes are seen on N. Williams corridor or the Hawthorne bridge during the peak period. This analysis was performed for the LBI, the split LBI, and for the base case. The additional bicycles were added to the model (as opposed to removing vehicles to maintain the same overall volume of road users), increasing the total number of users. The number of bikes is shown in Table 3.4 below.

Table 3.4: Sensitivity Analysis Bicycle Volumes

% Bikes	*Number of Bikes*	*In at 119th (EB)*	*In at 130th (WB)*
1%	36	18	18
2%	71	36	36
3%	17	53	53
4%	143	71	71
5%	178	89	89
6%	214	17	17
7%	250	125	125
8%	285	143	143
9%	321	160	160
10%	357	178	178

The sensitivity analysis posed a second challenge: What to do about bicycle movements from the Quality Counts data that had zero bicyclists? It was decided to not alter the bicycle volumes on the minor approaches, and to adopt a scheme for the major treatment approaches where 15% of bicyclists turned right, and 15% turned left, while the remaining 70% used the through movements. The right-turning bicyclists turned from the bike lane into another bike lane. The left-turning bicyclists merged across traffic, using the left vehicle turn lane to complete the movement into the destination bicycle lane.

3.2.6 Coordinated Base Case

In order to set the datum to which the treatments would be compared, a base case scenario was developed. This base case used the modified intersection geometry, volumes and other parameters noted above. Once the base case was completed it was copied and the individual treatments were implemented into that copy, thereby ensuring valid comparisons. It was decided to adopt a coordinated signal strategy, and to develop the necessary signal timing using a combination of PBOT-provided timing plans and Synchro traffic modeling software. Although 122nd and Division was at one time run in coordination, it runs in free mode at present. Because of this the coordination had to be redeveloped. The results taken from Synchro included splits and offsets.

3.3 ANALYSIS AND RESULTS

The four simulation scenarios – LBI, split LBI, EBP and base case coordinated – were modeled in 10 run sets using VISSIM. The base case scenario was then compared to the LBI, split LBI and EBP in order to gauge the changes due to the treatments. Due to low bicycle volume the LBI and split LBI results contain a sensitivity analysis where the number of bicycles was increased as a function of the vehicle volume. The EBP used only the 1% volume scenario from the sensitivity analysis. The results of these will be explored below.

3.3.1 Coordinated Base Case

In order to establish the datum to which the test treatments would be compared, a base case scenario was modeled. This base case used the same modified geometry at 122nd and Division and was identical to the treatment scenarios (minus the treatments themselves). This includes using the same volumes as the treatments, including the bicycle volume sensitivity analysis. All base case results can be seen in the treatment comparisons within the following sections.

3.3.2 Leading Bicycle Interval (LBI)

In this research both LBI scenarios were examined simultaneously. The eastbound approach (phase 2) utilized the dedicated right-turn lane and bike lane (which extended to the stop bar), to implement the split LBI. The westbound approach (phase 6) lacked a dedicated right-turn lane, necessitating the stopping of the entire phase during the LBI. This allowed the testing of both LBI and split LBI treatments simultaneously. The modeling software, VISSIM, parses out the results of each movement, giving a simple method for extracting the metrics related to each LBI/split LBI treatment. Because of the low bicycle volumes present at the intersection a sensitivity analysis was performed where the bicycle volume was increased as a function of the percentage of mode share. The actual number of bicycles can be seen in Table 3.4. The results of each treatment have been separated for analyses and will be discussed individually below.

3.3.2.1 Traditional LBI (Westbound)

The westbound approach of the model (Phase 6) used the LBI treatment. Every cycle the bicyclist(s) were shown a green indication before the vehicles were. The vehicles in the through and shared through/right-turn lanes were shown a red indication for five seconds before being shown a green indication. All three approaches (bike lane, vehicle through lane, and vehicle through/right-turn lane) ended at the same time using the same amber and red clearance times.

Results of the LBI simulations can be seen for vehicles in Table 3.5, Figure 3.11 and Figure 3.12 below. All delays for the LBI treatment's movements were statistically significant to $p = 0.05$ The LBI showed a uniform increase in delay across all approaches. This is expected as the LBI impedes all vehicle traffic for five seconds, which (conveniently) is the same amount of increased delay seen regardless of bicycle volume.

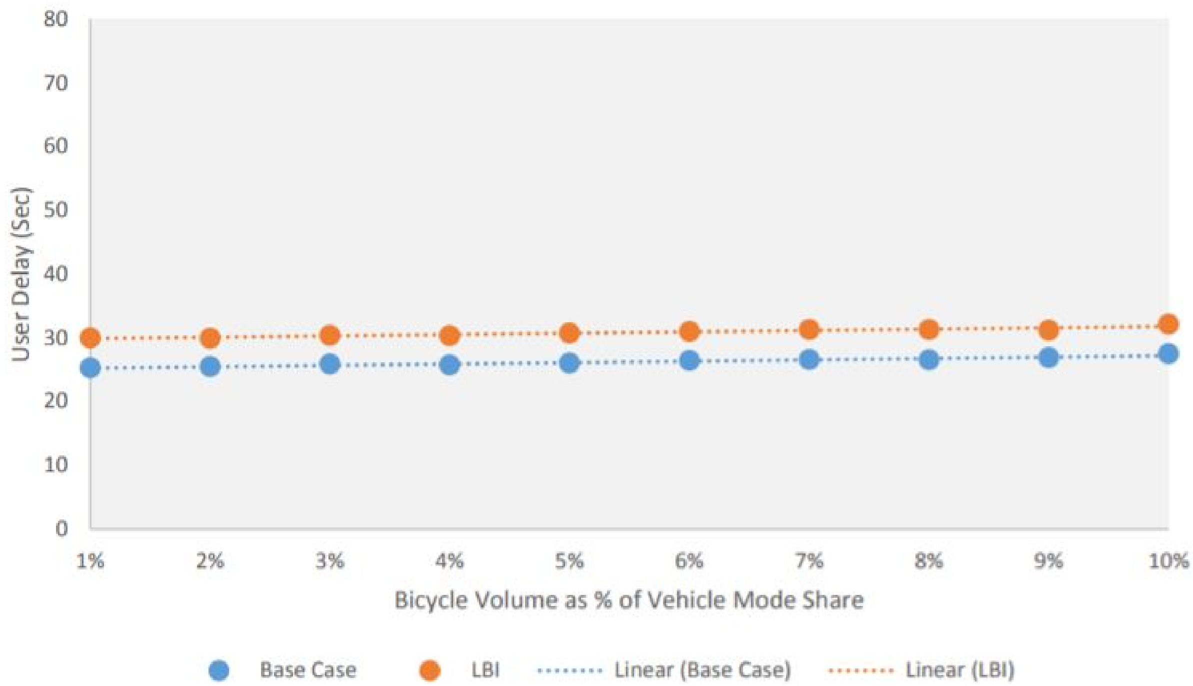


Figure 3.11: LBI Vehicle Through Movement Delay Results

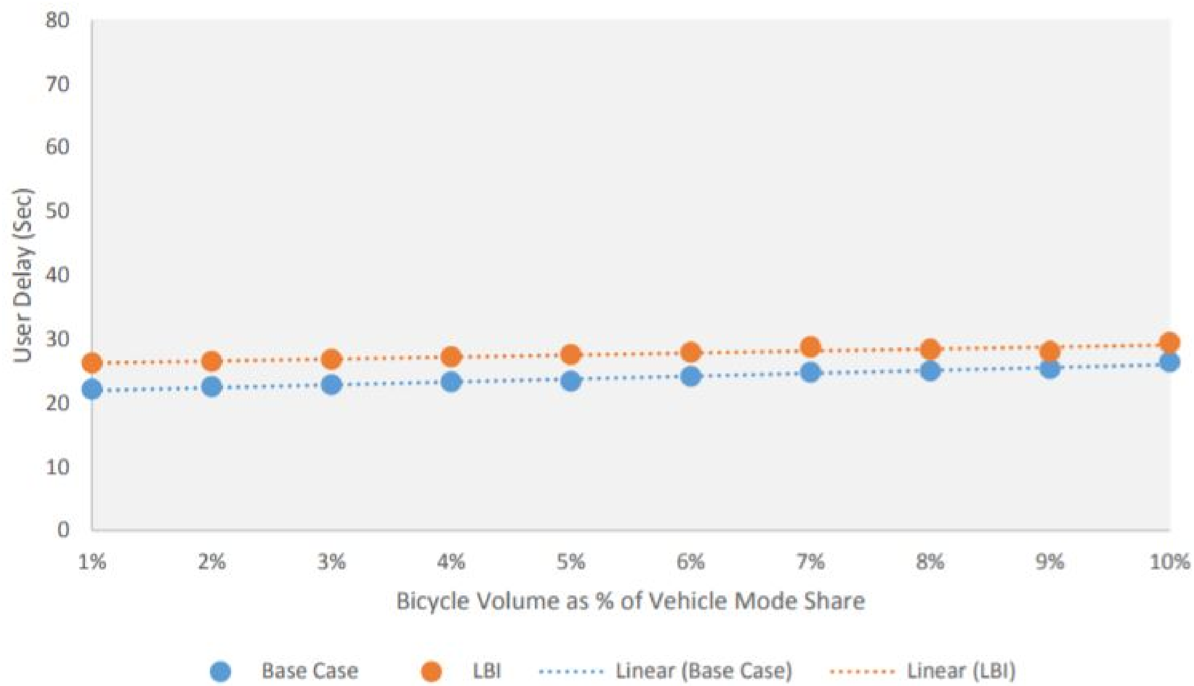


Figure 3.12: LBI Vehicle Right-turn Movement Delay Results

Table 3.5: LBI (Phase 6) Vehicle Sensitivity Analysis Delay Results

Movement and Case		Bicycle Volume as Percent of Mode Share, Delay (secs)									
		1%	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**
Through	Base Case Delay	25.3	25.5	25.9	25.8	26.0	26.4	26.6	26.6	26.9	27.5
	LBI Delay	**30.0**	**29.9**	**30.4**	**30.3**	**30.7**	**31.0**	**31.3**	**31.3**	**31.2**	**32.1**
	% Difference	19%	17%	17%	18%	18%	17%	18%	18%	16%	17%
Right Turn	Base Case Delay	22.2	22.6	22.9	23.3	23.4	24.2	24.8	25	25.4	26.5
	LBI Delay	**26.3**	**26.6**	**26.9**	**27.2**	**27.6**	**27.9**	**28.8**	**28.4**	**28.1**	**29.4**
	% Difference	19%	18%	18%	17%	18%	16%	16%	13%	11%	11%

Bolded cells are statistically significant to the ***95% CI****.*

Bicycle delay values did not follow this trend (Table 3.5, Figure 3.11 and Figure 3.12), instead showing little overall change, although none of the results were statistically significant. Indeed the change in percentage difference seen in Table 3.6 shows how little bicycle delay appears to be affected by the LBI treatment; not only were results of the percentage difference between the base case and the LBI low, but none of the results were statistically significant.

Table 3.6: LBI (Phase 6) Bicycle Sensitivity Analysis Delay Results

Movement and Case		Bicycle Volume as Percent of Mode Share, Delay (secs)									
		1%	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**
Through	Base Case Delay	17.8	18.8	17.3	18.1	20.5	20.1	21.1	23.6	25.1	22.5
	LBI Delay	18.1	18.7	16.9	18.7	21.0	20.4	20.9	24.3	25.1	22.6
	% Difference	2%	-1%	-2%	4%	2%	1%	-1%	3%	0%	1%
Right Turn	Base Case Delay	2.2	7.0	5.9	8.6	10.4	10.4	12.1	13.2	16.4	13.1
	LBI Delay	2.2	7.1	6.0	8.2	10.8	9.9	11.7	14.2	16.4	14.3
	% Difference	0%	2%	1%	-5%	4%	-4%	-4%	8%	0%	5%

Bolded cells are statistically significant to the ***95% CI****.*

3.3.2.2 Split LBI (Eastbound)

The eastbound approach of the model (phase 2) used the split LBI treatment. Every cycle the bicyclist(s) and the vehicle through movements were shown a green indication before the right-turning vehicles were. The vehicles in the right-turn lane were shown a red indication for five seconds before being shown a green indication. All three approaches (bike lane, vehicle through lane, and vehicle right-turn lane) ended at the same time using the same amber and red clearance times. Table 3.7, Figure 3.13 and Figure 3.14 show the vehicle delay results for the base case compared with the split LBI treatment.

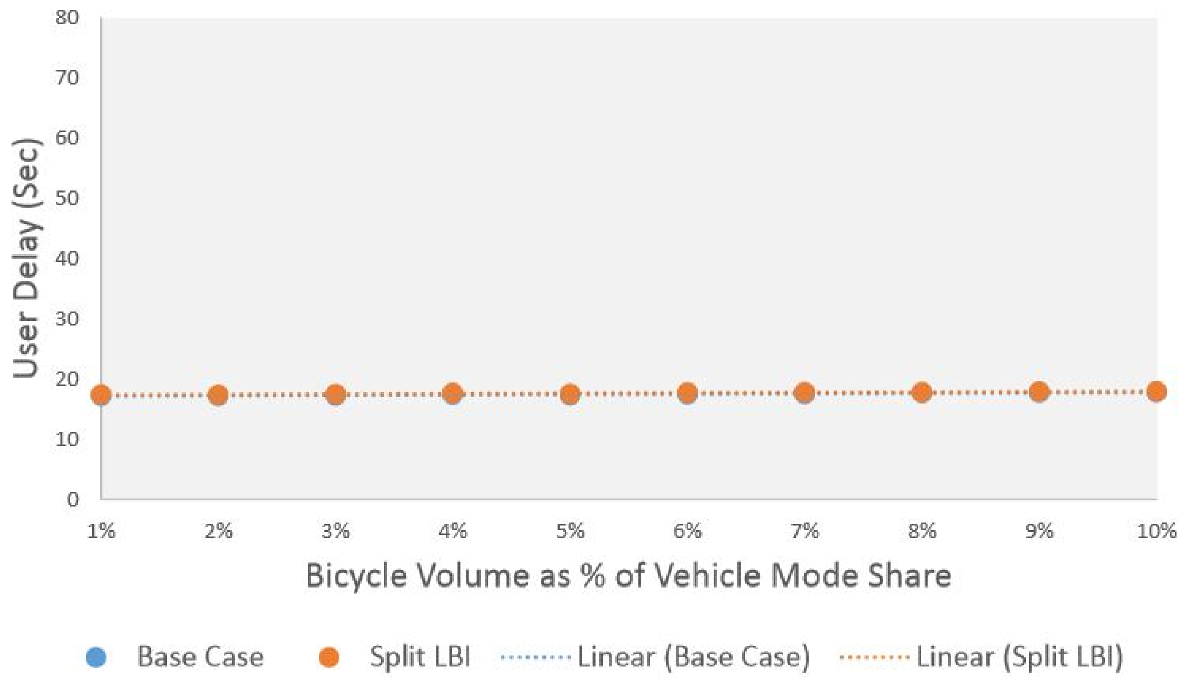


Figure 3.13: Split LBI Vehicle Through Movement Delay Results

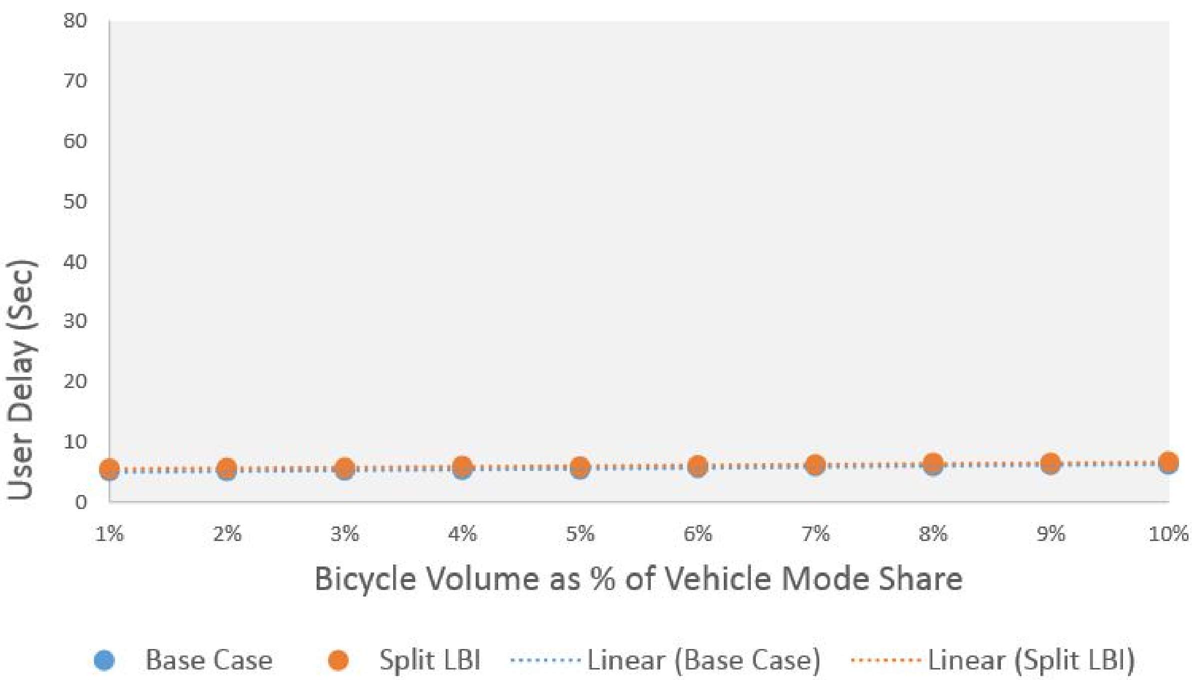


Figure 3.14: Split LBI Vehicle Right-turn Movement Delay Results

Table 3.7: Split LBI (Phase 2) Vehicle Sensitivity Analysis Delay Results

Movement and Case		Bicycle Volume as Percent of Mode Share, Delay (secs)									
		1%	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**
Through	Base Case Delay	17.2	17.2	17.3	17.4	17.3	17.5	17.5	17.7	17.7	17.8
	LBI Delay	**17.4**	17.4	17.5	**17.7**	17.5	**17.8**	**17.8**	17.8	17.9	17.9
	% Difference	1%	1%	1%	2%	1%	2%	2%	1%	1%	1%
Right Turn	Base Case Delay	5.15	5.18	5.26	5.39	5.43	5.71	5.97	5.99	6.18	6.23
	LBI Delay	**5.55**	**5.66**	**5.71**	**5.99**	**5.84**	**6.7**	**6.22**	**6.49**	**6.49**	**6.7**
	% Difference	8%	915	9%	11%	8%	6%	4%	8%	5%	8%

*Bolded cells are statistically significant to the **95% CI**.*

The difference in delay caused by the split LBI was nearly negligible for the unaffected through movements (which showed little statistical significance), and was relatively low (<1 second) for the right turns (but highly statistically significant). Both of these results are expected; the through movements are not impeded by the split LBI and would therefore be expected to show little change; the right turns are impeded for five seconds in the entire cycle length, minimizing the magnitude of the impact.

