# Improving Bicycle Crossings at Unsignalized Intersections

# through Pavement Markings:

# Analysis of the City of Portland Innovative Strategy

by

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## ABSTRACT

The increasing trend in the number of bicycle crashes in the U.S since 2009 has been a major challenge to safety. A review of 2019 motor vehicle crashes from FARS shows that, a total of 36,096 people were killed on U.S roadways and 846 (2.3%) of these fatalities were bicyclists. Around 75% of the bicycle fatalities occur in urban areas. Intersections are common locations of crashes. Many different types of bicycle crashes occur at these locations. The prevalent crash type is bicyclists failing to yield right of way. Safety of bicyclists at intersections is important for efficient operation of the bicycle network. Many bicycle crossing enhancements such as bike boxes, bicycle signals, curb extensions have been widely installed to improve safety at signalized intersections. An innovative treatment that the city of Portland has adopted to improve safety at unsignalized crossings is a high visibility cross-bike. This is a treatment installed at crossings in a similar way as pedestrian crosswalk but marked with green pavement markings. The goal is to improve visibility of the intersection as a bicycle crossing. Although cross-bikes do not require motorists to yield for bicycles who remain positioned as a vehicle, it has been hypothesized that the presence of the marking at crossings will alter motorists yielding behavior towards bicyclists. This thesis analyzed empirical data to evaluate the modifications in the rate of motorists yielding behavior at three unsignalized intersections in Portland, Oregon. Three intersections were evaluated in before and after experiment. A total of 48 hours of video data was analyzed. The sample resulted in 1,840 bicycle crossing events (897 before; 943 after) carried out by 2,219 bicyclists. (1,097 before; 1,122 after). The rates of motorists yielding to bicyclists improved after installing cross-bike markings. The yielding rates at NE Going and NE 15$^{th}$

Ave increased from 48% near side and 61 % far side for before cross-bike pavement markings to 91% near and 95% far sides after the markings. SE Salmon and SE 20th Ave also realized a significant increase in motorists yielding rates from 21% to 40% near side and 11% to 33% far side. Holman and NE 33rd depicted similar trend with rates improving from 38% and 36% near side to 77% and 82% far side. The changes in driver yielding behavior were all statistically significant. Data also showed that the operational efficiency of the intersections were improved by the reduction in bicyclists' wait times. Additionally, the facility was observed to have provided a positive guidance by providing consistent waiting area and a clear crossing path for bicyclists.

## ACKNOWLEDGMENTS

No achievement in life is without the support of some individuals who tirelessly work behind the scenes. I owe every measure of this research work to the array of inputs from so many people. Here are just a few of those who made this work possible: I would like to first and foremost give thanks and honor to God who made much grace abound unto me to successfully carry out this research. A very sincere gratitude goes to my advisor and committee chair Prof Chris Monsere for his continued support and guidance throughout the journey of my graduate studies. His support, guidance and directions led to the successful completion of this study. Much appreciation and thanks also go to my other committee members; Dr. Avinash Unnikrishnan and Jason Anderson for their unflinching support and constructive criticisms. Their collective effort greatly improved the outcome of this work. Another thanks goes to Roger Geller of Portland Bureau of Transportation for the data and other supportive materials he provided which formed the basis of the analysis for this study.

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**Table of Contents**

## Lists of Tables

**Lists of Figures**

# 1 INTRODUCTION

Active transportation has many associated benefits of which key among them include but not limited to reduction of emissions, decrease congestion in cities, and improving health. Walking and bicycling are the main forms of active transportation. These modes are the healthiest ways to get around cities, providing valuable physical activity for people daily. However, the safety issues associated with non-motorized traffic have discouraged many people from walking or biking to complete a trip. Geller's study describes the four different types of cyclists of which one group constituting about 60% are interested in biking but they are more concerned about their personal safety. Many bicyclists come under high stresses from motor traffic on roadways especially at crossings. Bicycle crossings have always been one of the major challenges in developing safe bicycle network for all cyclists. Data from the National Highway Traffic Safety Administration show that, there were 846 traffic deaths involving bicyclists which represented 2.3% of all traffic fatalities in the US in 2019. Around 75% of these crashes occurred in urban areas and mostly at intersections. With the increase in non-motorized traffic on our roadways, there is a major concern about safety more especially at intersections where they are more vulnerable.

In Oregon, Portland is one of the most bicycle friendly cities. Survey shows that 8% of commuters claim bicycling is their primary form of transportation and 10% resort to it as a secondary mode. This is ten (10x) times greater than the national average. Additionally, a bike count study by the Portland Bureau of Transportation showed that bicycle ridership has increased by over 211% in the last decade. (COP 2013). This rapid increase in ridership is enough to create congestion as well as increase the frequency of crashes at intersections.

It is therefore imperative for the city to heighten the visibility of some intersections as bicycle crossings.

Over the years, some treatments such as installation of bike boxes, median islands, removal of parking within intersections to enhance sight distance, and bicycle signals have been used to improve bicycle safety at crossings. An innovative way the city of Portland has adopted to improve safe crossings at unsignalized intersections is to install a cross-bike pavement markings.

## 1.1 Background

Cross-bikes are visibly prominent pavement markings that are the equivalent of crosswalks for bicyclists installed at intersections to heighten the visibility of the facility as a bicycle crossing. These markings are green and are marked similar to a continental pedestrian crosswalk. Figure 1 below shows a typical intersection with the cross-bike markings. The city of Portland has adopted this innovative strategy to heighten the visibility of intersections to enhance bicyclist's safety at intersections. The treatment has been installed at selected unsignalized intersections within the Portland metro area over the years. To understand the operational effectiveness of cross-bikes, a before and after data study has been conducted to be analyzed and identify improvements in motorists yielding behavior.


**Figure 1: Typical intersection with cross-bike pavement markings.** Source: Google Maps

### 1.2 Research Objectives

The objective of this research is to investigate the effectiveness of creating a visibly prominent bicycle crossing location; the equivalent of bicyclist’s crosswalk to enhance their visibility by drivers. While motorists are not legally required to yield to a bicycle waiting to cross an intersection installed with a cross-bike, it was hypothesized that motorist may increase their yielding behaviors. Delay is also important for comfort and safe behaviors. The average cyclists’ wait time at the crossing was included as part of the evaluation. Additionally, the utilization rate of the treatment will also be evaluated to establish how the installation of the treatment has provided positive guidance to cyclists crossing at these locations. This evaluation used before and after video data collected at three unsignalized intersections to investigate the change in these performance measures.

## 1.3 Organization of Thesis

This thesis is organized into the following chapters.

- Chapter 1- Introduction: A brief description of motivation, background, and objectives of the study

- Chapter 2- Literature review: An extensive review of previous studies and published articles related to this study.

- Chapter 3- Site Description: Describes the geometric characteristics, traffic volume, speeds and other cross-sectional elements of the roadway approaches forming the intersections as well as the crash history.

- Chapter 4- Data Collection, Reduction and Verification: This section explains how video data was obtained from the site, watched to extract key metrics, and cleaned before using it for the analysis.