The effects on bicycle traffic were also studied with the results being listed in Table 3.8, Figure 3.15 and Figure 3.16 below. Bicycle results for the through movements appeared to show minor changes in delay, but with only a few runs being statistically significant. The increase at the higher bicycle volumes is likely the result of queuing delays caused by the increasing number of bicyclists, which at higher bicycle volumes begin to experience platoon dispersion delays the same way a vehicle would.

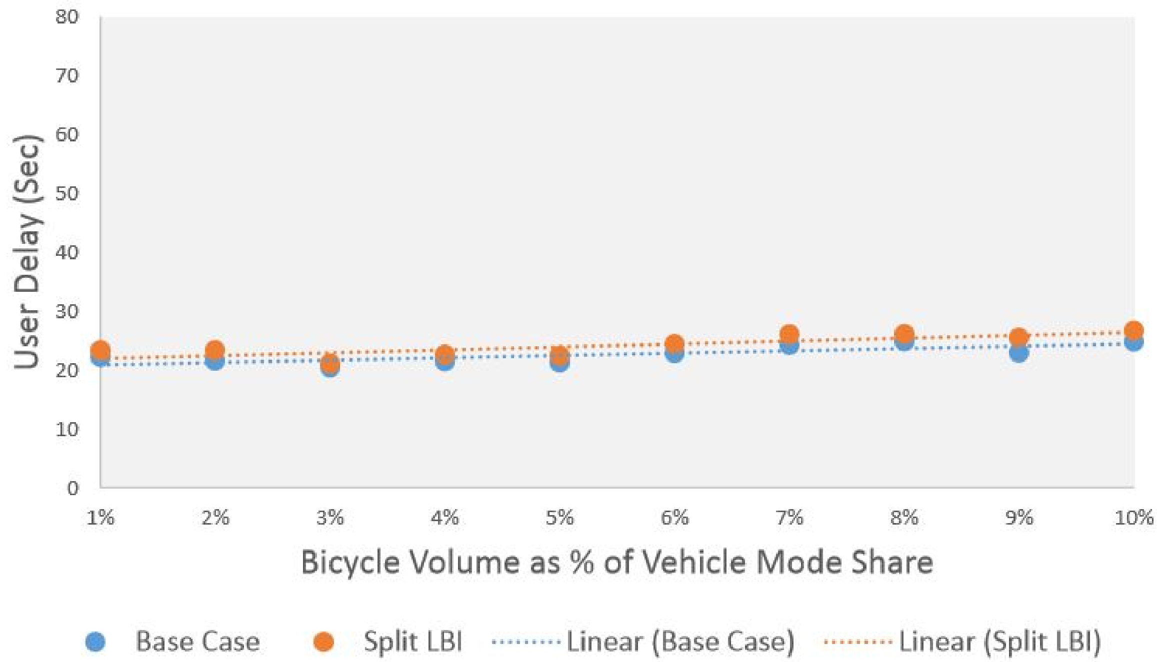


Figure 3.15: Split LBI Bicycle Through Movement Delay Results

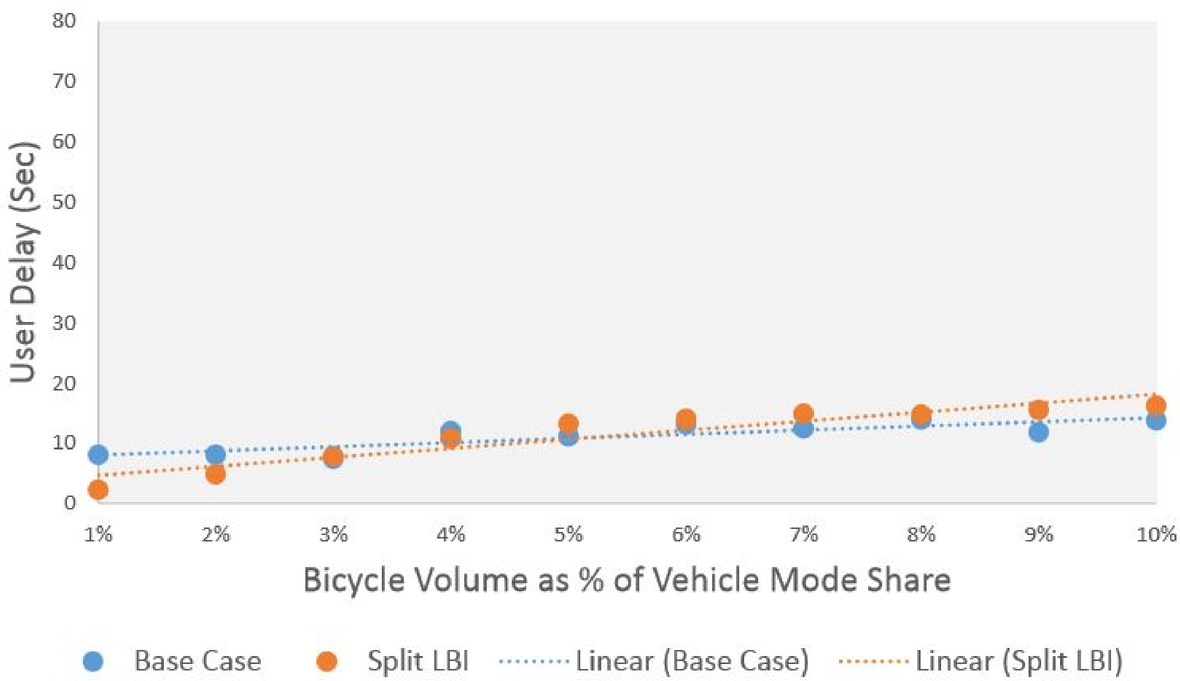


Figure 3.16: Split LBI Bicycle Right-turn Movement Delay Results

Table 3.8: Split LBI (Phase 2) Bicycle Sensitivity Analysis Delay Results

Movement and Case		Bicycle Volume as Percent of Mode Share, Delay (secs)									
		1%	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**
Through	Base Case Delay	22.2	21.5	20.4	21.4	21.2	22.8	24.2	24.9	22.9	24.8
	LBI Delay	23.3	23.3	21.1	22.6	22.4	24.4	**26.0**	26.1	**25.4**	**26.6**
	% Difference	5%	8%	3%	5%	6%	7%	7%	5%	11%	7%
Right Turn	Base Case Delay	8.0	8.0	7.4	11.9	11.1	13.1	12.4	13.9	11.8	13.7
	LBI Delay	2.2	4.8	7.8	10.7	13.2	14.0	14.9	14.7	**15.5**	16.2
	% Difference	-72%	-40%	6%	-10%	-19%	7%	20%	6%	32%	18%

Bolded cells are statistically significant to the ***95% CI****.*

Right-turning movements showed an odd trend where the split LBI began as having substantially less delay than the base case but increased quickly until the treatment delay surpassed the base case delay (although only the 9% bike volume scenario is significant). These results are almost certainly due to bike queuing issues. The more bicycles in the system the longer they will wait in the queue, as there is no dedicated right-turn lane for bicyclists. At lower volumes the bicyclists are less likely to encounter a queue and would have a better chance of making their turns without waiting.

3.3.2.3 Minor Approach Phases

The minor phases of the intersection were not altered in any way, including the low bike volumes obtained from Quality Counts. Bicycle results were excluded due to very low volumes, which riddled the results with small sample errors. Since the LBI and split LBI treatments do not directly affect the minor approaches they would be expected to experience very little impact from the implementation of the treatments. Table 3.9 shows the percentage difference in delay due to the treatments.

Table 3.9: Minor Phases (Phases 4 and 8) Vehicle and Bicycle Sensitivity Analysis Delay Results

Movement and Case		Bicycle Volume as Percent of Mode Share, Delay as Percent Difference									
		1%	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**
Southbound	Veh Through	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%
	Veh Right Turn	0%	0%	-2%	-2%	-3%	-1%	-1%	-2%	-1%	1%
	Bicycle Through	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Northbound	Veh Through	0%	0%	0%	0%	0%	1%	**1%**	**1%**	1%	**1%**
	Veh Right Turn	0%	0%	1%	-1%	1%	1%	2%	1%	0%	3%
	Bicycle Through	-15%	-15%	-16%	-15%	-15%	-15%	-15%	-15%	-15%	-15%

Bolded cells are statistically significant to the ***95% CI****.*

The results indicate little to no change at the minor approaches, with only a few being statistically significant. There are, however, two notable exceptions: southbound right turn and northbound bicycle through. Southbound right turn saw slight decreases in delay at the higher bike volume percentages, which is explained by the LBI. The same five seconds that impede the westbound through movements also give the southbound right turn an additional five seconds in which to make a turn.

The drop in delay seen in the northbound bicycle through movement is the result of small sample error. Specifically, the ninth run of each 10-run set in the base case scenario; the two bicyclists who used the approach had delay values of 74.56 seconds, compared to the 25.39 seconds of delay seen in the ninth run of the 10-run set for the LBI scenarios. Essentially, the same bicyclist arrived at the beginning of the red indication on the northbound approach for each of the nine runs. The bicyclist in question entered the model at the same time each run, regardless of the treatment type being implemented. Since the LBI scenario had different timing splits it would be expected that the state of an individual indication would be different for the base case and the LBI at the same time-step in the simulation, meaning that the bicyclist would enter at time X and hit the early stages of the red indication in the base case, and then arrive at time X in the LBI and receive a different indication, which in turn resulted in a decrease in delay. Additionally, only two bicyclists used the approach, and the small sample size disproportionately affects the results.

3.3.2.4 Left-Turning Phases

Left-turning phases of the intersection were not altered. Since the LBI and split LBI treatments do not directly affect the left-turn approaches, it would be expected that they would experience very little impact from the implementation of the treatments. Table 3.10 shows the percentage difference in delay results due to the treatments.

Table 3.10: Left-turn Vehicle Sensitivity Analysis Delay Results

Movement	Bicycle Volume as Percent of Mode Share, Delay as Percent Difference									
	1%	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**
WB LT	1%	1%	1%	0%	3%	2%	1%	2%	1%	1%
NB LT	3%	2%	2%	2%	3%	2%	2%	2%	3%	**3%**
EB LT	1%	1%	1%	1%	**2%**	0%	**3%**	1%	1%	1%
SB LT	1%	0%	1%	1%	1%	1%	1%	2%	2%	2%

Bolded cells are statistically significant to the ***95% CI****.*

The largest percentage difference in delay is 3%, which represents 1.5 seconds of additional delay. The remaining phases show little to no change, suggesting the LBI treatments had little effect on left turns. However, only a few of the results were statistically significant. Any vehicle delay increase in the left turns is likely the result of slight variations in vehicle arrivals.

3.3.2.5 Pedestrian Movements

All pedestrian movements, phases 1-8, were included in the VISSIM model. Pedestrian movements were not altered by the LBI treatments. The LBI and the corresponding pedestrian movement began at the same time, with the walk and the LBI/split LBI green turning on simultaneously. The percentage difference in delay for each movement is shown in Table 3.11, with statistical significance of the means being represented within these results.

Table 3.11: Left-turn Vehicle Sensitivity Analysis Delay Results

Crosswalk and Direction	Bicycle Volume as Percent of Mode Share, Delay as Percent Difference									
	1%	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**
Southside EB	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Southside WB	0%	0%	1%	1%	0%	1%	1%	0%	0%	0%
Westside NB	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Westside SB	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Northside EB	**1%**	1%	-1%	1%	0%	0%	0%	**1%**	1%	1%
Northside WB	0%	**2%**	1%	2%	1%	1%	1%	**2%**	**3%**	**3%**
Eastside NB	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Eastside SB	0%	0%	0%	0%	0%	0%	0%	0%	0%	-1%

Bolded cells are statistically significant to the ***95% CI****.*

The results show how little the LBI treatments affected the pedestrian movements. The only pedestrian phase that shows any meaningful change is phase 6 (the north side of the intersection), especially the westbound pedestrians. The largest percentage difference is 3% on “Northside WB,” which represents a 0.74 second difference in additional delay. Phase 6 pedestrian movements had the lowest volume of pedestrians for any of the four pedestrian approaches, with a total of 14 pedestrians each direction (14 eastbound and 14 westbound for a total of 28 pedestrians) for the entire hour. Many of the runs saw only one pedestrian use the approach in a cycle. Almost all runs that were statistically significant were seen on results from northside (pedestrian phase 6), the LBI treatment. The increases seen are likely the result of small sample errors, or what could be deemed normal fluctuations.

3.3.3 Exclusive Bicycle Phase (EBP)

The final treatment examined was the EBP. In this scheme all traffic is held in order to allow select bicycle movements unrestricted access to the intersection (similar to an exclusive pedestrian phase). In this study, the EBP was tested for bicycle volumes that were 1% of the motor vehicle volumes as seen in Table 3.4. In the version applied to this model only eastbound (phase 2) and westbound (phase 6) bicycles were given the EBP, while the minor northbound (phase 8) and southbound (phase 4) were not. While traditionally, the EBP will allow bicycles on all approaches to proceed through the intersection all at one, the decision to allow EBP for only the east and westbound bicycles was taken due to the complexity involved in changing the network geometry on the northbound and southbound approaches to accommodate the bicycle lanes.

Results from the simulation are shown in three tables below; Table 3.12 shows the vehicle delay results, Table 3.13 shows the bicycle delay results, and Table 3.14 shows the pedestrian delay results. Each will be discussed in turn.

Table 3.12: Exclusive Bicycle Phase (Phases 2 and 6) Vehicle Delay Results

Movement	Base Case (sec)	EBP (sec)	% Difference
EB TH	17.2	**21.68**	26%
EB RT	5.15	**5.52**	7%
EB LT	62.5	**74.52**	19%
WB TH	22.28	**21.23**	-16%
WB RT	22.16	**19.26**	-13%
WB LT	52.23	**56.25**	8%
SB TH	34.12	35.15	3%
SB RT	6.12	6.7	-1%
SB LT	54.81	65.81	20%
NB TH	37.1	37.64	1%
NB RT	7.4	7.77	5%
NB LT	53.1	**54.74**	3%

*Bolded cells are statistically significant to the **95% CI**.*

Vehicle delay in Table 3.12 showed mixed results, with the eastbound movements experiencing substantial increases which were also statistically significant. The westbound through and right-turn movements showed decreases in delay and were statistically significant. Southbound and northbound showed little change and were not statistically significant, with the exception of northbound left turn which saw a minor increase in delay. Left turns saw increases in delay, with three of the four being statistically significant.

These increases and decreases appear to be the result of an unintentional favoring of the westbound (phase 6) approach in the coordination scheme. The Synchro time-space diagrams show not only the travel paths of vehicles but also delay estimates. The diagrams showed an increase in delay for the eastbound (phase 2) approach (increasing from 15 seconds in the base case to 18 seconds in the EBP), while the westbound approach (phase 6) showed a decrease in delay (from 29 seconds in the base case to 24 seconds in the EBP). This would explain the odd results seen in Table 3.12.

Table 3.13: Exclusive Bicycle Phase (Phases 2 and 6) Bicycle Delay Results

Movement	Base Case (sec)	EBP (sec)	% Difference
EB TH	22.17	**45.63**	16%
EB RT	8.2	6.1	-25%
EB LT	42.65	**85.46**	100%
WB TH	17.75	**44.65**	152%
WB RT	2.15	14.29	565%
WB LT	29.29	40.77	39%
SB TH	33.29	**30.62**	-8%
SB RT	0	0	-
SB LT	0	0	-
NB TH	35.36	25.72	-27%
NB RT	3.22	3.26	1%
NB LT	54.62	**50.66**	-7%

*Bolded cells are statistically significant to the **95% CI**.*

Table 3.13 bicycle delay results for eastbound bicycles showed an increase in the through and left-turn movements, but a decrease in the right turns, with only the former being statistically significant. Westbound bicycles showed a statistically significant increase in delay for the through movement. Southbound bicycles showed a statistically significant decrease in delay for the through movement, with zero values for the right and left turns (because no bicyclists used them, see Section 4.2 above). Northbound bicycles showed a statistically significant decrease in bicyclist delay for the left-turn movement.

Since the EBP only allows bicyclists to proceed at the end of the signal cycle (during phase 9 only), increases in delay would be expected and the results seem to demonstrate this increase. Although caution should be used in that the eastbound and westbound turning values are the result of only a few bicyclists, strongly suggesting small sample influence.

The drop in delay seen on the minor northbound and southbound right-turn movements is probably the result of increased opportunity to make unencumbered right turns; conflicting eastbound or westbound bicycles are stopped at the EBP for the majority of the signal cycle.

Table 3.14: Exclusive Bicycle Phase (Phases 2 and 6) Pedestrian Delay Results

Crosswalk and Direction	Base Case (sec)	EBP (sec)	% Diff
Southside EB	29.8	**33.59**	16%
Southside WB	27.75	**33.86**	22%
Westside NB	50.73	51.19	1%
Westside SB	50.37	51.8	3%
Northside EB	30.77	**35.95**	17%
Northside WB	26.67	**31.16**	17%
Eastside NB	24.1	52.4	-4%
Eastside SB	52.3	50.1	-4%

Bolded cells are statistically significant to the ***95% CI****.*

Pedestrian delay results seen in Table 3.14 showed statistical significance for only the westbound and eastbound movements, both of which saw pronounced increases in delay. This is expected as both phases, like the vehicle phases, were delayed by the EBP. Southbound and northbound saw small, statistically non-significant changes in delay values, and both were not directly affected by the EBP.

The EBP pedestrian phases saw a near uniform ±five second increase in delay, while the minor approaches saw little to no change, which could be the result of cycle length reallocation. Since cycle length remained at 110 seconds, with the EBP taking up approximately 16 seconds of that. That difference in time was taken largely from phases 2 and 6 (southside and northside in Table 3.14). This had the impact of reducing the available time for rest-in-walk, which in turn reduced the potential time that pedestrians had to access the intersection. This would be expected to increase pedestrian delay, which is what was observed.

3.4 SUMMARY

In order to understand the effects to intersection efficiency from the three bicycle-specific treatments, microsimulation was used. The LBI, split LBI and EBP were modeled using VISSIM, and each treatment was compared to a coordinated base case. The effects on user delay were recorded and analyzed.

Results for the LBI revealed little change in vehicle delay for the unaffected approaches (northbound and southbound), but a near uniform five-second increase for the affected westbound approach. This five seconds is roughly the same as the five seconds from the LBI. Bicycle delay showed little change in delay, due largely to an unintentional favoring of the westbound approach in the coordination scheme.

Results for the split LBI also revealed little change in vehicle delay for the unaffected approaches, including the unaffected through movements on the split LBI approach. There was a significant increase for the affected eastbound right-turn movement, due to the treatment itself. The bicycles saw a slight increase in delay, which was likely the result of the eastbound approach being the unfavored approach in the coordination scheme. For both LBI and split LBI, pedestrian movements were all but unaffected.

The EBP vehicle delay results showed mixed outcomes; there was increased delay for the eastbound approach and decreased delay for the westbound. This difference is probably due to a favoring of the westbound approach in the coordination scheme. Minor phases were all but unaffected. EBP bicycle results showed a general increase, which is probably due to the lack of signal time the EBP allocates to the bicycle movements (±10 seconds). Pedestrian movements showed an increase in delay from the EBP, which was inferred to be the product of decreased pedestrian signal time as the result of cycle length reallocation (which was an outcome of the EBP). Minor pedestrian phases were unaffected.

3.4.1 Areas of Further Research

Bicyclist's behavior within VISSIM was not as realistic as it could have been. Queuing and turning movements were two areas that were not particularly accurate. It was observed that during queueing bicyclists were spaced farther apart than they would be in real life. This could be remedied by adjusting the "Standstill Distance" for bicyclists, allowing for tighter "packing in" of bicyclists.

The turning movements for bicyclists had several issues: The left-turning movements were coded in the model so that bicyclists used the intersections as a vehicle would. For left turns this means that the bicyclists would merge over two 35-mph lanes of traffic to queue up with the left-turning vehicles. In real life, very few bicyclists would do this, preferring to either use the sidewalks and crossing as a pedestrian would or to make a two-stage left turn. For the right turns many bicyclists would be expected to use the sidewalks to circumnavigate the intersection itself, either to avoid the potential right-hook conflict or to avoid any queuing-related delays.

If the experiment was to be performed again the recommendation would be use all of those options and code the bicyclists so that a certain percentage completed each turn type. For example, with the left turns 10% of bicyclists would perform the turn as a vehicle would; 30% would complete a two-stage turn; and the remaining 60% would use the pedestrian facilities. These values are illustrative in nature, but video analysis would probably reveal the actual preferences of bicyclists.

A final area of exploration would be modifying the model to allow for bicyclists overtaking each other and queuing side by side. The model used in this research limited bicyclists to a single lane, which prevented both overtaking of slower bicyclists and also forced single-file queueing. Neither of these assumptions are completely realistic, and the model could be adjusted to show this.

The safety of bicyclists is of paramount concern and is the reason that the treatments studied here were developed. All three treatments could be studied further to find the changes in conflicts that occur from their implementation.

4.0 DATA AND METHODS FOR CONFLICT ANALYSIS

This chapter reviews the data and methodology used to study conflicts between bicycles and motor vehicles at signalized intersections with various signal timing strategies. The strategies studied include LBI, split LBI and traditional phasing. Additionally, mixing zones were studied. While mixing zones are not a signal timing strategy, they are also used as a treatment to minimize conflicts between bicycles and turning vehicles at signalized intersections.

4.1 DATA OVERVIEW

Five intersections in total were chosen to be analyzed for bicycle vehicle conflicts. Each intersection will be described in the following sections. A summary of these intersections and the treatments that were analyzed before and after the implementation of the previously defined signal timing treatments are shown in Table 4.1 below.

Table 4.1: Data Overview

Intersection	**Before**			**After**		
	Treatment	Date	Hours	Treatment	Date	Hours
1st Ave and 61st St	-	-	-	Split LBI	3/16/2017	10:30 a.m.-7:30 p.m.
2nd Ave and 74th St	-	-	-	Mixing Zone	5/18/2017	8 a.m.-7 p.m.
6th Ave and 23rd St	Concurrent with LPI	6/7/2017	8 a.m.-7 p.m.	Split LBI	2/20/2017	7 a.m.-6 p.m.
12th and Campbell	Concurrent	9/12/2017 – 9/16/2017	8 a.m.-8 p.m.	LBI	9/19/2017 – 9/25/2017	8 a.m.-8 p.m.
Grand and Multnomah	-	-	-	Mixing Zone	7/10/2017	7 a.m.-7p.m.

4.1.1 1st Avenue and 61st Street, New York City

1st Avenue and 61st Street are both one-way streets. From left to right, 1st Avenue has one buffered bike lane with median separation near the intersection, one vehicle left-turn lane, three vehicle through lanes, and one “Bus Only” lane. 61st Street has two through lanes and one through right-turn lane. The outside lanes on 61st Street can be used for parking, so in general most vehicles will travel down the center through lane. Figure 4.1 shows the geometry of the intersection. For further clarification, vehicle lanes are shown with a solid line, bicycle lanes are shown with a square dotted line, and bus lanes are shown with a hashed line.

Figure 4.1: 1st Avenue and 61st Street, New York City

This intersection was analyzed after the implementation of a split leading bike interval (split LBI) on March 16, 2017, from 10:30 a.m.to 7:30 p.m.. Timing plans were obtained for this intersection, and are shown in Figure 4.2. Phase A allows all 1st Avenue traffic to proceed, phase B allows 61st Avenue traffic to proceed, and phase C shows the split LBI for 1st Avenue. The average cycle length is 90 seconds, with 40 seconds for phases A and B, and eight seconds for the split LBI in phase C.

Phase A

Phase B

Phase C

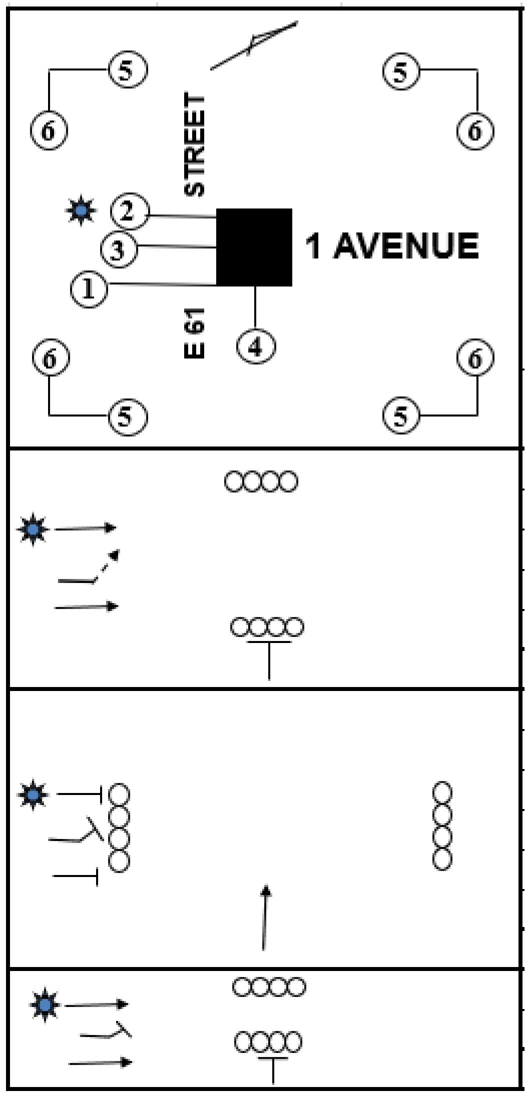


Figure 4.2: Signal Timing Plan for 1st Avenue and 61st Street, Showing the Split LBI in Phase C.

4.1.2 2nd Avenue and 74th Street, New York City

2nd Avenue and 74th Street are both one-way streets. From left to right, 2nd Avenue has one buffered bike lane, one vehicle left-turn lane, three vehicle through lanes, and one “Bus Only” lane. 74th Street has one vehicle through lane with street parking on both sides of the street. Figure 4.3 shows the geometry of the intersection. For further clarification, vehicle lanes are shown with a solid line, bicycle lanes are shown with a square dotted line, and bus lanes are shown with a hashed line.

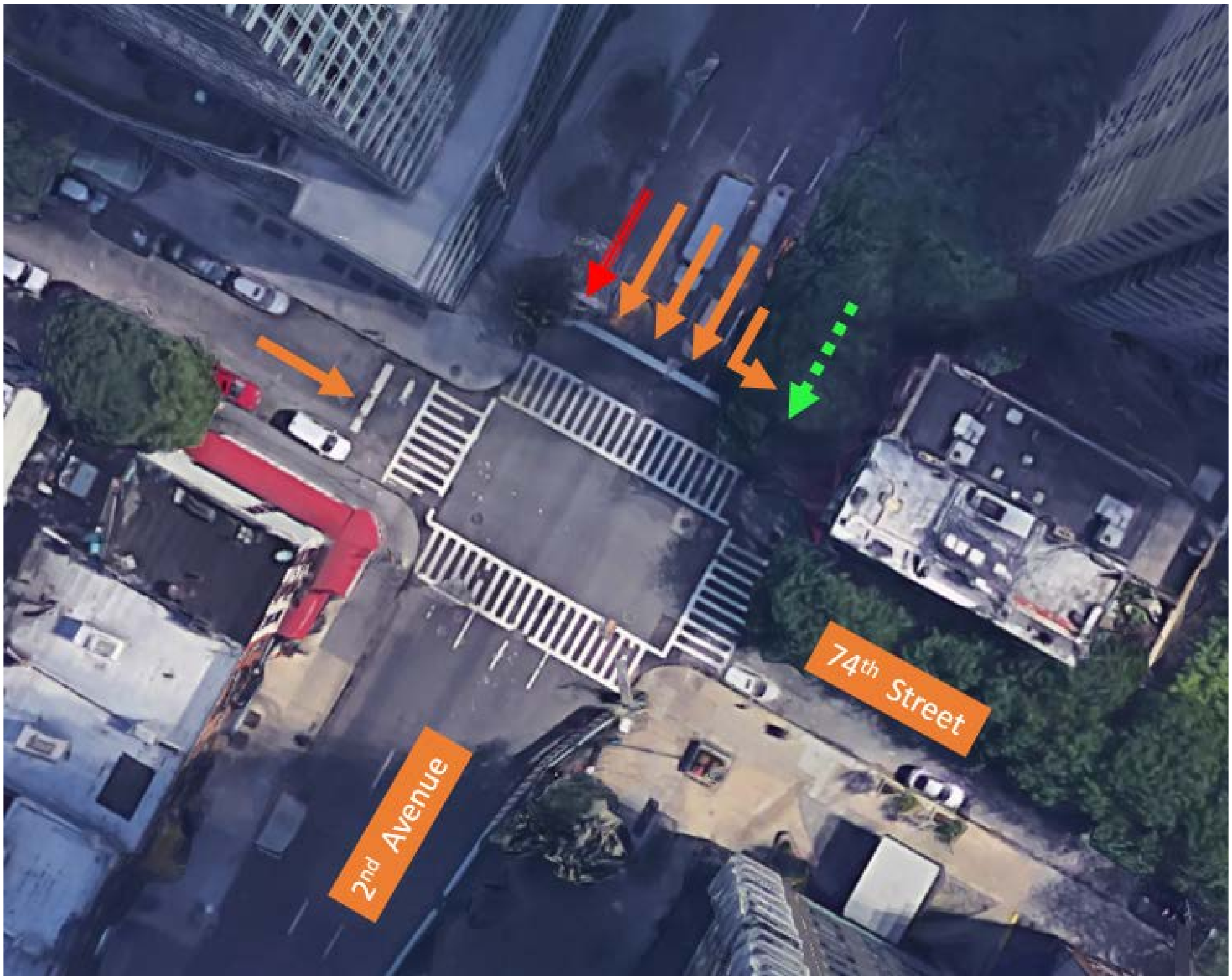


Figure 4.3: 2nd Avenue and 74th Street, New York City

This intersection was analyzed after the implementation of a mixing zone on May 18, 2017, from 8 a.m.to 7 p.m.. Timing plans were obtained for this intersection, and are shown in Figure 4.4. Phase A allows all 2nd Avenue traffic to proceed, and phases B and C allow 74th Avenue traffic to proceed. The average cycle length is 90 seconds, with 50 seconds for phase A, and 40 seconds for phases B and C.

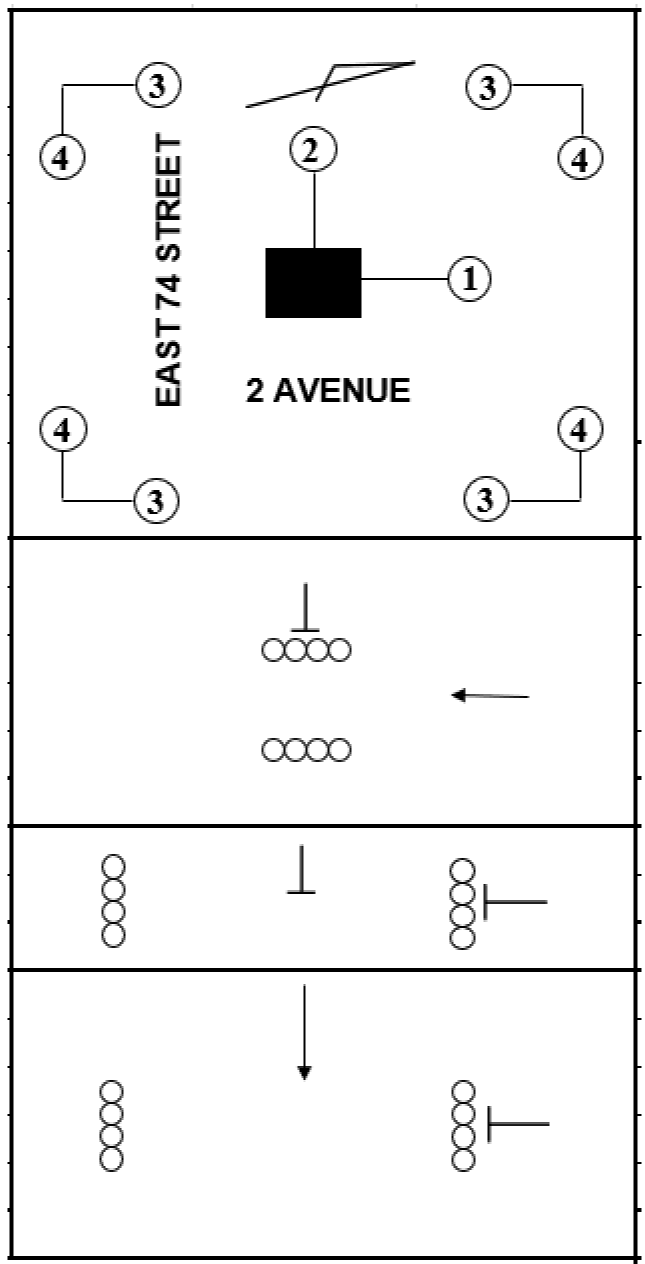


Figure 4.4: Signal Timing Plan for 2nd Avenue and 74th Street

4.1.3 6th Avenue and 23rd Street, New York City

6th Avenue is a one-way street and 74th Avenue is bidirectional. From left to right, 6th Avenue has one bike lane, one vehicle left-turn lane, four vehicle through lanes, and one vehicle right-turn lane. 74th Avenue has two northwest bound lanes and two southeast bound lanes, each direction with one vehicle through lane and one “Bus Only” lane. Figure 4.5 shows the geometry of the intersection. For further clarification, vehicle lanes are shown with a solid line, bicycle lanes are shown with a square dotted line, and bus lanes are shown with a hashed line.

Figure 4.5: 6th Avenue and 23rd Street, New York City

This intersection was analyzed both before and after the implementation of a split LBI. The initial signal timing of the intersection included a LPI, therefore the intersection was analyzed under the LPI conditions first on June 7, 2017, from 8 a.m.to 7 p.m.. Following the implementation of a split LBI, the intersection was analyzed on Feb. 20, 2017, from 7 a.m. to 6 p.m.

Timing plans were obtained for this intersection, and are shown in Figure 4.6 and Figure 4.7. Figure 4.6 shows traditional signal timing, with phases A and C allowing all 6th Avenue traffic to proceed, and phase B allowing 23rd Street traffic to proceed. The average cycle length is 90 seconds, with 50 seconds for phases A and C, and 40 seconds for phase B.

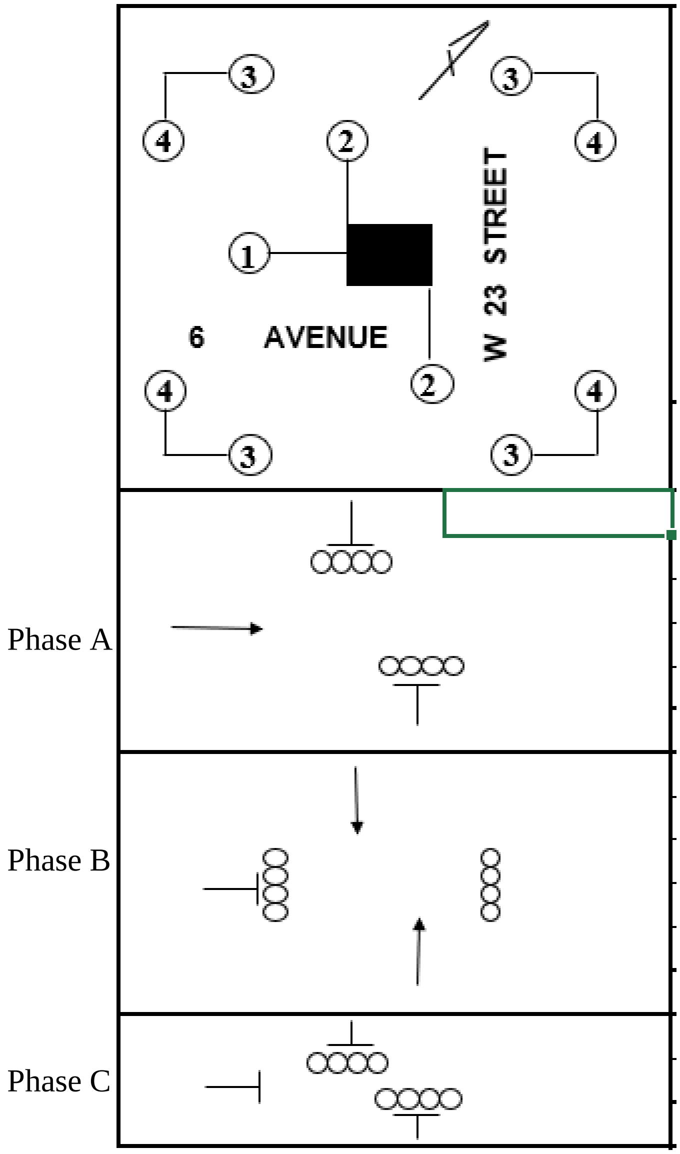


Figure 4.6: Traditional Signal Timing at 6th Avenue and 23rd

Figure 4.7 shows signal timing with the split LBI. Phase A allows all 6th Avenue traffic to proceed, phase B allows 23rd Street traffic to proceed, and phase C shows the split LBI for 6th Avenue. The average cycle length is 90 seconds, with about 40 seconds each for phases A and B, and seven seconds for the split LBI in phase C.