- Chapter 5 – Analysis and Discussion: A summary of the analysis of key metrics used to evaluate the effectiveness of the cross-bike pavement markings.

- Chapter 6- Conclusion: Summary of findings of the research

# 2 LITERATURE REVIEW

This chapter explores several past studies carried out to evaluate the various pedestrian and bicycle crossings in terms of design and safety. Pedestrians and bicyclists are the most vulnerable road users. While there are numerous literatures on safety of pedestrians at crosswalks, studies pertaining to safety of cross bikes are rare. With several similarities in behaviors between pedestrians and bicycles at crossings, principles guiding the design of pedestrian infrastructure can be adopted for that of bicycles. This review is structured to focus on studies related but not limited to:

- Bicycle Networks and Connectivity
- Level of Traffic Stress for Cyclists at Crossings
- Design Characteristics of intersection that tend to reduce bicycle risks.
- Safety of Bicycles at Mid-block and Trail Crossings

## 2.1 Bicycle Network and Connectivity

A well planned and carefully designed bicycle network is safe, convenient, and easy to use. Such system attracts many riders. Portland's Bicycle Plan for 2030 promotes certain design principles that will ensure that the network is fully utilized once they are installed. These guiding principles are safety, comfort, attractiveness, directness of routes, and cohesive system. Adopting them in design help to produce a network of bikeways that provide seamless and connected access to broad variety of destinations whiles ensuring safety and comfort of all users. Ensuring connectivity of bikeways creates many intersecting locations where cyclists become vulnerable due to conflicts in traffic movements. At busy street crossings, it is imperative to provide safe crossing of bicycles to ensure efficient and safe operation of the system. Also providing low stress crossing help increase ridership. Summary of past studies that have been done to evaluate network connectivity are discussed below.

Network connectivity is explained as the ability to get to variety of destinations or key places using routes prioritized for bicycle traffic. It can be quantified to evaluate the connectivity of networks in neighborhoods. (Lowry et al, 2017). This study suggested a positive correlation between connectivity and utilitarian trips. This correlation strengthens the evidence that a connected bikeway network will attract and increase ridership.

Abad et al 2018 developed exploratory score that was used to quantify the network connectivity of bikeways in Lisbon using open data. Their study computed a score for each part of the city based on the number of important destinations accessed using bicycle facility on roadways with low traffic stress and speeds. Based on the weighted average score for the overall connectivity of the network, the city of Lisbon scored 8.6 out of 100 points. This simply shows how the current city architecture does not support biking**.** (Abad et al, 2018).

The performance of bicycle network can also be evaluated using how the bikeways are connected and the directness of the bike routes to variety of destinations. (Boisjoly G et al, 2016, Boldry, et al, 2019). Several literatures reviewed posit it that increasing network connectivity raises bicycle ridership and enhance safety and accessibility.

## 2.2 Level of Traffic Stress for Bicycles

The measure of performance of any transportation facility is determined by the level of service. It describes how well the facility or transportation service operates. For motor vehicles, it is assessed using the measure of delay, speed, throughput, and efficiency. However, for non-motorized traffic, the measure of the performance of the facility is strongly based on the user perception of safety and comfort. The bicycle level of traffic stress is an index system with four levels of stress that approximate user perception of safety and comfort when using the facility. Level of Traffic Stress 1 (LTS1) is the least stress level with LTS 4 being highly stressed. A summary of each stress level is discussed below.

**LTS 1,** this represents the least traffic stress experienced by most cyclists when using a bicycle facility. It requires less attention to other road users and suitable for all cyclists including children. Such facilities are low stressed due to low volume of motorized traffic, speeds, and land use types.

**LTS 2,** this represents little traffic stress and require some considerable level of attention other than what young children would be expected to deal with. Traffic volumes are considerably high with varying low speeds and roadway lanes can be up to three lanes wide for both directions.

**LTS 3** represents moderate stress and requires good level of attention to other traffic. Traffic volumes are moderately high with medium to high speeds. This level is tolerated by Geller's confident group of cyclists.

**LTS 4** are stress levels tolerated by cyclists who are characterized as strong and fearless. It represents high stress due to moderate to high speeds and high traffic volumes. At busy intersections, there are complex, wide, and high volume/speed of traffic that can be perceived as unsafe by adult users which make it difficult to cross safely. The figure below shows example of each stress level and the facility type.


**Figure 2:Types of roadways with associated bicycle level of traffic stress. Source : BLTS Types**

The bicycle level of traffic stress criteria are used to assess three categories of roadway sections namely, segments, intersection approaches and intersection crossings. For this thesis, the focus will be on intersection crossings.

### *2.2.1 BLTS Intersection Crossing Criteria*

The bicycle level of traffic stress generally depends on number of lanes and posted speeds of the roadway facility. For intersections, depending on whether it is signalized or not the criteria is different. The section below describes the criteria for unsignalized crossing.

Unsignalized intersections with high number of lanes, speeds and traffic volumes can be challenging for bicyclists to cross safely. The crossing can be an impediment to travel if cyclist must cross five or more lanes at speeds greater than 35mph on four-lane street. The basic criteria for traffic stress determination at these locations includes consideration for presence of median of adequate width to provide for a two-stage crossing. Grade separation crossings for bicycles are considered as a separate facility and rated as having BLTS 1. Such facilities eliminate interactions with motor traffic and therefore create low stress for bicyclists.

In the absence of a median island, the traffic stress is determined by the speed, and two-way average daily traffic (or functional class if ADT is not available). The look up tables for determining the bicycle level of traffic stress are shown below.

**Table 1: BLTS Criteria for Unsignalized Crossing without a Median**

| Prevailing Speed or Speed Limit (mph) | Total Through/Turn Lanes Crossed (Both Directions)2 | | | | | |
|---|---|---|---|---|---|---|
| | ≤ 3 Lanes | | | 4 -5 Lanes | | ≥ 6 Lanes |
| | Functional Class/ADT (vpd) | | | | | |
| | Local | Collector | Arterial | Arterial | | Arterial |
| | ≤ 1,200 | 1,200 - ≤3,000 | >3,000 | ≤ 8,000 | >8,000 | Any ADT |
| ≤ 25 | BLTS 1 | BLTS 1 | BLTS 2 | BLTS 3 | BLTS 4 | BLTS 4 |
| 30 | | BLTS 1 | BLTS 3 | BLTS 3 | BLTS 4 | BLTS 4 |
| 35 | | BLTS 2 | BLTS 3 | BLTS 4 | BLTS 4 | BLTS 4 |
| ≥ 40 | | BLTS 3 | BLTS 4 | BLTS 4 | BLTS 4 | BLTS 4 |