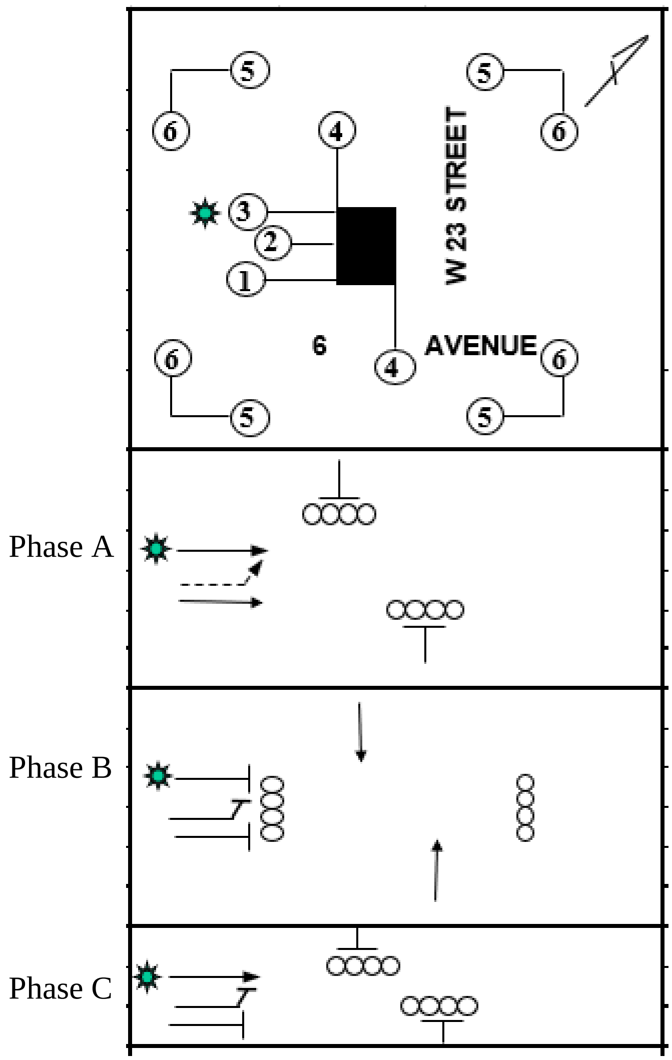


Figure 4.7: Signal Timing with a Split LBI on 6th Avenue and 23rd Street

4.1.4 12th and Campbell, Phoenix

12th Street and Campbell Avenue are both bidirectional roadways. In both directions, 12th Street has one vehicle through left lane, one bike lane, and one vehicle right-turn lane. Campbell Avenue is also mirrored in both directions from left to right, with one vehicle left-turn lane and one vehicle through right lane. Figure 4.8 shows the geometry of the intersection. For further clarification, vehicle lanes are shown with a solid line and bicycle lanes are shown with a square dotted line.

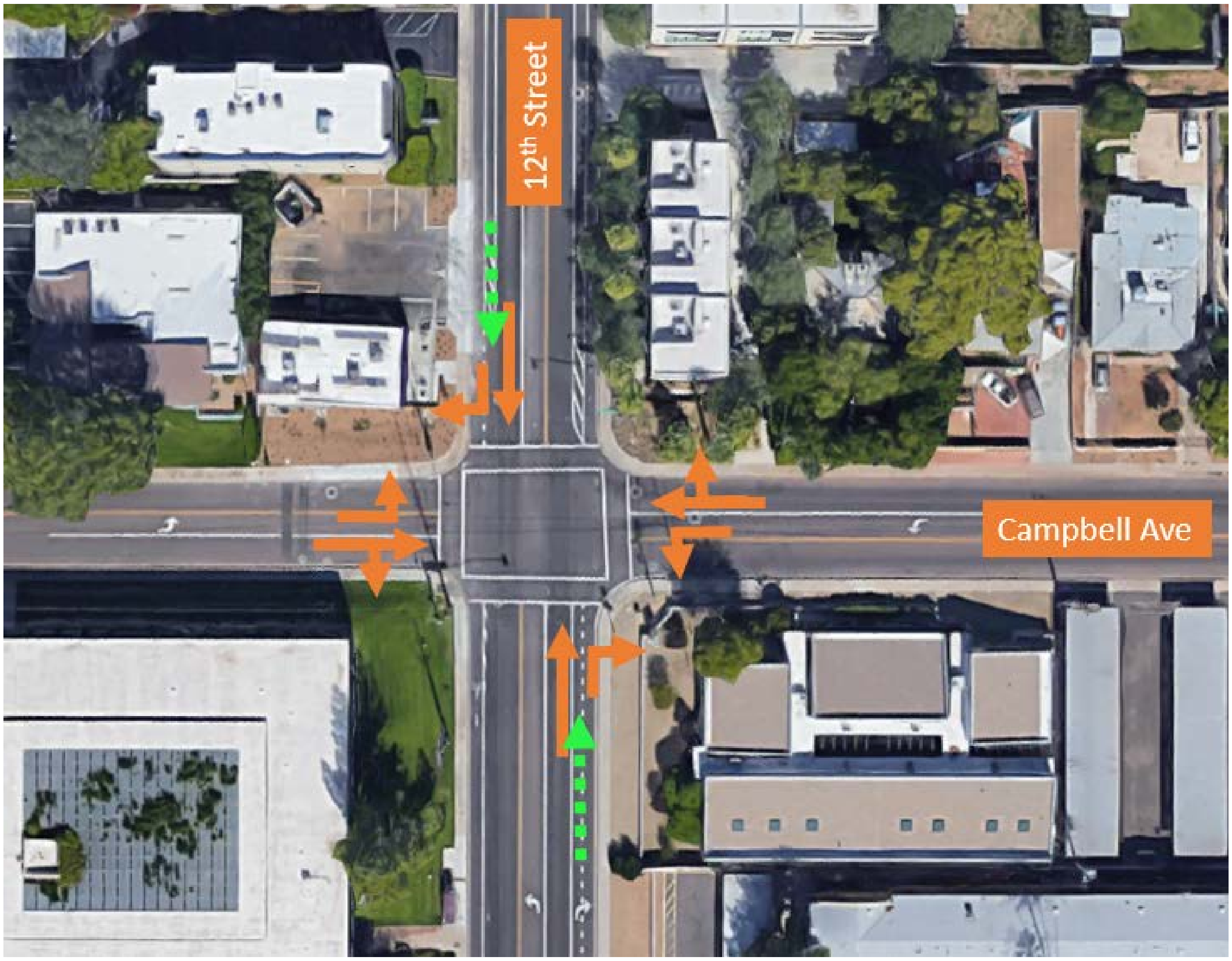


Figure 4.8: 12th Street and Campbell Avenue, Phoenix

This intersection was analyzed both before and after the implementation of a LBI. The traditionally timed intersection was analyzed from Sept. 12, 2017, to Sept. 16, 2017, from 8 a.m. to 8 p.m. Following the implementation of the LBI signal timing treatment, the intersection was analyzed from Sept. 19, 2017, to Sept, 25, 2017, from 8 a.m. to 8 p.m.

4.1.5 Grand and Multnomah, Portland

Grand Avenue is a one-way street and Multnomah Street is bidirectional. From left to right, Grand has one vehicle left through lane, two vehicle through lanes, and one vehicle through right lane that is shared with the Portland Streetcar. Multnomah Street has varying geometries for each direction. Westbound, Multnomah Street has one vehicle left-turn lane, one vehicle through lane, and one vehicle right-turn lane that is shared with a bicycle lane. Eastbound, Multnomah Street has one vehicle left-turn lane, and one vehicle right through lane that is shared with a bicycle lane. Figure 4.9 shows the geometry of the intersection. For further clarification, vehicle lanes are shown with a solid line, bicycle lanes are shown with a square dotted line, and vehicle lanes shared with the Portland Streetcar are shown with a rectangle dotted line.

Figure 4.9: Grand Avenue and Multnomah Street, Portland

This intersection was analyzed after the implementation of a mixing zone on July 10, 2017, from 7 a.m. to 7 p.m. Timing plans were obtained for this intersection, and are shown in Figure 4.10. Phase 2 allows Grand Avenue traffic through the intersection, and phases 4, 7 and 8 allow Multnomah Street traffic through the intersection. The average cycle length is 90 seconds. Phase 2 has a minimum green time of eight seconds and a maximum green time of 45 seconds. Phase 4, which is the eastbound movement of Multnomah Street, has a minimum green time of eight seconds and a maximum green time of 41 seconds. Phase 7, which is the eastbound left-turn movement of Multnomah Street, has a minimum green time of five seconds and a maximum green time of 15 seconds. Phase 8, which is the westbound movement of Multnomah Street including the mixing zone, has a minimum green time of six seconds and a maximum green time of 27 seconds. The pedestrian movements are noted as: “P2,” “P3,” and “P8.” Their timing is associated with each phase number.

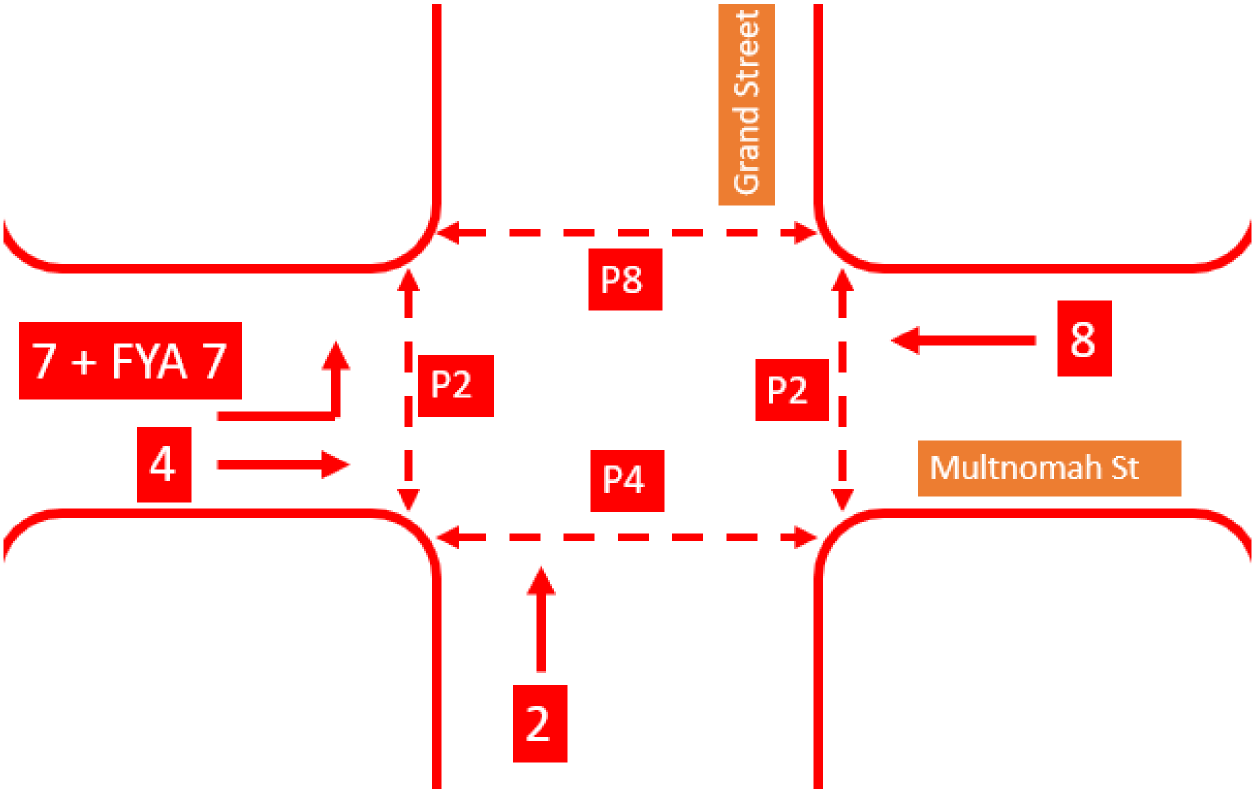


Figure 4.10: Signal Phasing for Grand and Multnomah

4.2 METHODS FOR CONFLICT ANALYSIS

As mentioned previously, post-encroachment time (PET) was used to analyze bicycle-vehicle conflicts throughout the various treatments at each intersection. In order to calculate the PET, a video analysis was done using software that had the ability to advance frame by frame with video resolution greater than one second.

As each bicycle or vehicle entered the frame, a time stamp was recorded along with a specification of bicycle or vehicle. Once the next type of vehicle entered the frame, a time difference was calculated between the two types of candidates for an event. It should be noted that more than one bicycle may be associated as a potential event with only one vehicle, therefore one motor vehicle may count as multiple events. The same may be said for multiple vehicles and one bicycle. If the time difference was ≤ five seconds, the event was classified as an "incident."

To calculate the speed of each bicycle or vehicle, two monuments were identified and the distance between them recorded. Field measurements were preferred, but when unavailable Google Maps was used. The elapsed time between the arrival of a candidate at monument one and the arrival of the same candidate at monument two was noted. The difference was recorded. The speed was calculated by dividing the distance between the two monuments by the elapsed time.

Additionally, the time since bicycle green was measured and recorded. If the signals were visible in the video, the difference in time between the green and the time stamp was subtracted. If the signals were not visible in the video, the movement of the vehicles in the through lanes was taken, added to 1.5 seconds for perception/reaction time, and then the time stamp was subtracted.

In order to calculate the PET, the area of potential collision was defined as the intersection of the bicycle lane (or its extension through the intersection as if it was continuously marked) and the motor vehicle's footprint as it travels across the bicycle lane. The time between one candidate leaving an area of potential collision and the arrival of the next was noted. It was also noted whether the bicycle slowed, swerved, changed lanes, or otherwise maneuvered to avoid collision with a motor vehicle.

Table 4.2 provides a summary of the metrics that were recorded and used to classify an event.

Table 4.2: Metrics Recorded to Calculate PET

Candidate Event	Time Stamp	Time Difference	Incident	PET Value	Elapsed Time for Speed Measurement	Speed	Elapsed Time Bicycle Green	Collision if No Evasive Action Taken
Bicycle or Vehicle	00:00	00:00	Yes or No	00.00	00:00	00.00	00:00	Yes or No

4.3 SUMMARY

This chapter reviews the data and methodology used to study conflicts between bicycles and motor vehicles at signalized intersections in New York City, Phoenix and Portland. Various signal timing strategies were analyzed including LBIs, split LBIs, mixing zones and traditional phasing. The following chapter will describe the analysis of each intersection in greater detail.

5.0 RESULTS

This chapter contains the analysis of each treatment implemented to analyze bicycle-vehicle conflicts. The chapter is divided into sections by treatment. Table 5.1 summarizes the PET value ranges and their associated severities. The assumed perception/reaction time for all intersections was 1.5 seconds.

Table 5.1: PET Severity Summary

PET Value	Severity
≤ 1.5 s	Very Dangerous Interaction
$1.5 \text{ s} < x \leq 3\text{s}$	Dangerous Interaction
$3\text{s} < x \leq 5\text{s}$	Mild Interaction
$x > 5\text{s}$	No Interaction

5.1 TRADITIONAL CONCURRENT PHASING

The following section describes the analysis of the intersections with traditional signal timing.

5.1.1 6th Avenue and 23rd Street, New York City (Before)

A total of 10 hours was analyzed from 8 a.m. to 7 p.m. on June 7, 2017. This data represented the condition when the concurrent timing was operational for bicycles along with a leading pedestrian interval. Data following the installation of the split LBI treatment can be found in Section 5.2.2. Table 5.2 summarizes the data collected. A total of 1,952 bicycles were observed at this intersection along with 1,034 vehicles in the lane next to the bike lane. The 443 incidents observed represented 22.18% proportion of incidents with respect to the total number of bicycles.

Table 5.2: Summary of 6th Avenue and 23rd Street with Concurrent Timing and LPI

Number of Bicycles	1,952
Number of Motor Vehicles	1,034
Number of Incidents	443
Percentage of Incidents Based on Number of Bicycles	22.18%
Near Misses	8
Number of Collisions if No Evasive Action Taken	147

Table 5.3 provides a summary of the total number of incidents and their associated severities. Of the incidents observed, 32% were categorized as very dangerous, 29% dangerous, 30% mild and 6% were classified as no interaction.

Figure 5.1 provides a visual representation of this information, showing the frequency that each PET value appears in the data. A value of "0" for a PET value indicates the bicycle went around the car. From this data we can see that about one-fifth of the total number of bicyclists were involved in an incident. The severity of incidents is evenly distributed, apart from those with no interaction.

Table 5.3: Severity Summary for 6th Avenue and 23rd Street with LBI

Severity	Total Incidents of Specified Severity	Percentage of Total Incidents
Very Dangerous Interaction	142	32.1%
Dangerous Interaction	129	29.1%
Mild Interaction	134	30.2%
No Interaction	28	6.3%

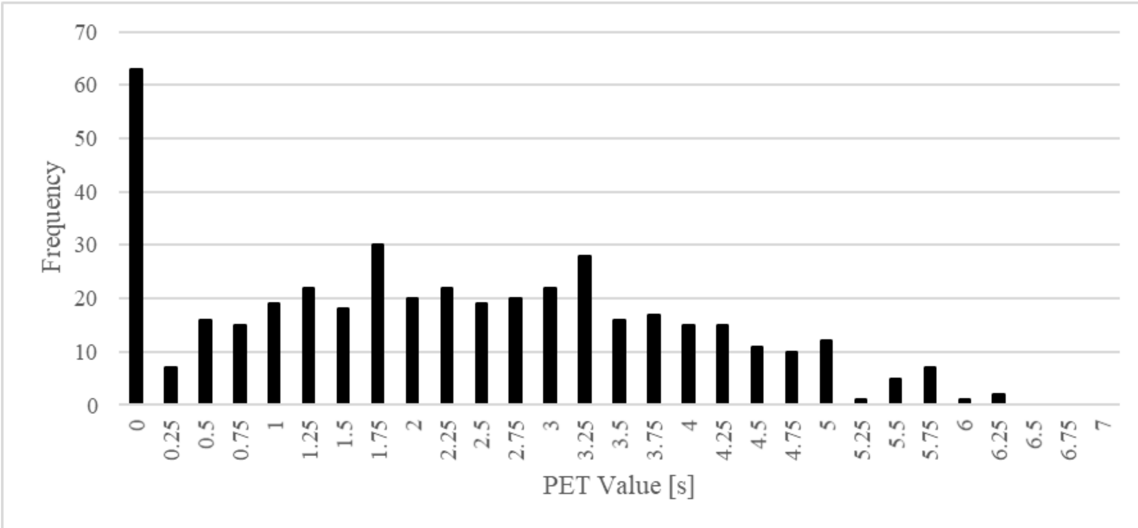


Figure 5.1: Frequency of PET Values at 6th Avenue and 23rd Street with LPI

Figure 5.2 shows the frequency of each calculated time difference between conflicting bicycles and vehicles entering the intersection. Again, the time differences are somewhat evenly distributed, which explains the similarly distributed PET values.

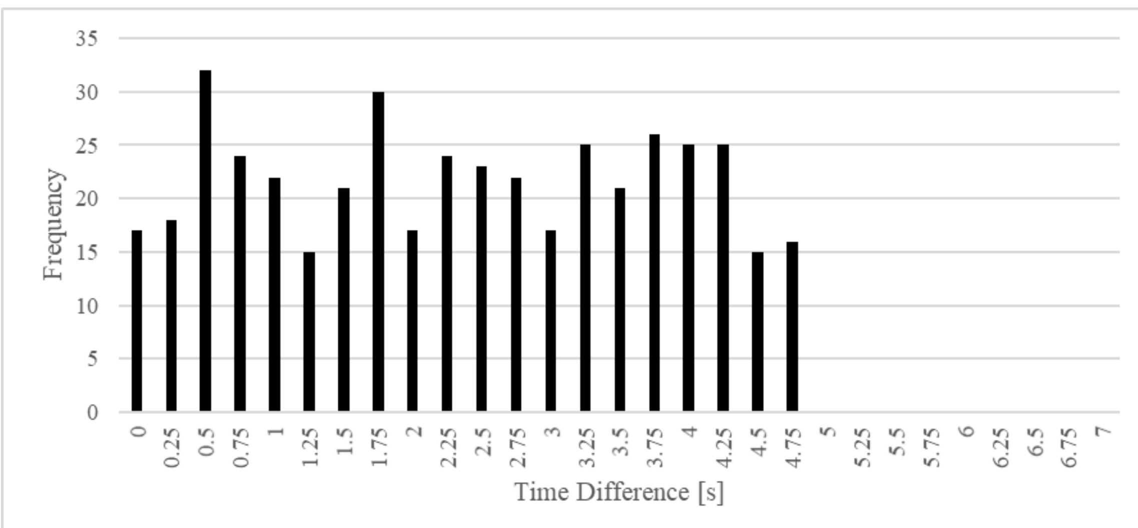


Figure 5.2: Time Difference Between Conflicting Bicycles and Vehicles at 6th Avenue and 23rd Street with LBI

Figure 5.3 shows the number of conflicts after an elapsed green time. At this intersection, although no LBI was present, our observations revealed that few bicyclists used the lead interval provided for pedestrians.

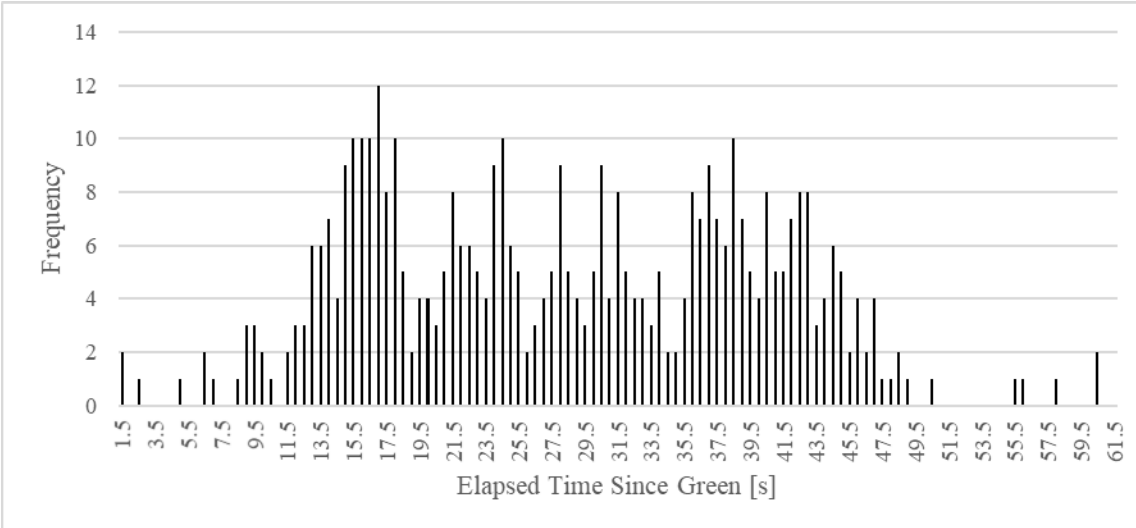


Figure 5.3: Elapsed Time Since Green at 6th Avenue and 23rd Street with LBI

Figure 5.4 compares the speed of bicycles and vehicles traveling through the intersection. The distribution of motor vehicle speed is lower than the majority of the bicycle speeds, due to the turning maneuver.

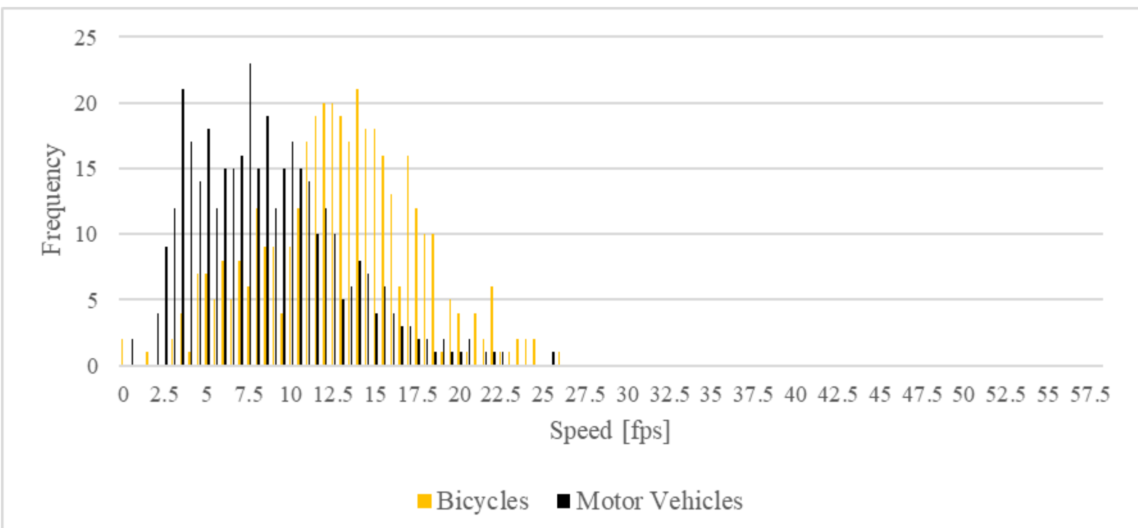


Figure 5.4: Speed of Bicycles and Motor Vehicles Through 6th Avenue and 23rd Street with LBI

5.1.2 12th and Campbell, Phoenix (Before)

A total of six days of video data was collected from Sept. 12, 2016, to Sept. 16, 2016. This data represented the condition when traditional signal timing was operational. Data following the installation of the LBI can be found in Section 5.3.1. Eighty-seven bicycles were observed in the before period. However, no incidents were recorded during this time period, therefore no PET values were calculated.

5.2 SPLIT LEADING BIKE INTERVAL (SPLIT LBI)

The following section describes the analysis of the intersections with split LBI.

5.2.1 1st Avenue and 61st Street, New York City (After)

A total of nine hours of video data were available and analyzed from 10:30 a.m.to 7:30 p.m. on March 16, 2017. This data represented the condition when the split LBI treatment was installed and operational. Data prior to the installation of the split LBI treatment was not available, and hence a before-after analysis could not be conducted. Table 5.4 summarizes the data collected. A total of 1,166 bicycles were observed at this intersection along with 1,619 vehicles in the lane next to the bike lane. The 445 incidents observed represented 38.16% proportion of incidents with respect to the total number of bicycles.

Table 5.4: Summary of 1st Avenue and 61st Street

Number of Bicycles	1,166
Number of Motor Vehicles	1,619
Number of Incidents	445
Percentage of Incidents Based on Number of Bicycles	38.16%
Near Misses	11
Number of Collisions if No Evasive Action Taken	197

Table 5.5 provides a summary of the total number of incidents and their associated severities. The majority of the incidents at this intersection (61%) were classified as very dangerous interactions based on their PET values. Figure 5.5 provides a visual representation of this information, showing the frequency that each PET value appears in the data. A value of “0” for a PET value indicates the bicycle went around the car. From this data we can see that over one-third of the total number of bicyclists were involved in an incident, and over half of those bicyclists experienced a very dangerous interaction.

Table 5.5: Severity Summary for 1st Avenue and 61st Street

Severity	Total Incidents of Specified Severity	Percentage of Total Incidents
Very Dangerous Interaction	272	61.1%
Dangerous Interaction	142	31.9%
Mild Interaction	29	6.5%
No Interaction	2	0.4%

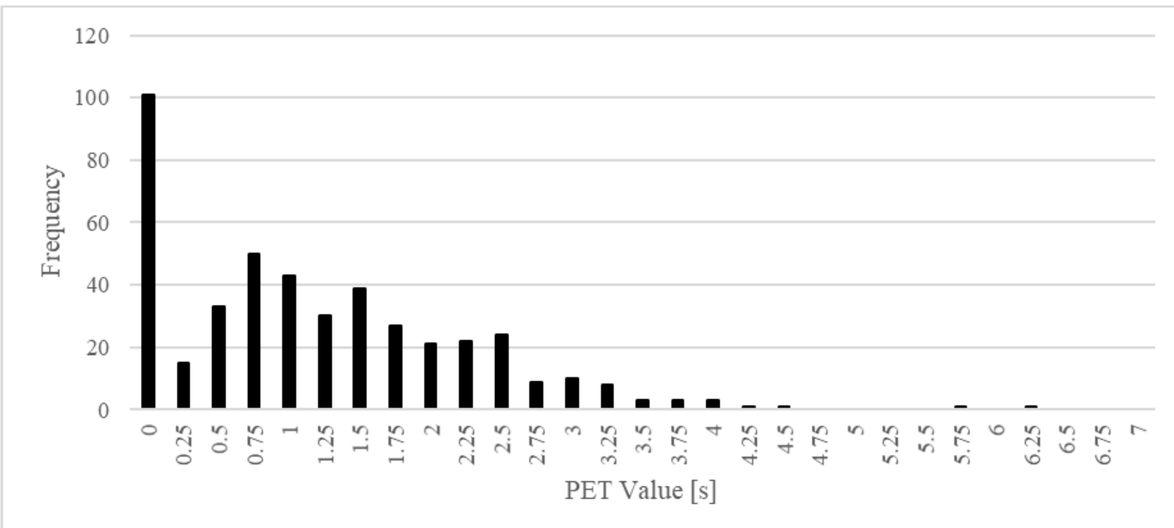


Figure 5.5: Frequency of PET Values at 1st Avenue and 61st Street

Figure 5.6 shows the frequency of each calculated time difference between conflicting bicycles and vehicles entering the intersection. The majority of the values are at three seconds and below, which describes why most PET values were in the "very dangerous" and "dangerous" interaction ranges.

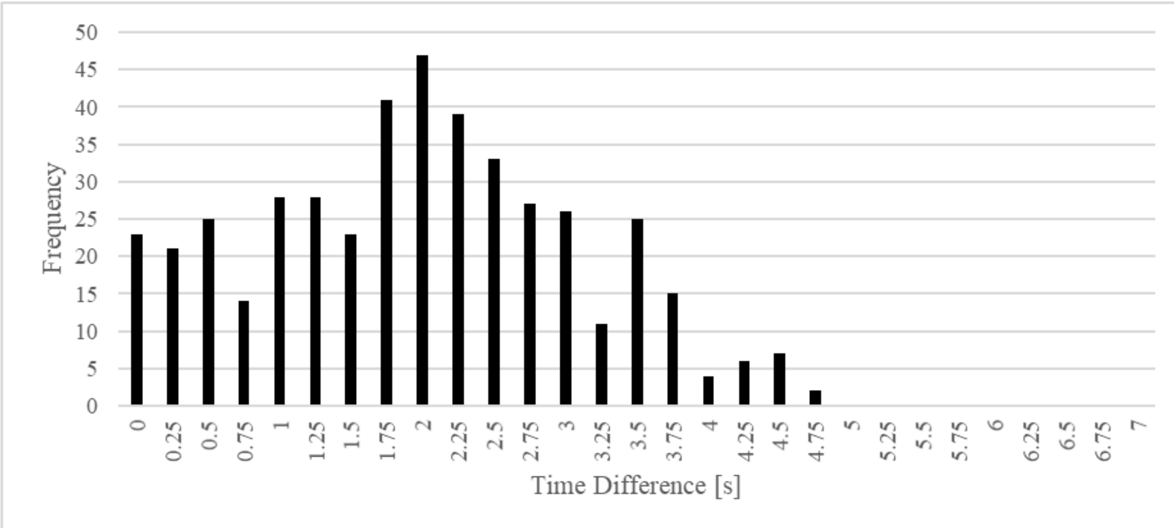


Figure 5.6: Time Difference Between Conflicting Bicycles and Vehicles at 1st Avenue and 61st Street

Figure 5.7 shows the number of conflicts after an elapsed green time. Notably, with the eight-second lead interval for bicyclists, there are only three conflicts occurring during this time period. The majority of the conflicts occur during the “stale green.”

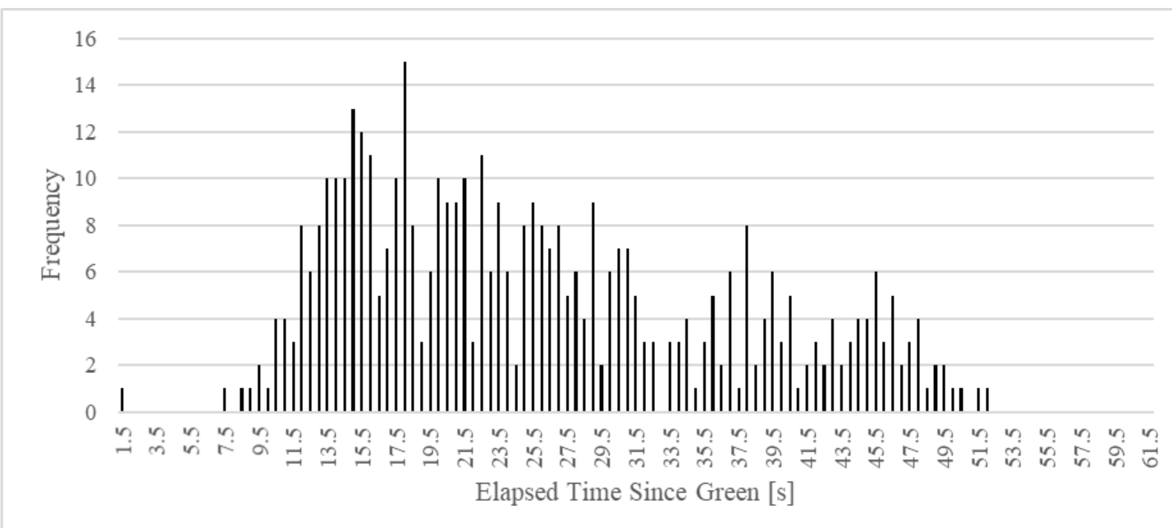


Figure 5.7: Elapsed Time Since Green at 1st Avenue and 61st Street

Figure 5.8 compares the speed of bicycles and vehicles traveling through the intersection. The distribution of motor vehicle speed is more consistent, while the majority of bicycle speeds are around 10 to 17.5 feet per second.

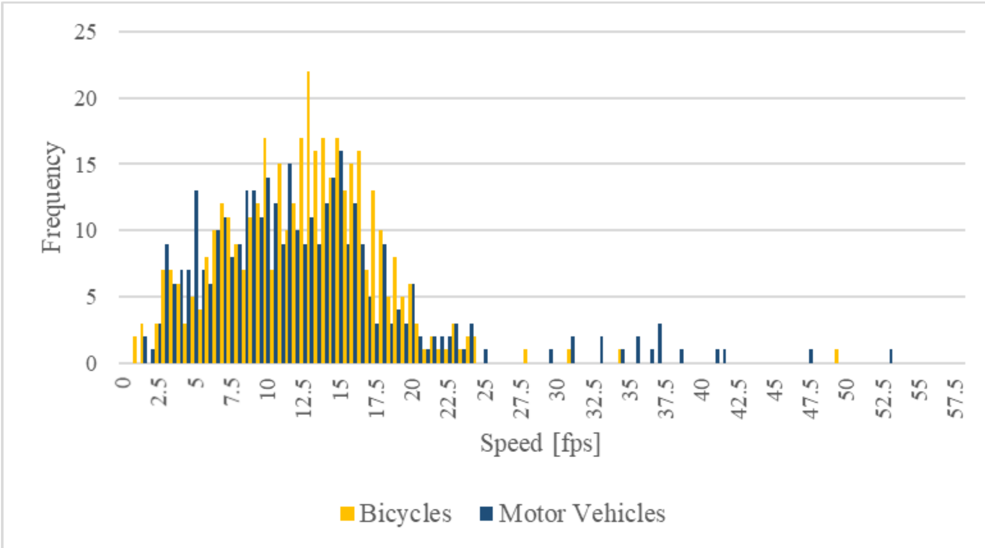


Figure 5.8: Speed of Bicycles and Motor Vehicles Through 1st Avenue and 61st Street

5.2.2 6th Avenue and 23rd Street, New York City (After)

A total of 11 hours was analyzed from 7 a.m. to 6 p.m. on Feb. 20, 2017. This data represented the condition when the split LBI treatment was installed and operational. Data prior to the installation of the split LBI treatment can be found in Section 5.1.1. Table 5.6 summarizes the data collected. A total of 1,300 bicycles were observed at this intersection along with 773 vehicles in the lane next to the bike lane. The 221 incidents observed represented 17% proportion of incidents with respect to the total number of bicycles.

Table 5.6: Summary of 6th Avenue and 23rd Street with Split LBI

Number of Bicycles	1,300
Number of Motor Vehicles	773
Number of Incidents	221
Percentage of Incidents Based on Number of Bicycles	17.00%
Near Misses	0
Number of Collisions if No Evasive Action Taken	46

Table 5.7 provides a summary of the total number of incidents and their associated severities; 43% of the interactions were classified as very dangerous, followed by 23% as dangerous, 26% as mild and 8% as no interaction. Figure 5.9 provides a visual representation of this information, showing the frequency that each PET value appears in the data. A value of “0” for a PET value indicates the bicycle went around the car. From this data we can see that nearly one-fifth of the total number of bicyclists were involved in an incident. While over two-fifths of the bicyclists

involved in an incident experienced a "Very Dangerous" interaction, the frequency of each severity is more evenly distributed than at 1st Avenue and 61st Street.