1 For street being crossed.
2 For one-way streets use Table 2. Source: ODOT/BLTS

**Table 2: BLTS Criteria for Unsignalized Crossing with a Median.**

| Prevailing Speed or Speed Limit (mph) | Maximum Through/Turn Lanes Crossed per Direction | | | |
|---|---|---|---|---|
| | 1 Lane | 2 Lanes | 3 Lanes | 4 + Lanes |
| ≤ 25 | BLTS 1[2] | BLTS 2[2] | BLTS 2 | BLTS 3 |
| 30 | BLTS 1[2] | BLTS 2 | BLTS 3 | BLTS 3 |
| 35 | BLTS 2 | BLTS 3 | BLTS 4 | BLTS 4 |
| ≥ 40 | BLTS 3 | BLTS 4 | BLTS 4 | BLTS 4 |

1 For street being crossed.
2 Refuge should be at least 10 feet to accommodate a wide range of bicyclists (i.e., bicycle with a trailer) for BLTS 1, otherwise BLTS=2 for refuges 6 to < 10
Source: ODOT/BLTS

Intersections are generally locations where cyclists experience high stresses from other traffic. It is intuitively apparent that the bicycle level of traffic stress is positively correlated with the number of reported crashes with their associated injury severity. (Chen C et al, 2017). Not all treatments for bikes at the intersection impact the perception of safety for every bicyclist. Some treatments only alter the perception of safety for confident riders but have no impact on that of the non-confident ones. (Wang et al, 2018)

While the bicycle level of stress can be significantly improved for various sections of the roadway especially segments and intersection approaches, the stress levels at intersections have always been considerably high and unbearable for many cyclists.

## 2.3 Design Characteristics of Intersections

Intuitively, intersections are generally locations where many road users mainly pedestrians and cyclists become more exposed to a lot of risks due to the number of conflicting movements of traffic. However, certain design characteristics of these facilities often tend to reduce the risks bicycles are exposed to. A review of studies on such treatments are discussed in the following sections.

The visibility of the various types of crosswalk markings sometimes tend to influence motorists yielding behavior to pedestrians and bicycles. (Fitzpatrick et al, 2015)**.** This suggests that enhancing the visibility of crossing treatments improves driver yielding for non-motorized traffic. Much of the literature reviewed posit that highly visible crossing treatments are visible to drivers at adequate sight distance and hence presents them with the opportunity to stop for other traffic that will be using the treatment at the time they arrive.

In addition to providing high visibility crosswalks at intersections to improve motorists yielding, certain geometric features provided at the intersections also contribute to modifying motorists yielding. For instance, the installation of curb extensions, median refuge islands further enhances the visibility of a waiting bicyclist scanning for a safe gap to cross the street. Turning vehicles pose more threat to bicyclists and therefore reducing the turning radius significantly lower speeds of turning vehicles. Reduced speeds give drivers adequate time to react and safely bring their vehicles to a safe stop whenever they encounter a bicyclist in the lane they turn into.  Some scientific research affirms that geometric elements at intersections impacts driver yielding behavior include a study by

Randal et al., 2005. This was a study carried out at 4th Avenue and Lyon Street intersection in Albany, Oregon. The crosswalk installation was such that at one end a curb extension was present, and the other end had no such geometric treatment. This allowed for the evaluation of driver yielding behavior when a curb extension is present and when there is none. The results of the data analyzed showed a statistically significant difference in the average number of vehicles that passed the crosswalk before a pedestrian could cross for both near and far side. Additionally, the percentage of pedestrian crossings where motorists yielded had improvements for the side with the curb extension for both near and far side. Kang et al., 2019 explored the impact of eleven street design elements on reducing vehicle-bicyclists vehicle collisions in New York. About 118 intersections with an implemented geometric element were reviewed and the results showed that treatments with refuge islands and curb extensions had significant reduction in pedestrian-vehicle collisions. (Kang et al, 2019).

## 2.4 Safety of Crosswalks at Unsignalized Intersections

Vehicle-bicycle interactions at unsignalized crossings can be complicated on many occasions. Motorists are not more likely to yield the right of way to pedestrians and bicycles at such locations unless they exhibit some risky behavior whiles scanning for safe gaps to cross the street. This unpredictability from both road users is more likely to lead to crashes with the slightest misjudgment from any of the two sides. The probability of driver yielding the right of way to bicyclists depends on the speed of the vehicle and closeness of the cyclist to the driver. (Silvano et al, 2016).

The data on safety of cyclists within priority intersections in built areas shows that most frequent crashes that occur between motor traffic and cyclists are caused by failure to yield. In most instances the bicyclists had the right of way, but drivers failed to yield the way to them. However, cycle tracks that are separated from the intersections tend to enhance the safety of bicyclist crossings. (Schepers et al, 2011)

Contrary to what is expected for crosswalks, many scientific studies show that more pedestrian-vehicle collisions occur at marked crosswalks than unmarked. (Zegeer et al, 2001). This finding suggest that markings alone do not all the time guarantee the safety of pedestrians. Some other additional treatments are needed to increase driver awareness of a pedestrian at the crossing. Enhanced treatments at mid-block crossings improve safety and reduce vehicle-pedestrian/bicycle crashes. Over the years, many pedestrian enhancing elements such as RRFBs, curb extensions, median refuge islands, have been systematically implemented to achieve safe crossings at mid-block and trail crossings. Rapid Rectangular Flashing Beacons have proven to be a useful tool in alerting motorists of the presence of pedestrians waiting to cross the street. Several studies have established its significant impact on motorists yielding behavior across many jurisdictions. A wide range of motorists yielding rates ranging from 19% to almost 98% have been associated with the tool from several studies. The effectiveness of this tool is based on the change in motorists yielding behavior before and after the treatment is installed. Other studies have also evaluated the safety effectiveness of RRFB’s and found crash modification factors of 0.53 and 0.71, indicating a significant reduction in pedestrian-motor vehicle crashes post-installation. (Fitzpatrick et al, 2015). Many of the pedestrian enhancement studies have been focused on midblock crossings with little focus on trail crossings. Trails have high pedestrian activities and therefore their crossings across major roadways demand that adequate safety treatments are provided. A study that evaluated RRFB at Pinellas trail crossing in Florida considered about 1000 bicyclists and pedestrians. The video data collected and analyzed revealed that the delays before trail users began to cross was considerably reduced after the tool was installed. Motorists yielding rates improved by recording a significant increase from 2% to 35% after installation. When flashing is activated, motorists yielding further improved to 54%. This further strengthens the evidence of the usefulness of the tool in creating driver awareness of a pedestrian crossing or scanning for a safe gap to cross. (Hunter et al, 2012). At-grade trail crossings are common sites for many bicycle crashes. A study explored best practices across several trail crossings statewide in Minnesota and across the US to establish guidance for safety treatment applications at trail crossing designs. The study produced a documented guidance that transportation professionals can fall on to adopt the best treatment in designing trails. (Noyce et al, 2013). B. Jestico et al, 2017 compared attributes of reported incidents and crashes at multiuse trail-road intersections to those at road-road intersections and found higher proportion of collision (38%, 17/45 total reports) at multiuse trail-road intersection as compared to road-road intersection. Cyclists' volumes, vehicular traffic volume and trail sight distances were some of the common causes of the frequent reports of incidents at multi use trail-road intersections. Thus, certain components of the multi-use trail-road intersections accounted for the higher proportions of crashes. Other literature reviewed quantified the statistical relationship between trail user crashes and variety of trail crossing characteristics to develop a trail crossing crash model using crashes reported at 197 trail crossings in

Minneapolis and Milwaukee. The model showed a significant correlation between user crashes and trail traffic volume as well as crossing distance. (Schneider et, al 2021). Findings from this study validate earlier literature by B. Justico et al 2017. Certain components of trail crossings such as trail sight distance, crossing length, and traffic volume have impact on the frequency of crashes at these locations. To improve safety at trail crossings, it is important to make adequate provisions to address these factors.

## 2.5 Summary

From the literature reviewed, there has been several studies on the effects of high visibility pedestrian crosswalks at intersections, midblock and trail crossings. These studies have established that providing highly visible crosswalks modifies motorists yielding behavior and reduce pedestrian-vehicle crashes. While there has been extensive research on pedestrian crosswalks, bicyclists' crossings at unsignalized intersections have received very little focus.

# 3 SITE DESCRIPTIONS

This chapter presents a detailed description of how the empirical data used for the analysis was obtained. The City of Portland had already collected the before and after video data for three unsignalized intersections in Portland. The before data was collected between August and September 2016 with the after data being collected a year after installation of the treatment. The three intersections used for data collection were sites selected by the City of Portland's Bureau of Transportation.

## 3.1 NE Going & NE 15$^{th}$ Ave.

NE Going and NE 15$^{th}$ Ave is a four-leg unsignalized intersection with a two-way road for all the approaches. NE Going runs east to west with average daily traffic of 890 vehicles including bicycles. NE 15$^{th}$ Ave has been prioritized for bicycles and hence serves some bicycle traffic. There are on-street parking for both crossroads with a marked crosswalk and transit bus stops on both approaches of NE 15$^{th}$ Ave. Figure 3 shows the plan view of the location.

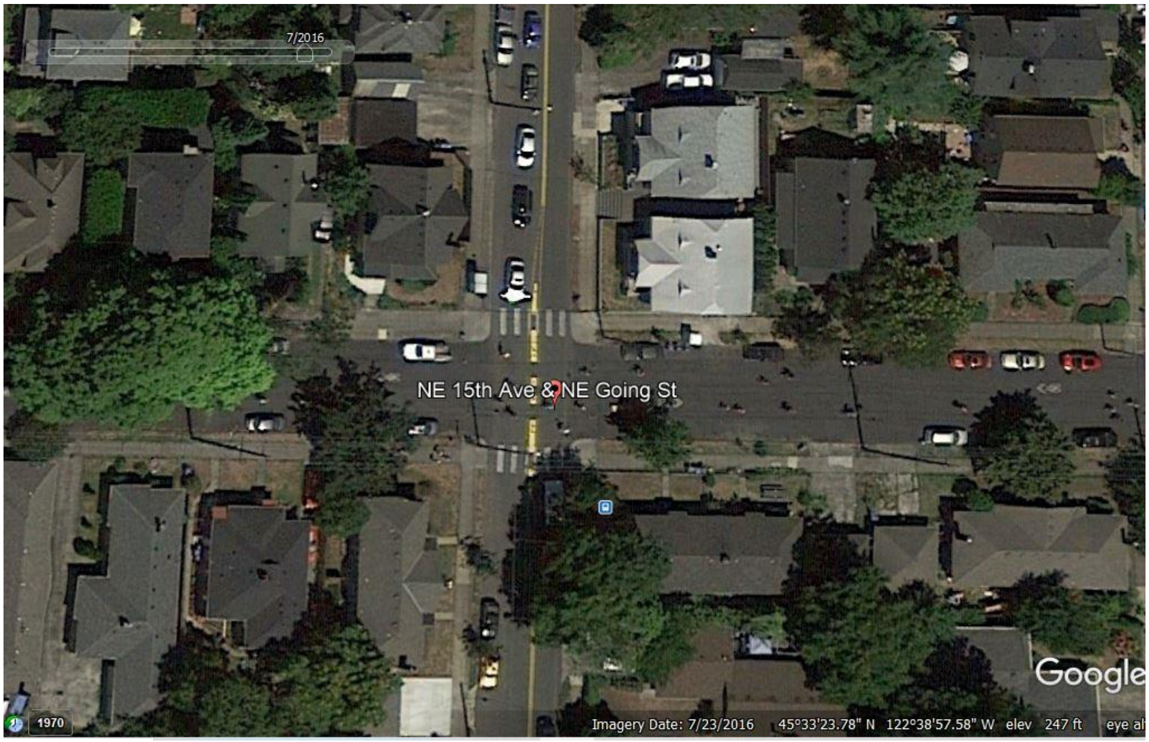



Figure 3: Plan view of NE Going & NE 15th Ave before cross-bike. Source: Google Earth (2016).

Figure 4: Plan view of NE Going & NE 15th Ave after marking. Source: Google Map

### 3.2 SE Salmon & SE 20th Ave.

Also, a four-leg unsignalized intersection with a two-way road for all the approaches. All approaches have posted speeds of 25mph. SE 20th Ave is a north south roadway and serves a mixed traffic with average daily traffic of about 4,000 which are predominantly motor vehicles. SE Salmon is a bicycle boulevard. It serves average traffic of about 785 vehicles including bicycles. The site had no marked crosswalk on any of the approaches prior to the studies.


**Figure 5: Plan view of SE Salmon & SE 20th Ave. Source: Google Earth (2016).**


**Figure 6: Plan view of SE Salmon & SE 20th Ave after cross-bike marking. Source: Google Map Photo.**

### 3.3 NE 33rd & Holman

NE 33rd is in the north south direction and has a median and a marked crosswalk on its approaches. It is a busy approach that serves average daily traffic of about 5,420 vehicles at a posted speed of 30 mph. NE Holman is a bicycle boulevard that serves mixed traffic which are predominantly bicycles. It serves a relatively low average traffic of about 270 and has a posted speed of 20mph. The presence of median island on NE 33rd make crossing from either approach for motor vehicles on NE Holman impossible except for right turning onto NE 33rd. However, bicycles, can cross from either side of Holman through the gaps created through the median for them.