Table 5.7: Severity Summary for 6th Avenue and 23rd Street with Split LBI

Severity	Total Incidents of Specified Severity	Percentage of Total Incidents
Very Dangerous Interaction	94	42.5%
Dangerous Interaction	51	23.1%
Mild Interaction	58	26.2%
No Interaction	18	8.1%

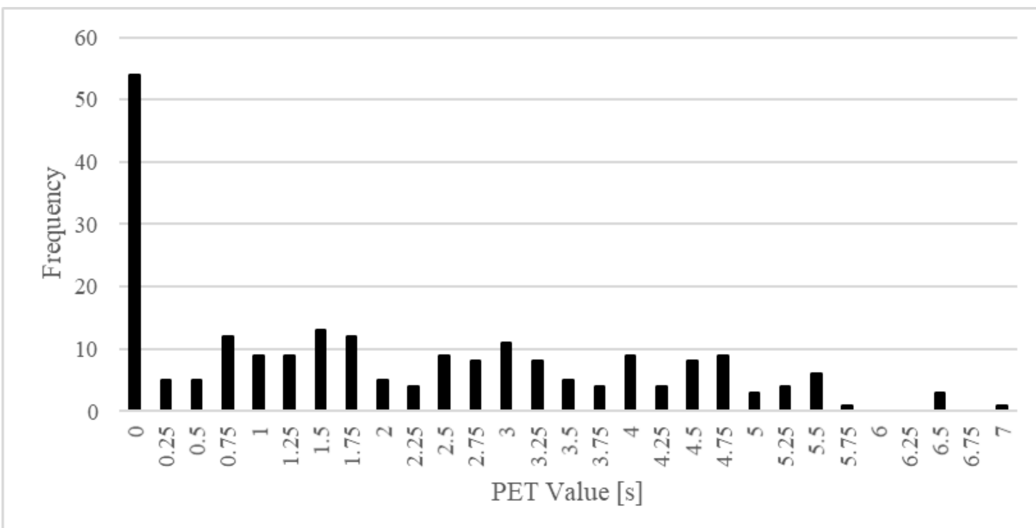


Figure 5.9: Frequency of PET Values at 6th Avenue and 23rd Street with Split LBI

Figure 5.10 shows the frequency of each calculated time difference between conflicting bicycles and vehicles entering the intersection. Again, the time differences are more evenly distributed, with a larger portion being below 1.5 seconds in the PET severity category of "Very Dangerous."

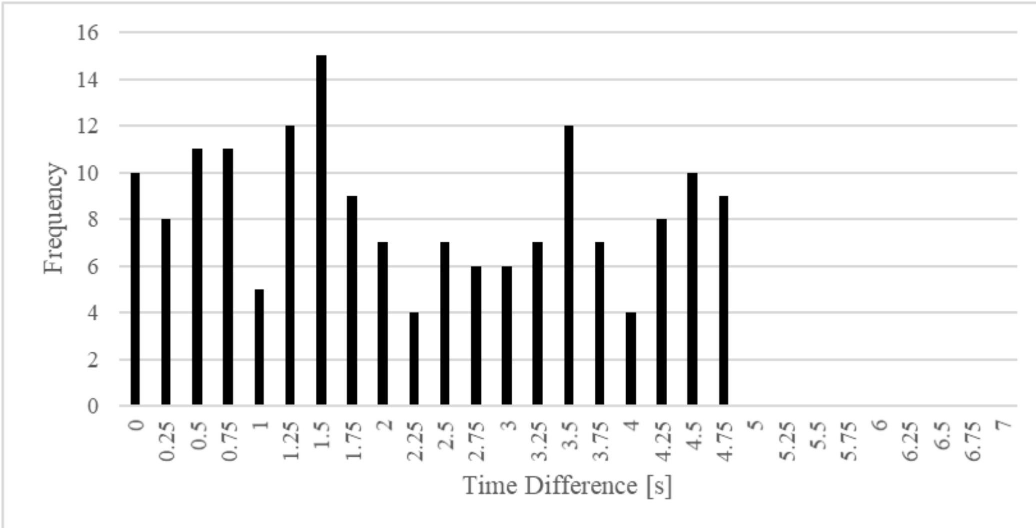


Figure 5.10: Time Difference Between Conflicting Bicycles and Vehicles at 6th Avenue and 23rd Street with Split LBI

Figure 5.11 shows the number of conflicts after an elapsed green time. Notably, only one conflict occurs during the seven-second lead interval for bicyclists, and the majority of conflicts occur well after the lead interval.

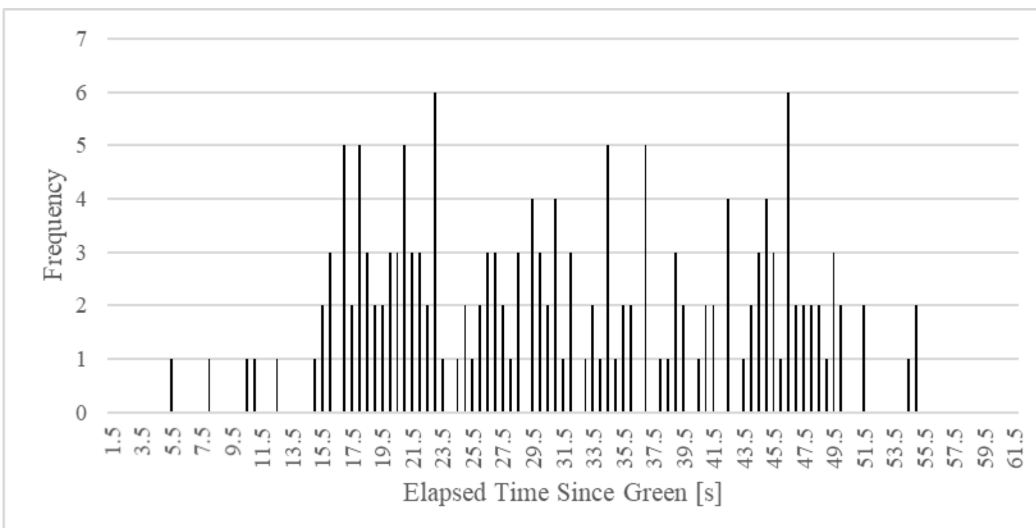


Figure 5.11: Elapsed Time Since Green at 6th Avenue and 23rd Street with Split LBI

Figure 5.12 compares the speed of bicycles and vehicles traveling through the intersection. The distribution of motor vehicle speed is lower than the majority of the bicycle speeds.

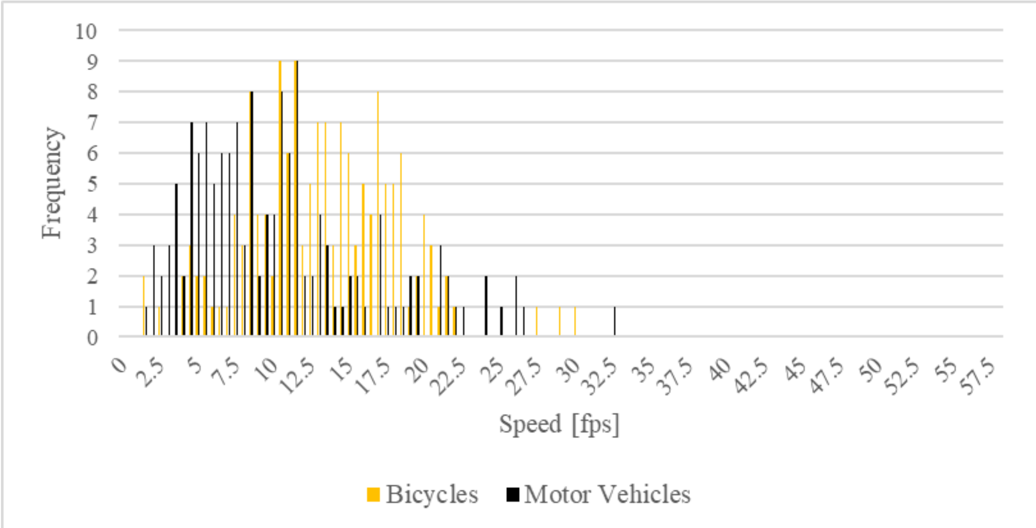


Figure 5.12: Speed of Bicycles and Motor Vehicles Through 6th Avenue and 23rd Street

5.3 LEADING BIKE INTERVAL (LBI)

The following section describes the analysis of the intersections with LBI.

5.3.1 12th and Campbell, Phoenix (After)

A total of six days of data was collected from Sept. 19, 2016, to Sept. 25, 2016. This data represented the condition when the LBI treatment was installed and operational. Data prior to the installation of the LBI treatment can be found in Section 5.1.1 Seventy-four bicycles were observed after the LBI was implemented. No incidents were recorded during this time period; therefore no PET values were calculated.

5.4 MIXING ZONE

The following section describes the analysis of the intersections with a mixing zone.

5.4.1 2nd Avenue and 74th Street, New York City

A total of 11 hours was analyzed from 8 a.m. to 7 p.m. on May 18, 2017. This data represented the condition when the mixing zone treatment was installed and operational. Data prior to the installation of the mixing zone was not available, and hence a before-after analysis could not be conducted. Table 5.8 summarizes the data collected. A total of 1,425 bicycles were observed at this intersection along with 1,206 vehicles in the lane next to the bike lane. The 253 incidents observed represented 18% proportion of incidents with respect to the total number of bicycles.

Table 5.8: Summary of 2nd Avenue and 74th Street

Number of Bicycles	1,425
Number of Motor Vehicles	1,206
Number of Incidents	253
Percentage of Incidents Based on Number of Bicycles	17.75%
Near Misses	4
Number of Collisions if No Evasive Action Taken	57

Table 5.9 provides a summary of the total number of incidents and their associated severities. Figure 5.13 provides a visual representation of this information, showing the frequency that each PET value appears in the data. A value of "0" for a PET value indicates the bicycle went around the car. From this data we can see that nearly one-fifth of the total number of bicyclists were involved in an incident. The number of "Very Dangerous" and "Dangerous" interactions are almost the same, and account for three-fourths of the total number of incidents shown in the graph as higher frequencies of lower PET values.

Table 5.9: Severity Summary for 2nd Avenue and 74th Street

Severity	Total Incidents of Specified Severity	Percentage of Total Incidents
Very Dangerous Interaction	95	37.5%
Dangerous Interaction	93	36.8%
Mild Interaction	54	21.3%
No Interaction	11	4.3%

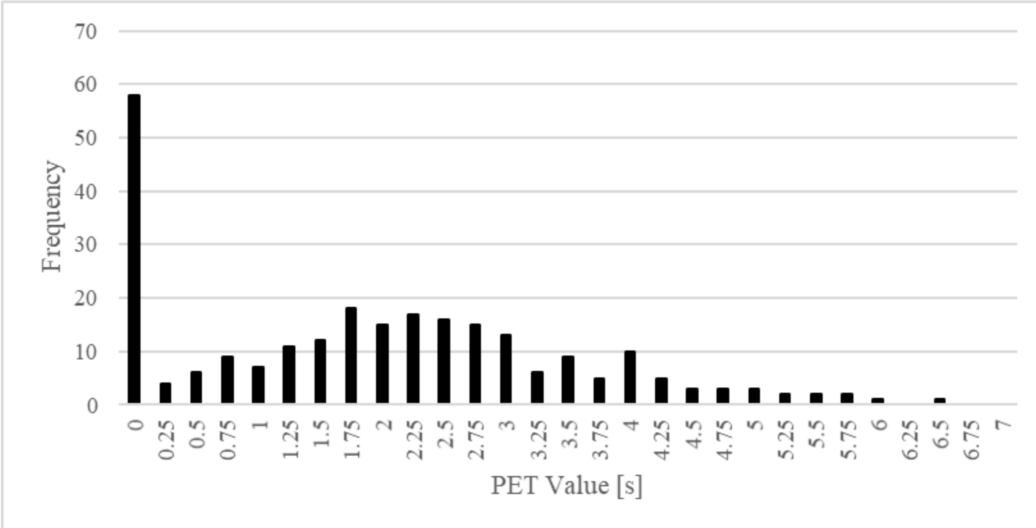


Figure 5.13: Frequency of PET Values at 2nd Avenue and 74th Street

Figure 5.14 shows the frequency of each calculated time difference between conflicting bicycles and vehicles entering the intersection. There is a higher distribution of values at lower time differences, followed by a more inconsistent distribution following 1.5 seconds.

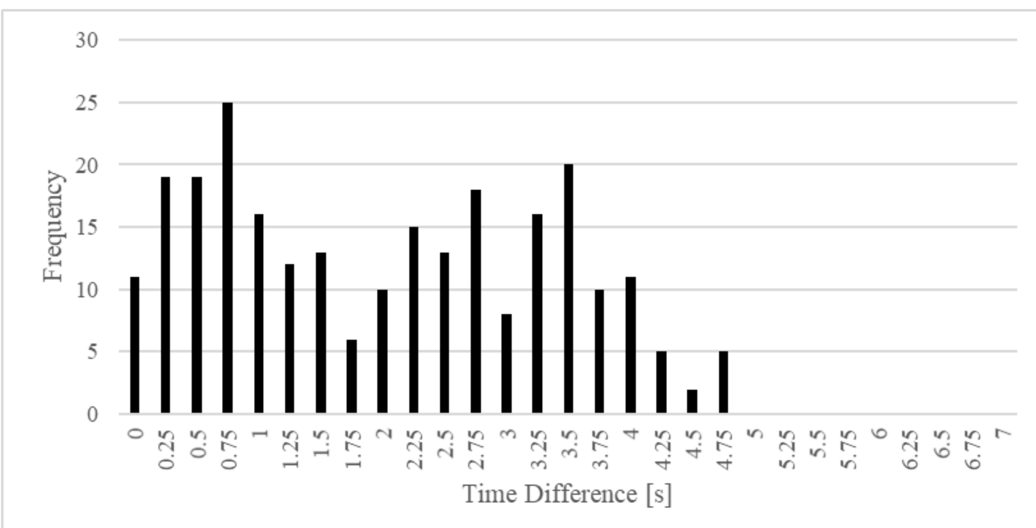


Figure 5.14: Time Difference Between Conflicting Bicycles and Vehicles at 2nd Avenue and 74th Street

Figure 5.15 shows the elapsed time that occurs after a green light before vehicles proceed through the intersection. Notably, even though the mixing zone treatment does not provide a leading interval for bicyclists there are no cars leaving before 7.5 seconds, showing a higher compliance rate than treatments with LBI.

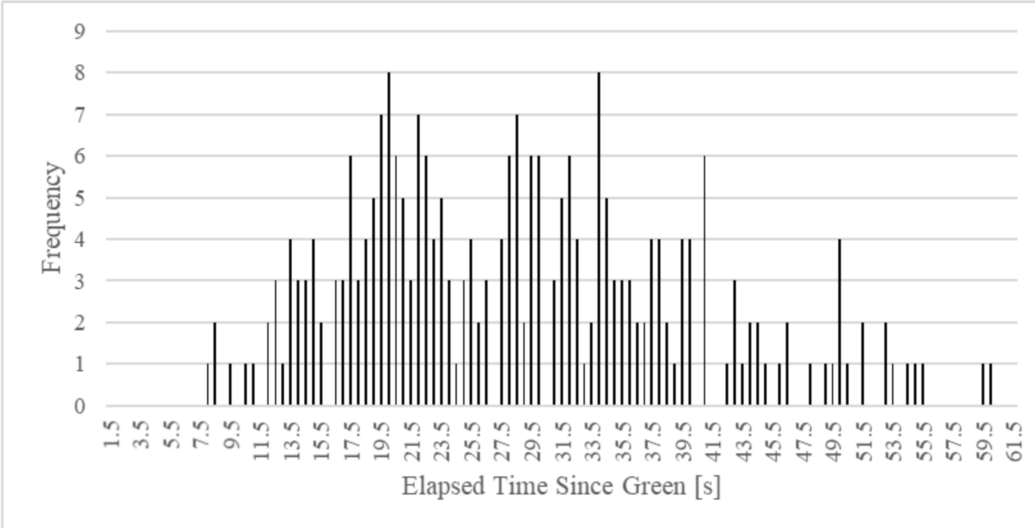


Figure 5.15: Elapsed Time Since Green at 2nd Avenue and 74th Street

Figure 5.16 compares the speed of bicycles and vehicles traveling through the intersection. The distribution of motor vehicle speed is lower than the majority of the bicycle speeds.

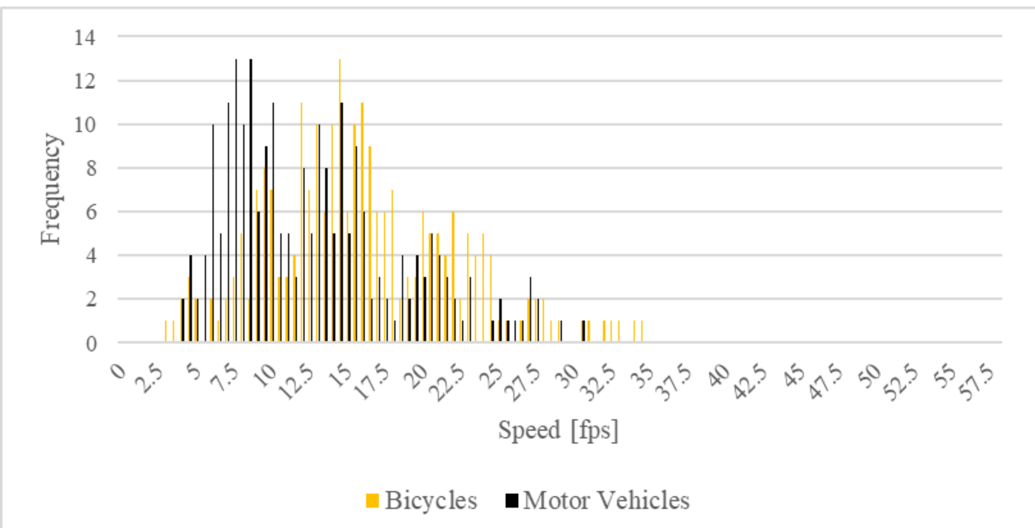


Figure 5.16: Speed of Bicycles and Motor Vehicles Through 2nd Avenue and 74th Street

5.4.2 Grand and Multnomah, Portland

A total of 11 hours was analyzed from 7 a.m. to 7 p.m. on July 10, 2017. This data represented the condition when the mixing zone treatment was installed and operational. Data prior to the installation of the mixing zone was not available, and hence a before-after analysis could not be conducted. Table 5.10 summarizes the data collected. A total of 352 bicycles were observed at this intersection along with 1,143 vehicles in the lane next to the bike lane. The 76 incidents observed represented 22% proportion of incidents with respect to the total number of bicycles.