**Figure 7: Plan view of Holman & NE 33rd Ave before marking. Source: Google Earth (2016).**

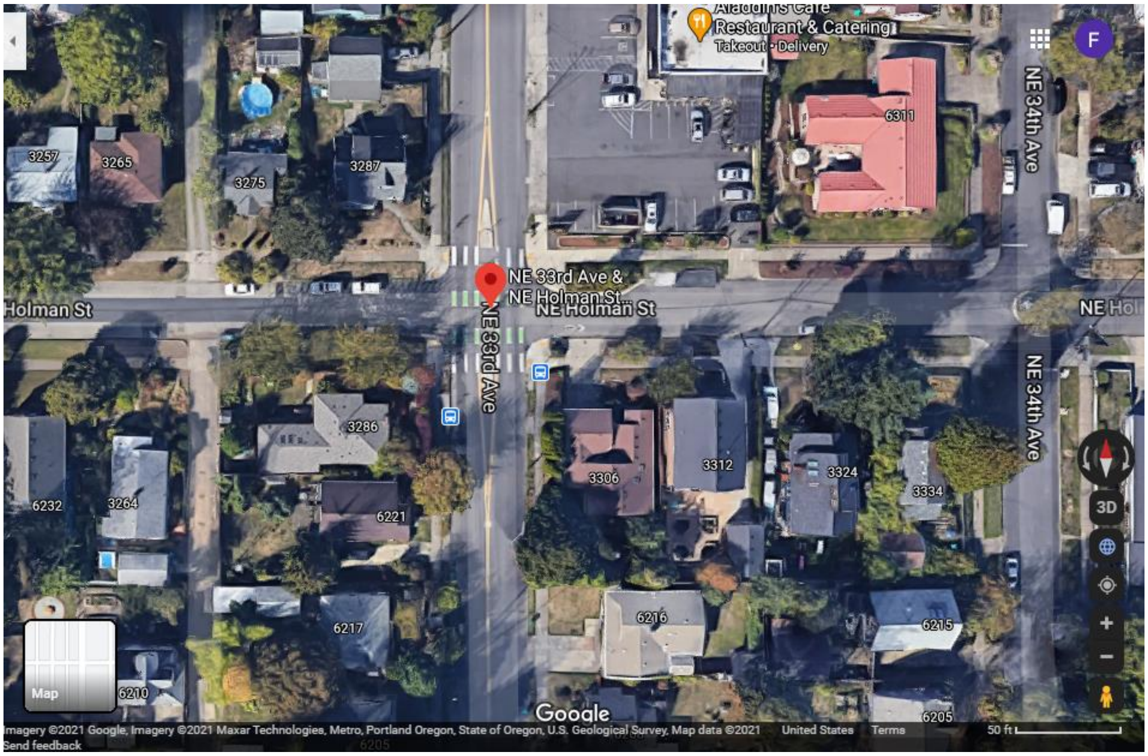



**Figure 8: Plan of Holman & NE 33rd Ave after cross-bike. Source: Google Map Photo**

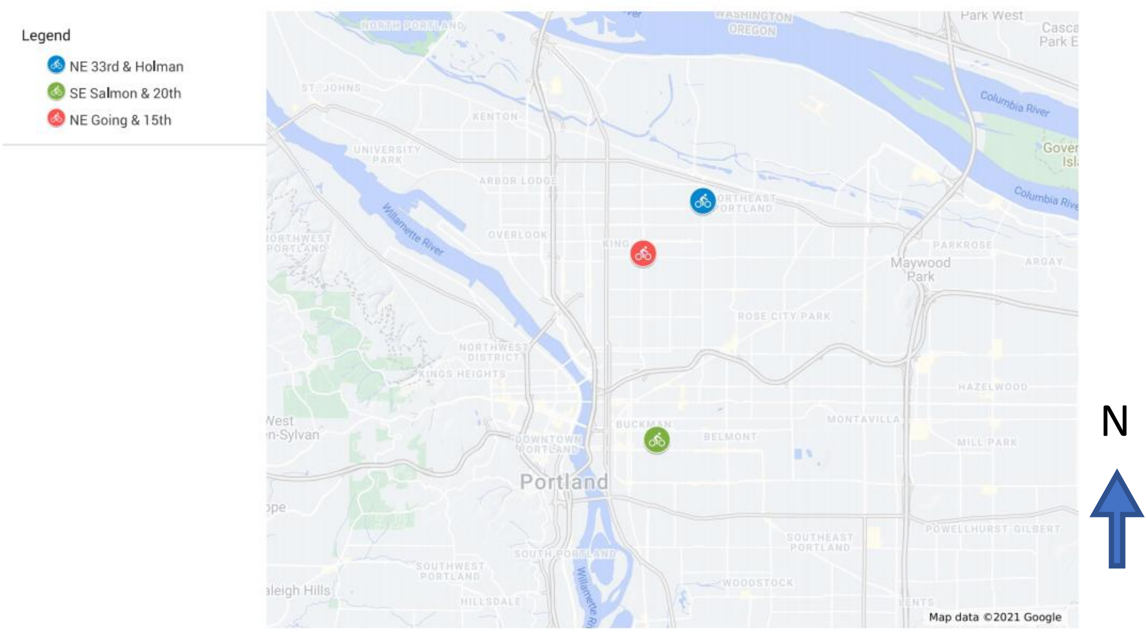



**Figure 9: Location map of study sites**

**Table 3: Summary of site characteristics.**

| Element | Summary of Site Characteristics | | | | | |
|---|---|---|---|---|---|---|
| | NE Going & NE 15th Ave | | SE Salmon & SE 20th Ave | | Holman & NE 33rd | |
| | NE Going | NE 15th Ave | SE Salmon | SE 20th Ave | Holman | NE 33rd Ave |
| ADT (Include Bicycles) | 890 | 1080 | 785 | 4,000 | 270 | 5,420 |
| Traffic Control Device | Stop controlled | Uncontrolled | Stop controlled | Uncontrolled | Stop controlled | Uncontrolled |
| Land Use | Residential | | Residential | | Residential | |
| Posted Speed (mph) | 25 | 30 | 25 | 25 | 20 | 30 |

## 3.4 Crash History

Intersections are challenging locations in developing bicycle boulevards. Bicyclists are more prone to crashes due to the number of conflicting movements. The 10-year crash data for the sites are shown in table 3 below. The data shows SE Salmon and SE 20$^{th}$ Ave had the highest total number of 15 crashes over the period with Holman and 33$^{rd}$ Ave having 5 crashes followed by NE Going and NE 15$^{th}$ Ave with 4 crashes. SE Salmon and 20$^{th}$ Ave averaged about 2 crashes every year with the remaining sites averaging a crash every year.

**Table 4: Summary of crashes at intersections. (2010-2019).**

| Year | Summary of bicycle motor vehicle crashes at intersections | | |
|---|---|---|---|
| | NE Going & NE 15th Ave | SE Salmon & SE 20th Ave | NE 33rd & Holman |
| | Total number of crashes (2010-2019) | | |
| 2010 | 3 | | 1 |
| 2011 | 1 | 3 | 1 |
| 2012 | - | | 3 |
| 2013 | - | 3 | - |
| 2014 | - | 1 | - |
| 2015 | - | 2 | - |
| 2016 | - | 3 | - |
| 2017 | - | 1 | - |
| 2018 | - | 2 | - |
| 2019 | - | - | - |