Table 5.10: Summary of Grand and Multnomah

Number of Bicycles	352
Number of Motor Vehicles	1,143
Number of Incidents	76
Percentage of Incidents Based on Number of Bicycles	21.59%
Near Misses	0
Number of Collisions if No Evasive Action Taken	4

Table 5.11 provides a summary of the total number of incidents and their associated severities. Figure 5.17 provides a visual representation of this information, showing the frequency that each PET value appears in the data. A value of "0" for a PET value indicates the bicycle went around the car. From this data we can see that nearly one-fifth of the total number of bicyclists were involved in an incident. The number of "Very Dangerous" and "Dangerous" interactions are exactly the same; however, the number of "Mild" interactions is greater. There is an interesting gap in Figure 5.17 where no PET values are recorded from 0.25 – 0.5, which would be the most dangerous PET values.

Table 5.11: Severity Summary for Grand and Multnomah

Severity	Total Incidents of Specified Severity	Percentage of Total Incidents
Very Dangerous Interaction	22	28.9%
Dangerous Interaction	22	28.9%
Mild Interaction	25	32.9%
No Interaction	7	9.2%

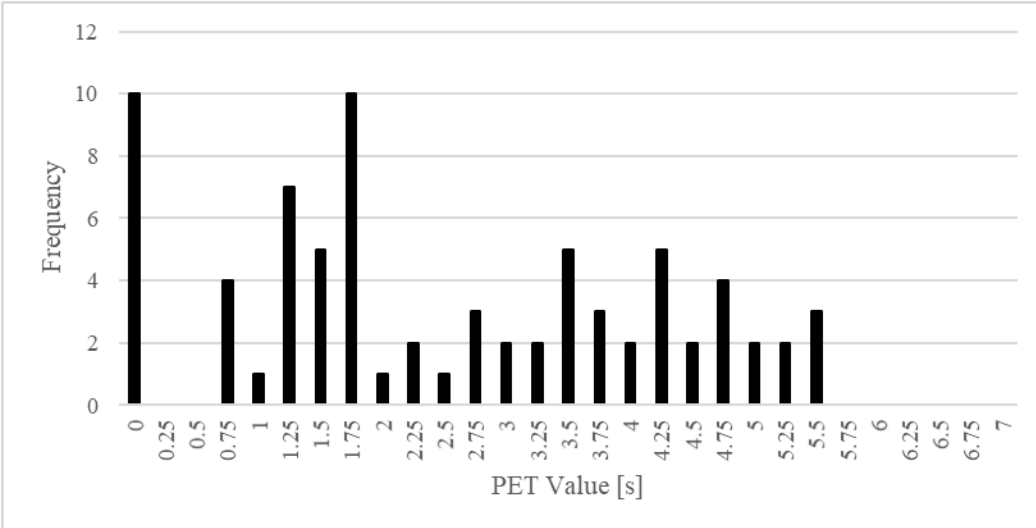


Figure 5.17: Frequency of PET Values at Grand and Multnomah

Figure 5.18 shows the frequency of each calculated time difference between conflicting bicycles and vehicles entering the intersection. The entire distribution is shifted more to the right than graphs in the previous sections, showing that bicycles and vehicles at Grand and Multnomah had more time to avoid a potential collision.

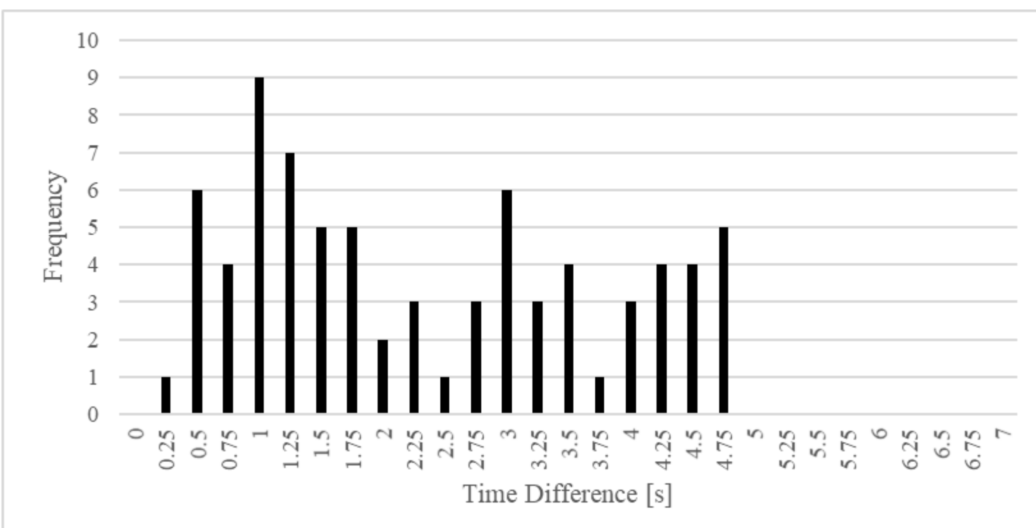


Figure 5.18: Time Difference Between Conflicting Bicycles and Vehicles at Grand and Multnomah

Figure 5.19 shows the elapsed time that occurs after a green light before vehicles proceed through the intersection. Notably, this intersection shows a more even distribution of elapsed time since green than the other study intersections, with larger gaps between frequent data points.

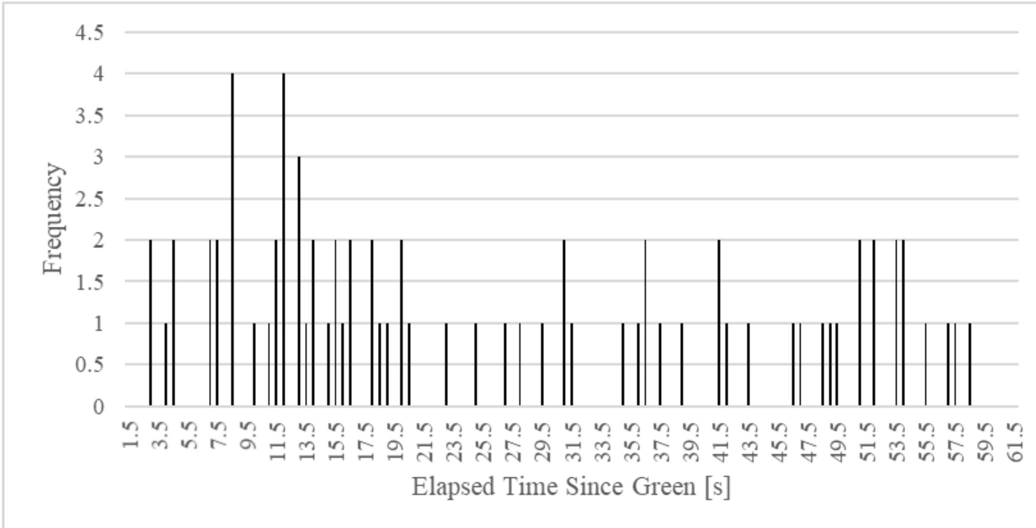


Figure 5.19: Elapsed Time Since Green at Grand and Multnomah

Figure 5.20 compares the speed of bicycles and vehicles traveling through the intersection. The distribution of motor vehicle speed is very similar to the distribution of bicycle speeds.

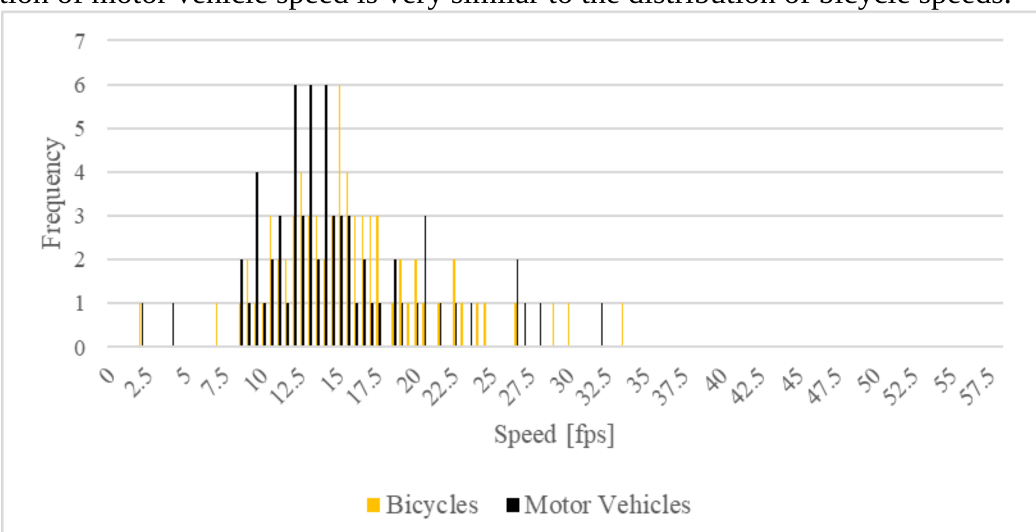


Figure 5.20: Speed of Bicycles and Motor Vehicles Through Grand and Multnomah

5.5 SUMMARY

This chapter contained the results observed from the video analysis of each treatment implemented to analyze bicycle-vehicle conflicts. Five locations were analyzed and PET times were derived at each location. The following chapter discusses the results.

6.0 DISCUSSION OF RESULTS

This study analyzed geometric and signal timing treatments to address bicycle-vehicle conflicts. The treatments analyzed include traditional with LPI, split LBI and mixing zones. Table 6.1 shows the summary of the results from all the sites.

Table 6.1: Summary of Conflict Analysis

Location	Treatment	Hours	Total # of Bicycles	Total # of Motor Vehicles	Total Incidents	% Total Incidents	Near Misses	# of Collisions without Evasive Action
6th Ave and 23rd St (B)	LPI	10:00	1,952	1,034	433	22.18	8	147
1st Ave and 61st St	Split LBI	8:57	1,166	1,619	445	38.16	11	197
6th Ave and 23rd St (A)	Split LBI	11:00	1,300	773	221	17.00	0	46
2nd Ave and 74th St	Mixing Zone	11:00	1,425	1,206	253	17.75	4	57
Grand and Multnomah	Mixing Zone	11:00	352	1,143	76	21.59	0	4

The percentage of total incidents, which is computed as the ratio of total incidents to the total number of bicycles, is highest at the1st Avenue and 61st Street intersection with the split LBI treatment. The research team hypothesized that the higher percentage of incidents was due to the higher number of motor vehicles at this site compared to other sites. One vehicle may interact with multiple bicycles, thus giving rise to multiple incidents. The percentage of total incidents at the two split LBI locations were significantly different. The percentage of total incidents at the two mixing zone sites were similar and varied between 18% and 22%.

Table 6.2 shows the classification of PET values at each of these intersections. The highest proportion of very dangerous interactions occur at the 1st Avenue and 61st Street intersection, followed by 6th Avenue and 23rd Street with the split LBI treatment. Dangerous interactions were highest at the 2nd Avenue and 74th Street location. The highest proportion of mild interactions were observed at Grand and Multnomah.

Table 6.2: Classification of PET

Location	Very Dangerous Interaction (PET ≤ 1.5 s)	Dangerous Interaction (1.5 s < PET ≤ 3 s)	Mild Interaction (3 s < PET ≤ 5 s)	No Interaction (PET > 5 s)
6th Ave and 23rd St (B)	142 (32.79%)	129 (29.79%)	134 (30.95%)	28 (6.47%)
1st Ave and 61st St	272 (61.12%)	142 (31.91%)	29 (6.51%)	2 (0.45%)
6th Ave and 23rd St (A)	94 (42.53%)	51 (23.08%)	58 (26.24%)	18 (8.14%)
2nd Ave and 74th St	95 (37.55%)	93 (36.76%)	54 (21.34%)	11 (4.34%)
Grand and Multnomah	22 (28.95%)	22 (28.95%)	25 (32.89%)	7 (9.21%)

6.1 TRADITIONAL WITH LPI

This treatment was observed at one intersection, 6th Avenue and 23rd Street, in the before condition. At this location, pedestrians were provided with a leading pedestrian interval, but a corresponding leading bike interval was not provided. However, our observations revealed that the bicyclists also took advantage of the LPI and started moving during the pedestrian walk phase. Video observations revealed queue buildup in every cycle. Since the parking lane was right next to the curb, in the absence of available parking cab drivers were often observed waiting in the bicycle lane, which caused bicyclists to go around them. Additionally, the absence of an exclusive turn lane led to queue backup, as the turning vehicles stopped to let the pedestrians cross.

6.2 SPLIT LBI

With the split LBI treatment, there is little to no risk for bicyclists during the leading interval. However, the risk for bicyclists is shifted towards the stale green portion of the phase. During the latter portion of the green phase, turning vehicles have to yield to through bicyclists. The visibility of bicyclists, especially if they are approaching the intersection during the stale green, is of concern, particularly if turning motorists are not paying attention.

The proportions of very dangerous and dangerous interactions are significantly higher at the 1st Avenue and 61st Street location compared to the 6th Avenue and 23rd Street location. The higher proportion of severe interactions could be a result of the higher turn volumes observed at 1st and 61st. Additionally, there is a downhill grade at this location, which could have impacted the speed of bicyclists. The impact of crossing pedestrians on PET could not be determined due to the camera angle.

The geometric changes at 6th Avenue and 23rd Street were beneficial towards improving overall mobility at the intersection. In the after condition with the split LBI treatment, an exclusive right-turn lane was added and the bicycle lane was moved to be curb tight, replacing on-street parking.

The video observations showed that queues were less frequent and bicyclists were also observed to go around vehicles less. Installing an exclusive left-turn lane also improved bicycle visibility.

6.3 MIXING ZONE

With the mixing zone treatment, the percentage of total incidents at both locations were comparable. However, our observations revealed significant confusion exhibited by both cyclists and drivers with respect to the correct action to be taken. Our observations revealed that a significant percentage of the vehicles merged into the mixing zone at the very last second, thus adding to the confusion. Our findings align with previous findings by Monsere et al. who also found evidence of confusion in mixing zones (Monsere et al., 2014). Monsere et al. found that only 63% of the bicyclists observed in their study used the mixing zone correctly.

6.4 STRATEGY IMPLEMENTATION

Although safety is of paramount concern for practitioners while choosing a signal timing strategy, its efficiency must also be considered. Based on the microsimulation analysis conducted in this study, concurrent phasing was the most efficient treatment while exclusive bicycle phasing was the least efficient. The ranking of strategies by efficiency is shown in Table 6.3. Mixing zone treatment is not shown in this table, because it is not a signal timing strategy and the timing for a mixing zone treatment is similar to concurrent timing.

Table 6.3: Ranking of Signal Timing Treatments for Bicycles Based on Efficiency

Treatment	Rank (1 is the highest)
Concurrent	1
Split LBI	2
LBI	3
Exclusive Bicycle Phase	4

Ranking the strategies by safety impacts is harder, because all the signal timing strategies were not evaluated in this study via video observations and conflict analysis. Additionally, there was no observable trend with respect to the percentage of total incidents and a particular strategy (For example, 1st Avenue and 61st Street had higher proportions of total incidents when compared to the two mixing zone locations; however, the 6th Avenue and 23rd Street location had a lower proportion of total incidents). Exclusive bicycle phases, in theory, can be the safest treatment because they remove all conflicts by allotting bicycles their own phase. However, this treatment was not studied during the field data collection. Split LBIs and LBIs offer safe passage for bicycles during the leading interval; however, during the latter portion of the green phase, the risk for conflicts still exists. In concurrent phasing, the risk for conflicts and crashes exists during the entire green interval.

Practitioners must also consider the vehicular-turning volumes and bicycle volumes at each location. Figure 6.1 shows the recommended strategy based on vehicle-turning volume and bicycle volume. Separating the phases may be warranted with higher vehicular and bicycle volumes. When turning-vehicular volume and bicycle volume are moderately high, either split LBI or LBI may be useful. Compared to the LBI, the split LBI may offer additional efficiency gains; however, implementing it at locations without a blanket no-right-on-red policy may warrant additional dynamic signage, which may increase costs. The mixing zone strategy involves the bicyclist and vehicles sharing space and is dependent on their cues. This may be most suited for medium-low volumes. The concurrent phase is the most commonly used strategy in the tool box, and may be best suited when vehicular-turn volume and bicycle volumes are both low. Further research is needed to define the volume thresholds for each of these strategies.