**Note:** - means zero crash**.**

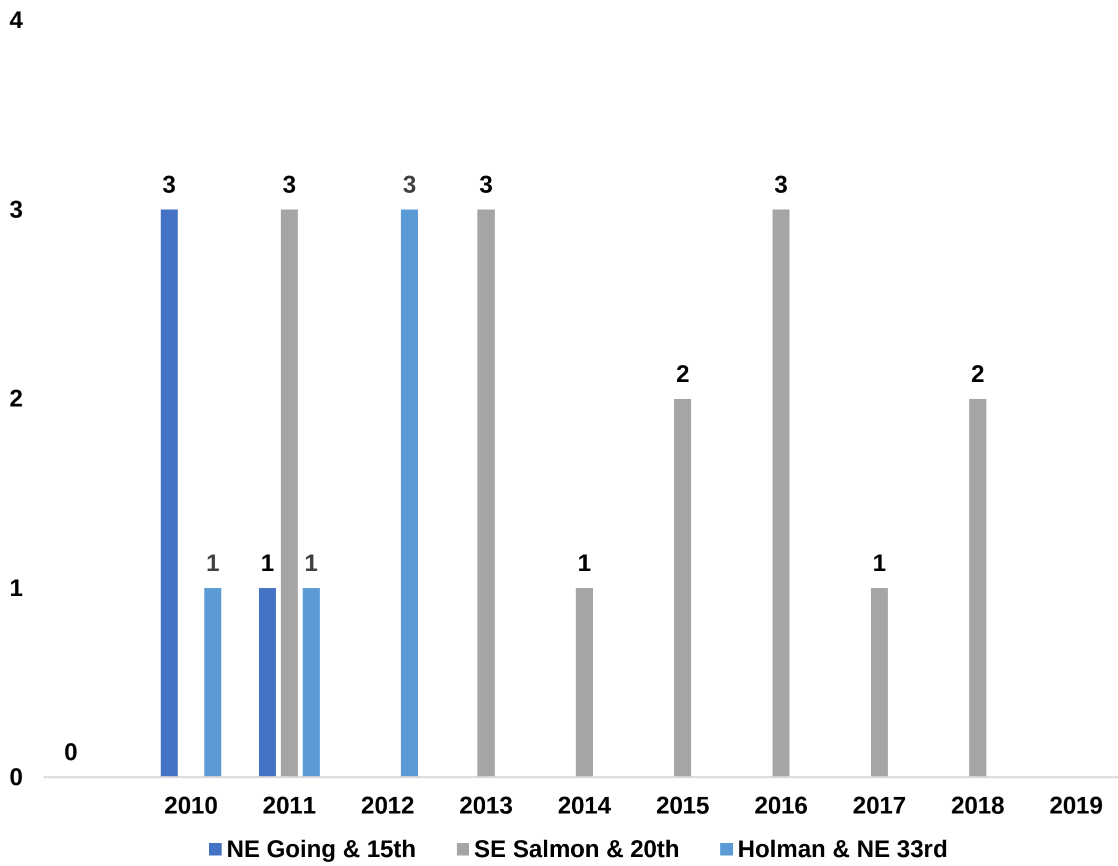


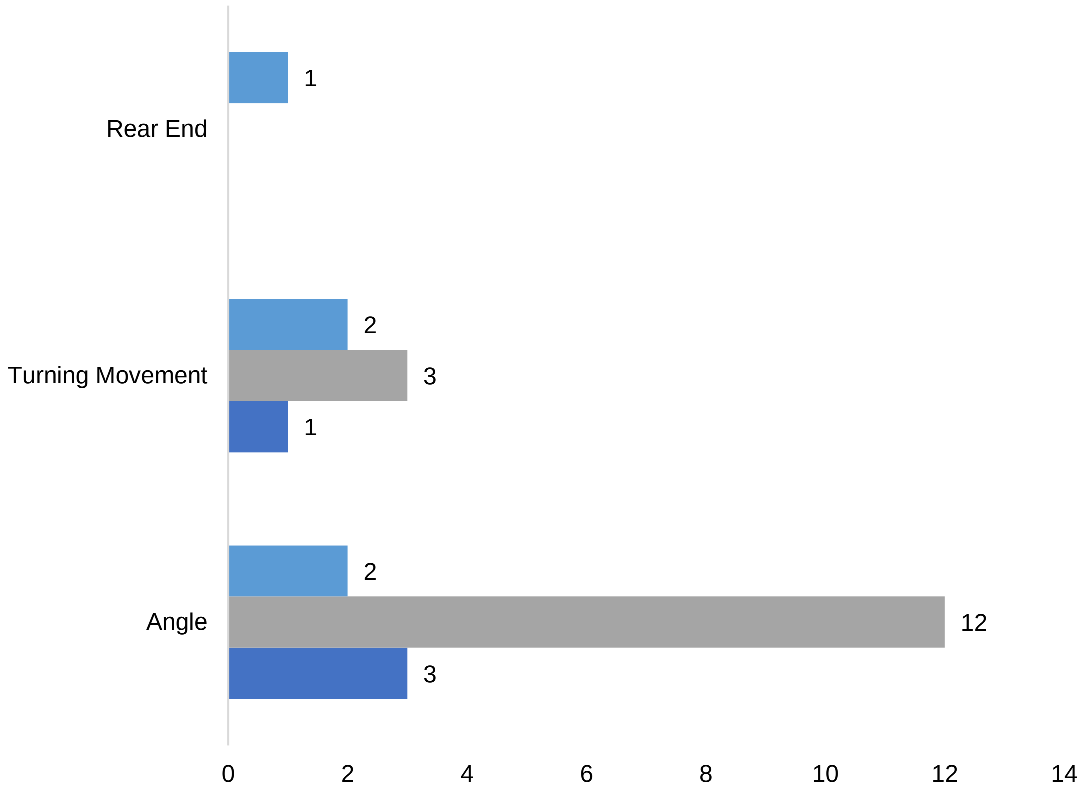

**Figure 10: Number of crashes by year for each intersection.**

### *3.4.1 Crash Type*

A detail look into the types of crashes that was overrepresented at these sites revealed that angle crashes constituted about 70% of the total crashes followed by 25 % of turning movement. Rear-end crash constituted about 5%. All these crashes resulted in only property damages. The table and figure below give detail representation of the crash types.

**Table 5: Summary of collision type by site.**

| Crash Type | Summary of crashes at intersections | | |
|---|---|---|---|
| | NE Going & NE 15th Ave | SE Salmon & SE 20th Ave | NE 33rd & Holman |
| | Total number of crashes (2010-2019) | | |
| Angle | 3 | 12 | 2 |
| Turning Movement | 1 | 3 | 2 |
| Rear End | - | - | 1 |




| | Angle | Turning Movement | Rear End |
|---|---|---|---|
| Holman & NE 33rd | 2 | 2 | 1 |
| SE Salmon & 20th | 12 | 3 | |
| NE Going & 15th | 3 | 1 | |

**Figure 11: Number of crashes by collision type**

# 4 DATA COLLECTION, REDUCTION AND VERIFICATION

Data from the sites were collected using the video recording technique. The video data recordings were saved on SanDisk memory cards of size 64 gigabytes. Each of the site's video disk was watched using Ever Focus media player that played the video.

## 4.1 Data Collection

Empirical data was obtained from the three unsignalized intersections through video recordings. The data was collected mostly on good weather days. However, at NE 33rd and Holman, the before data collection had some rain showers at mid-day during the data collection period. In collecting the data, the City of Portland installed cameras on nearby utility poles and recorded the interactions between bicycles crossing the collector streets and motor vehicles travelling through the intersection. Each site had an average of eight-hour video recording for the before installation of the cross bike. About a year after installation of the cross bike, another set of data was collected through the video recording technique for same period during the day. Using the two sets of data, the before and after analysis were performed.

At each of the three unsignalized intersection sites, two cameras were installed at vantage positions to capture traffic interactions of motor vehicles with bicycles from both approaches on the minor streets to cross the major streets. Cameras were positioned to capture the pedestrian crosswalks; if present, in the field of view to better observe whether traffic yielded for bicycles or the pedestrians in the crosswalk. Before collecting the data, at each site, the safe stopping sight distance (SSD) is measured and marked with cones or markers. After marking the SSD, when vehicles approach the intersection from beyond the stopping sight distance, the waiting bicyclists waits for the oncoming vehicle to either yield or travel through the intersection before crossing the road as shown in Table 5. Data reduction was carried out in daytime light condition. The daytime light condition presented drivers the opportunity to clearly see bicyclists waiting at the edge of the road to cross and allows them ample time to react by either yielding or not. The study was also performed throughout the day to capture the variations in traffic and its subsequent influence on motorists yielding behavior. The summary of the video data collection are shown below.

**Table 6: Summary of Data Collection**

| Intersection | Video Footage Details | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Date(s) | | Hours | | No. of Observations | | No. of Cyclists | |
| | Before | After | Before | After | Before | After | Before | After |
| NE Going & NE 15th Ave | 8/30/2016 | 9/11/2017 | 7 | 8 | 548 | 507 | 705 | 618 |
| SE Salmon & SE 20th Ave | 9/19/2016 | 8/14/2017 | 7 | 8 | 266 | 354 | 309 | 408 |
| Holman & NE 33rd | 10/4/2016 | 9/27/2017 | 10 | 8 | 83 | 82 | 83 | 96 |
| Total | | | 24 | 24 | 897 | 943 | 1097 | 1122 |

## 4.2 Data Reduction

The key metrics extracted from watching the video clips and used for the analysis are briefly explained below.

**Location**: refers to the site being observed.

**Cross bike present**: this indicates whether the site had the treatment installed at the site. If the site has cross bike it is indicated by ticking “yes” otherwise “no”.

**Observation number**: Each observation is numbered sequentially. An observation begins when a cyclist appears at the intersection and ends when that cyclist crosses the intersection. If multiple cyclists appear – either all at once or following the initial cyclist, it still counts as one observation if all cyclists cross with the first cyclists who appeared. If not all cyclists cross, then record a new observation.

**Cyclist appears/Cyclist departs**: Record the time stamp when the first cyclist appears. Record this time when the cyclists either reaches the stop bar (or where the stop bar would be) or when they come to a complete stop (even if before the stop bar). Record the time when they depart the intersection.

**Number of cars passing mark without cyclist crossing**: Record here, for each camera, the number of cars passing the mark in the roadway without the cyclist being able to cross the roadways. For each car passing the mark without the cyclist being able to leave, mark an "N". Mark "Y" when a car passes the mark and the cyclist can leave the intersection, passing in front of the car. A typical entry may look like "NNY", meaning that four cars passed the mark, and it was only the last one when the cyclist was able to leave the intersection.

**Bicycle Crossing Event Type**. (1,2, or 3). For this study, the car yielding was categorized into three different types namely, ***Type 1, Type 2, and Type 3***.

- ***Type 1*** refers to instances where a motorist yields and stops for waiting bicyclists to cross the street.

- ***Type 2*** is when bicyclists waits for all the non-yielding cars to clear the intersection before crossing.

- ***Type 3*** is where cyclists are able to cross the intersection without any car being present at the time of crossing.

**Any peds? (yes/no)**.: Were there any pedestrians present at the intersection crossing major roadway? Because motorists may yield to pedestrians in the marked crosswalk that must be known if pedestrians were present.

**# of cyclists** is used to record the total number of cyclists crossing the roadway in this observation.

**Cyclists crossing both directions**? This is also a yes/no answer. Were there cyclists waiting on both sides of the roadway to cross who then successfully crossed the roadway?

**Notes**: Used this to record anything unusual or otherwise noteworthy about the observation.

**Near & Far side:** Relative to the location of the waiting bicyclist, the near and far side at the crossing changes. The near side is usually the immediate lane where the cyclists waits for safe gap to cross the street. The figure below gives a pictorial detail of the positions being discussed. The lane adjacent the waiting cyclist is the near side whiles the lane where the blue car is the far side with respect to this bicycle crossing.


**Figure 12: Plan view of NE Going & NE 15th Ave illustrating near and far sides for a bicycle crossing.**

Prior to the video reduction, some volunteers had watched and completed the data coding for the city of Portland. This data was obtained from the city of Portland's Bureau of Transportation. The video was watched and the data elements including cyclist's arrival time, departure time and car yielding type were observed and recorded in an Excel spreadsheet for the yielding analysis. For sites with marked crosswalk the presence of pedestrian in crosswalk was indicated for each cyclist's crossing event. Several spot checks were run on the data obtained from the city. After the video coding checks were completed, an extensive data cleaning exercise was undertaken to ensure that the data elements were coded correctly. All inconsistent data entries were identified and fixed. For instance, bicycle crossing type "3", there should not be any car present when the cyclists cross the street. However, the data provided by the city sometimes recorded some number of cars present for such car yielding type. In such situations the video is re-watched and if there were no car present the correction is effected. The reduced and cleaned data was used to calculate the following metrics:

$$\textbf{Cyclist Wait time at intersection} = \textit{Time Cyclist Arrives} - \textit{Time Cyclist Departs}$$

$$\textbf{Yielding Rate} = \frac{\textit{Total number of car yielding } (1)}{(\textit{Total number of car yielding} + \textit{Total number of vehicles not yielding})}$$

$$\textbf{Waiting Rate} = \frac{\textit{Total number of car not yielding } (2)}{(\textit{Total number of car yielding} + \textit{Total number of vehicles not yielding})}$$


**Figure 13: View of data reduction at NE Going & NE 15th Ave for before and after cross-bike installation.**

## 4.3 Data Verification

To ensure that accurate data formed the basis of the analysis, all the videos were re-watched for each site using the code instructions as a guide to validate the coded data obtained from the city. NE 33rd and Holman had to be watched for the first time since it had not been coded by the city. The video data re-watched were largely consistent with that already coded by the City of Portland. However, there were few instances where some corrections were made to better represent the accurate site observation. For instance, if the bicycle crossing type is recorded as “3” (Type 3 yielding is where no vehicle is present at the time the bicyclist crosses) there should not be any car present when the cyclist is crossing. Some entries had recorded numbers for vehicles present for this type of bicycle crossing. In all, 35 entries were corrected by this criterion for the after data for NE Going & NE 15th Ave 40 crossing entries were corrected for SE Salmon and 20th for the before data and 20 entries were changed using the same criterion for the after data. The before data for NE Going and 15th Ave had to be recoded due to the difference in the study time with the city's coded after data. The after data captured the full seven-hour observation whiles the city's coded before data captured only four hours (2pm-6pm). To ensure that the variations in traffic and yielding behavior are captured and compared with the after data, it was recoded to reflect the full video collection period during the day.