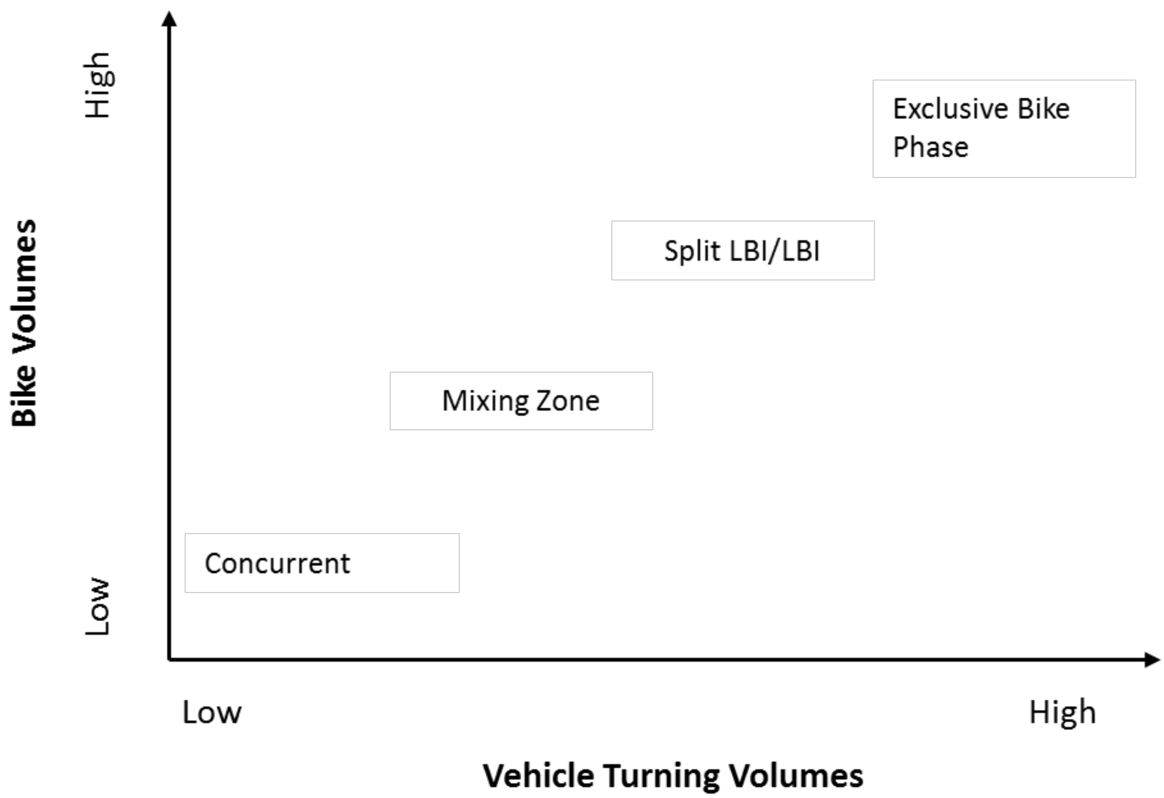


Figure 6.1: Choice of Strategy Based on Vehicle Turning Volume and Bicycle Volume

8.0 CONCLUSIONS AND RECOMMENDATIONS

The objective of this research was to develop an understanding of the safety and operational impacts of signal control strategies for bicycles such as LBIs, split LBIs and exclusive bicycle phasing (EBP). To accomplish these objectives, a robust research plan was followed. First a comprehensive review of the literature on signal timing strategies for addressing bicycle-vehicle conflicts was undertaken. The review found little to no literature on the operational and safety impacts of signal control strategies for bicycles. Next, a practitioner survey was undertaken to assess the state of the practice with respect to the use of signal control strategies for bicycles at intersections. The results from the survey revealed that while 52% of the respondents were aware of the split LBI treatment, only one respondent used it in their jurisdiction. Respondents were more familiar with the LPI treatment and used it than the similar treatments for bicycles. Following these tasks, the research team conducted two primary tasks:

1. The development and testing of a microsimulation model that examined the effects from the implementation of the following bicycle specific treatments at signalized intersections on all users (motor vehicles, heavy vehicles, bicyclists and pedestrians):
    a. Traditional concurrent timing (base case)
    b. Leading bike intervals
    c. Split leading bike intervals
    d. Exclusive bike phase
2. Video-based conflict analysis to understand the safety impacts of select signal timing strategies for addressing bicycle-vehicle conflicts.

The key conclusions from each of these will be discussed below.

8.1 MICROSIMULATION

An intersection was simulated in VISSIM to understand the impacts to intersection efficiency from the three bicycle-specific treatments, LBI, split LBI and EBP, and each treatment was compared to a coordinated base case. The effects on user delay were recorded and analyzed. Results for the LBI revealed little change in vehicle delay for the unaffected approaches (northbound and southbound), but a near uniform increase for the affected westbound approach. The increase in delay for vehicular movements is similar to the lead interval used in the study (five seconds). Bicycle delay showed little change, due largely to an unintentional favoring of the westbound approach in the coordination scheme.

Results for the split LBI also revealed little change in vehicle delay for the unaffected approaches, including the unaffected through movements on the split LBI approach. There was a significant increase for the affected eastbound right-turn movement, due to the treatment itself. The bicycles saw a slight increase in delay, which was likely the result of the eastbound approach being the unfavored approach in the coordination scheme. For both the LBI and split LBI treatments, delay for pedestrian movements were largely unchanged.

The EBP vehicle delay results showed mixed outcomes; there was increased delay for the eastbound approach and decreased delay for the westbound. This difference is probably due to a favoring of the westbound approach in the coordination scheme. Minor phases were unaffected. EBP bicycle results showed a general increase, which is probably due to the lack of signal time the EBP allocates to the bicycle movements (±10 seconds). Pedestrian movements showed an increase in delay from the EBP, which was inferred to be the product of decreased pedestrian signal time as the result of cycle length reallocation (which was an outcome of the EBP). Minor pedestrian phases were unaffected.

8.2 VIDEO-BASED CONFLICT ANALYSIS

A video-based conflict analysis was undertaken to understand the safety impacts of select signal control strategies – LBI and split LBI. PET, a surrogate safety measure, was used to explore the safety at five different locations. Initially, a before-after study was the chosen method of analysis. However, for some locations the treatment had already been implemented, and hence the before data was not available. At other locations, numerous other changes (including geometry) took place in the after condition, and hence the before-after comparison was not feasible. The research team therefore analyzed each treatment in an isolated manner without performing before-after comparisons.

8.2.1 Traditional with LPI

Traditional concurrent timing for bicycling with a corresponding LPI for pedestrians was observed at one intersection, 6th Avenue and 23rd Street, in the before condition. A corresponding bike interval was not provided. Ten hours of data were collected at this intersection and analyzed for conflicts, and 433 incidents were observed in the time period. The proportion of incidents at this intersection was 22.18%. Additionally, our observations revealed eight near misses and a potential for 147 collisions if no evasive action was taken. Our observations revealed that the bicyclists also took advantage of the LPI and started moving during the pedestrian walk phase. Severe congestion was observed leading to massive queue buildup during every cycle, and the geometry of the intersection (with a shared through/left lane) was not conducive to efficient traffic flow.

8.2.2 Split LBI

Two intersections with the split LBI treatment in New York City were analyzed in this study, 1st Avenue and 61st Street and 6th Avenue and 23rd Street (after condition). At the 1st Avenue and 61st Street location, approximately nine hours of video data were mined for conflicts. A total of 1,166 bicycles and 1,619 motor vehicles were observed, along with 445 incidents. The proportion of incidents was 38.16%. Additionally, 11 near misses and 197 potential collisions if no evasive action was taken were observed.

At the 6th Avenue and 23rd Street location in the after condition with the split LBI treatment, 11 hours of video data were mined. A total of 1,300 bicycles and 773 motor vehicles were observed, along with 221 incidents. The proportion of incidents was 17%, which was significantly lower than the proportion observed at the 1st Avenue and 61st Street location. Additionally, at this location, there were zero near misses and 46 potential collisions if no evasive action was taken were observed.

The proportions of very dangerous and dangerous interactions are significantly higher at 1st Avenue and 61st Street compared to 6th Avenue and 23rd Street. The higher proportion of severe interactions could be a result of the higher turn volumes observed at the 1st and 61st location. Additionally, there is a downhill grade at this location, which could have impacted the speed of bicyclists. Also, the impact of crossing pedestrians on PET could not be determined, due to the camera angle. With the split LBI treatment, there is little to no risk for bicyclists during the leading interval. However, the risk for bicyclists is shifted towards the stale green portion of the phase. There was no correlation between elapsed time since green and the number of incidents observed at both locations, implying that the incidents were evenly distributed throughout the green phase once the lead interval had elapsed.

8.2.3 Mixing Zone

Two intersections with the mixing zone treatment were analyzed in this study, 2nd Avenue and 74th Street in New York City and NE Multnomah Street and NE Grand Avenue in Portland, OR. At the 2nd Avenue and 74th Street location, approximately 11 hours of video data were mined for conflicts. A total of 1,425 bicycles and 1,206 motor vehicles were observed, along with 253 incidents. The proportion of incidents was 17.75%. Additionally, four near misses and 57 potential collisions if no evasive action was taken were observed.

At the NE Multnomah Street and NE Grand Avenue location,11 hours of video data were mined. A total of 352 bicycles and 1,143 motor vehicles were observed, along with 76 incidents. The proportion of incidents was 21.59%. Additionally, at this location zero near misses and four potential collisions if no evasive action was taken were observed.

With the mixing zone treatment, the percentage of total incidents at both locations were comparable. However, our observations revealed significant confusion exhibited by both cyclists and drivers with respect to the correct action to be taken. Our observations also revealed that a significant percentage of the vehicles merged into the mixing zone at the very last second, thus adding to the confusion.

8.3 RECOMMENDATIONS

This research evaluated the safety and operational impacts of signal control strategies for bicyclists. Below are the key recommendations:

1. Concurrent signal timing is best suited when volumes of bicycles and turning vehicles are low. This strategy is associated with the lowest overall delay as compared to other strategies. The potential for right/left-hook crashes exists during the entire green phase for this strategy.
2. Leading bike intervals and split leading bike intervals are suitable when the volume of bicycles and motor vehicles are medium-high. Split LBIs offer more efficiency compared to traditional LBIs. However, they are harder to implement in locations where a no-right-

on-red policy does not exist. In such cases, dynamic signage is required for the turning movements. The risk for bicyclists is present during the latter portion of the green phase for both treatments.

3. Exclusive bike phases are recommended when the volume of bicycles and motor vehicles is high. This type of phasing has the greatest delay but the separation of phases also eliminates conflicts.
4. Although mixing zones are not signal treatments, they may be best suited when volumes of vehicles and bicycles are medium-low. Previous study and this research have recorded confusion on the part of bicyclists and turning vehicles at locations where this treatment is implemented. Some education regarding the expected behavior of bicyclists and turning vehicles may help reduce the confusion.

8.4 FUTURE WORK

Going forward, there are several natural extensions for this work. First, more research is needed to determine the safety implications of these strategies. In addition to surrogate safety metrics, actual crash data should also be examined to determine safety impacts. Second, determination of the thresholds for bicycle and vehicle volumes and when each strategy should be applied would be very helpful for practitioners. Third, studying cyclist behavior with respect to gap acceptance, and perception of safety and how it varies among cities, would also be useful. Finally, quantifying the impact of pedestrian volumes on the adjacent crosswalks on implemented strategies would be helpful as well.

REFERENCES

A.C. Fayish and Frank Gross, “Safety effectiveness of leading pedestrian intervals evaluated by a before–after study with comparison groups,” Transportation Research Record No. 2198 pp.15–22, 2010.

R. Akçelik. "Microsimulation and Analytical Models for Traffic Engineering." Presentation at the ARRB-AUSTROADS Microsimulation Forum. Melbourne: ARRB-AUSTROADS, 2007.

Arizona Department of Transportation (ADOT). Arizona Motor Vehicle Crash Facts.
City of Flagstaff – Flagstaff Metropolitan Planning Organization. 2010-2014 Bike and Ped Crash Data.

City of Fort Collins. "FC Bikes." Basics - City of Fort Collins. https://www.fcgov.com/bicycling/safety.php?mobile_pref=0.

City of Phoenix Street Transportation Department. Phoenix 2010-2014 City Wide Bicycle Pivot.

Dill, Jennifer, and Nathan McNeil. 2013. "Four Types of Cyclists? Examination of Typology for Better Understanding of Bicycling Behavior and Potential." Transportation Research Record: Journal of the Transportation Research Board, No. 2387, pp 129–138, 2013.

Dill, J., Monsere, C. and N. McNeil. Evaluation of Bike Boxes at Signalized Intersections. Accident Analysis and Prevention, No. 44, pp. 126-134, 2012.

Federal Highway Administration (FHWA). Traffic Signal Timing Manual, 2nd Edition. 2015.

Federal Highway Administration (FHWA). Separated Bike Lane Planning and Design Guide. 2015.

Furth, Peter G., Peter J. Koonce, Yu Miao, Fei Peng, and Michael Littman. Mitigating Right-Turn Conflict with Protected Yet Concurrent Phasing for Cycle Track and Pedestrian Crossings, Transportation Research Record, Journal of the Transportation Research Board No. 2438, pp. 81-88, 2014.

Gettman, Douglas, and Larry Head. "Surrogate Safety Measures from Traffic Simulation Models." Transportation Research Record: Journal of the Transportation Research Board, No. 1840, pp. 104-15, 2003.

Hayward, John Charles. Near misses as a measure of safety at urban intersections. Doctoral thesis, Pennsylvania State University, Department of Civil Engineering. 1971.

Hurwitz, David, Mafruhatul Jannat, Jennifer Warner, Christopher Monsere, and Ali Razmpa. 2015. Towards Effective Design Treatment for Right Turns at Intersections with Bicycle Traffic. Final Report prepared for the Oregon Department of Transportation, SPR 767, 2015.

King, M. R. . Calming New York City Intersections. In Urban Street Symposium Conference , Transportation Research Board, Washington, DC., 1999.

Laureshyn, Aliaksei, Maartje De Goede, Nicolas Saunier, and Aslak Fyhri. "Cross-comparison of three surrogate safety methods to diagnose cyclist safety problems at intersections in Norway." Accident Analysis & Prevention No.105, pp. 11-20, 2017.

Mekuria, M. C., P. G. Furth, and H. Nixon. Low-Stress Bicycling and Network Connectivity. San José, CA: Mineta Transportation Institute, 2012.

Monsere, Chris, Jennifer Dill, Kelly Clifton, and Nathan McNeill. Lessons from the Green Lanes: Evaluating Protected Bike Lanes in the U.S. NITC Final Report no. 32182. Portland State University, 2014.

National Association of Street Transportation Officials. Urban Bikeway Design Guide, Second Edition, 2014.

National Highway Traffic Safety Administration. (NHTSA). Traffic Safety Facts 2013: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System. Publication DOT HS 812 151. U.S. Department of Transportation, 2013. http://www-nrd.nhtsa.dot.gov/Pubs/812151.pdf

New York Department of Transportation (NYDOT). Traffic Safety Statistical Repository (TSSR).

Manual on Uniform Traffic Control Devices for Streets and Highways. (MUTCD). Interim Approval for Optional Use of a Bicycle Signal Face (IA-16). 2013.

Massachusetts Department of Transportation (MassDot). Separated Bike Lane Planning and Design Guide. 2015.

Monsere, C., N. Foster, J. Dill, and N. McNeil. User Behavior and Perceptions at Intersections with Turning and Mixing Zones on Protected Bike Lanes. Transportation Research Record: Journal of the Transportation Research Board, No. 2520, Transportation Research Board, Washington, D.C., pp. 112–122, 2015.

ODOT. 2011. ODOT VISSIM Protocol. Salem, OR: Oregon Department of Transportation.

ODOT. 2014. 2013 Oregon Crash Summary. Transportation Data Section Crash Analysis and Reporting Unit, Oregon Department of Transportation, Salem, OR: Oregon Department of Transportation, 4.
https://www.oregon.gov/ODOT/TD/TDATA/car/docs/2013CrashSummaryBook.pdf.

Oregon Department of Transportation. (ODOT). Oregon Traffic Crash Summary 2013. Oregon Department of Transportation, Transportation Data Section, Crash Analysis and Reporting Unit, 2014.

Oregon Department of Transportation. (ODOT). Oregon Traffic Crash Summary 2009. Oregon Department of Transportation, Transportation Data Section, Crash Analysis and Reporting Unit, 2010.

Oregon Department of Transportation. (ODOT). Oregon Traffic Crash Summary 2008. Oregon Department of Transportation, Transportation Data Section, Crash Analysis and Reporting Unit, 2009.

Oregon Bicyclist Manual, ODOT Pedestrian and Bicycle Program, Oregon Department of Transportation, 2010.

Paulsen, K., Farley, W., Mobley, T., and M. Ard. SW Madison Street and SW 3rd Avenue Proposed Bike Detection Analysis. Final Report prepared for the Portland Bureau of Transportation.

Paulsen, Kirk, William Farley, Todd Mobley, Michael Ard, and Peter Koonce "Analysis of Active Warning Sign to Address Potential Bicycle 'Right Hook' Conflict at Signalized intersections." Transportation Research Board 95th Annual Meeting, 2016.

Perkins, S.; Harris, J. Traffic conflict characteristics accident potential at intersections, Highway Research Board, 225: 35-43, 1967.

Portland Bureau of Transportation. 2014. High Crash Corridors. August 5. Accessed September 16, 2015. http://www.portlandoregon.gov/transportation/article/439832.

Preusser, David F, William A Leaf, Karen B DeBartolo, and Richard D Blomberg. The Effect of Right-Turn-On-Red on Pedestrian and Bicyclist Accidents. USDOT, 1981.

PTV Group. 2014. VISSIM 7 Manual. Karlsruhe, Germany: PTV Group. Accessed May 2016.

Pucher, J., R. Buehler, and M. Seinen. Bicycling renaissance in North America? An update and re-appraisal of cycling trends and policies. Transportation Research Part A: Policy and Practice, Vol. 45, No. 6, pp. 451-475, 2011.

Räsänen, M., and H. Summala. Attention and expectation problems in bicycle–car collisions: an in-depth study. Accident Analysis & Prevention, Vol. 30, No. 5, pp. 657-666, 1998.

Stokes, Bruce, Richard Wike, and Jill Carle. 2015. Global Concern about Climate Change, Broad Support for Limiting Emissions. Pew Research Center. Nov 5. Accessed May 9, 2016. http://www.pewglobal.org/2015/11/05/global-concern-about-climate-changebroad-support-for-limiting-emissions/.

Sanders, R. "Examining the Cycle: How Perceived and Actual Bicycling Risk Influence Cycling Frequency, Roadway Design Preferences, and Support for Cycling among Bay Area Residents." Accident Analysis & Prevention No. 75, pp. 26-34, 2013.

Summala, H., E. Pasanen, M. Räsänen, and J. Sievänen. Bicycle accidents and drivers' visual search at left and right turns. Accident Analysis & Prevention, Vol. 28, No. 2, pp. 147-153, 1996.

Summala, H. Risk control is not risk adjustment: The zero-risk theory of driver behavior and its implications. Ergonomics, Vol. 31, No. 4, pp. 491-506, 1998.

Thompson, Sam R. Bicycle-Specific Traffic Signals: Results from a State-of-the-Practice Review. 2013.

TRB's National Cooperative Highway Research Program (NCHRP). Signal Timing Manual - Second Edition.

U.S. Department of Transportation: Federal Highway Administration. n.d. Innovative Intersection Safety Improvement Strategies and Management Practices: A Domestic Scan. Accessed May 8, 2016.
http://safety.fhwa.dot.gov/intersection/other_topics/fhwasa06016/chap_3.htm.

USDOT: NHTSA. 2015. Traffic Safety Facts, 2015 Data. Washington, D.C.: US Department of Transportation: National Highway Traffic Safety Administration.

Van der Horst, ARA. A time based analysis of road user behaviour in normal and critical encounters. Publication no. HS-041 255. Transport and Road Research Laboratory (TRRL). 1990.

R. Van Houten, R.A. Retting, C.M. Farmer and J. Van Houten. Field Evaluation of a Leading Pedestrian Interval Signal Phase at Three Urban Intersections. In Transportation Research Record: Journal of the Transportation Research Board, No. 1734, TRB, National Research Council, Washington, D.C., pp 86-92, 2000.

A. Wachtel, and D. Lewiston. "Risk Factors for Bicycle-Motor Vehicle Collisions at Intersections*." ITE Journal, pp. 30-35, 2013.

Zangenehpour, Sohail, Taras Romancyshyn, Luis F. Miranda-Moreno, and Nicolas Saunier. Video-Based Automatic Counting for Short-Term Bicycle Data Collection in a Variety of Environments. Publication. Transportation Research Board. 2015.

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