# 5 ANALYSIS AND RESULTS

This chapter presents the analysis and results of the observed bicycle and motorists' interactions from the reduced data. The effectiveness of the cross-bike treatment at the unsignalized intersection is assessed through the analysis that consists of: motorists yielding behavior towards bicyclists, comparison of motorists yielding rates by sites. This comparative analysis sought to investigate the differences in motorists yielding behavior among the three sites. Due to the differences in existing site characteristics at the various intersections, the difference in motorists yielding will be compared among sites to evaluate if any existing site treatment contributed to the improvement of the rate of motorists stopping for bicyclists., cyclists waiting rates, the average total wait time of cyclists at the intersection, the average wait time by car yielding type and finally the utilization rate of the markings.

Prior to delving into the evaluation analysis, a brief overview of the data is discussed below to give insight into the number of cyclists arriving at each intersection by time of day.

## 5.1 Bicycle arrivals

### *5.1.1 NE Going and NE 15th Ave.*

NE 15th is a bicycle boulevard that serves a considerable number of bicycle traffic. From the data, the number of cyclists arriving varied continuously throughout the day with high number of arrivals being observed during peak hours. The average number of bicycle arrivals was 64 for the before condition and 56 after the installation of the markings. The figure below shows the number of bicycle arrivals. The highest number of observations for before and after at this intersection is 210 and 144, respectively. This occurred at 5pm during the evening peak hour. The least observation occurred at 8am with no cyclists in the before condition and 2 cyclists after. The table and figure below detail the variations throughout the day.

**Table 7:Number of cyclists arriving at NE Going & NE 15th Ave.**

| No. of cyclists arriving at intersection | | |
|---|---|---|
| Time of day | Tuesday, 08/30/2016 (Before) | Monday, 09/11/2017 (After) |
| 8:00 am | - | 2 |
| 9:00am | 1 | 95 |
| 10:00 am | 52 | 46 |
| 11:00 am | 69 | 56 |
| 12:00 pm | 66 | 30 |
| 13:00 pm | 51 | 38 |
| 14:00 pm | 48 | 52 |
| 15:00 pm | 75 | 60 |
| 16:00 pm | 130 | 81 |
| 17:00 pm | 210 | 144 |
| 18:00 pm | 3 | 14 |

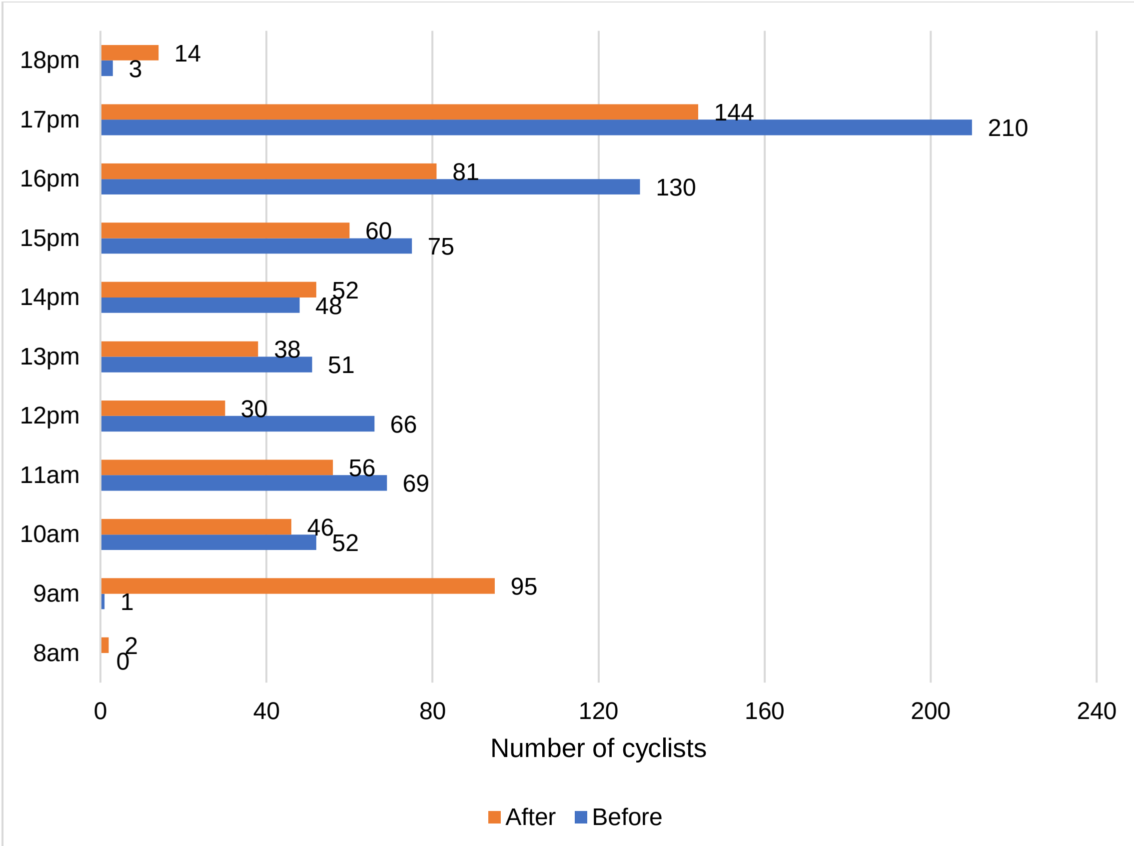



**Figure 14: Number of cyclists arriving at NE Going & NE 15th Ave.**

### *5.1.2 SE Salmon and SE 20th Ave.*

The results of the cyclist's arrival at the intersection for SE Salmon and SE 20th Ave also revealed a pattern which is consistent with that at NE Going and NE 15th Ave. The average rate of arrival was 39 and 40 for before and after, respectively. The off-peak hours showed varying differences in the frequency of arrival which ranged from 16 to 41. The typical morning and evening peaks shown in the cyclists' arrival data suggests most cyclists commute to work using the routes selected for the study.

**Table 8: Number of cyclists arriving at SE Salmon & 20th**

| No. of cyclists arriving at intersection | | |
|---|---|---|
| Time of day | Monday, 09/19/2016 (Before) | Monday, 08/14/2017 (After) |
| 8:00 am | - | 38 |
| 9:00 am | - | 71 |
| 10:00 am | 16 | 37 |
| 11:00 am | 45 | 29 |
| 12:00 pm | 41 | 23 |
| 13:00 pm | 31 | 34 |
| 14:00 pm | 45 | 28 |
| 15:00 pm | 38 | 31 |
| 16:00 pm | 80 | 66 |
| 17:00 pm | 18 | 51 |
| 18:00 pm | - | - |

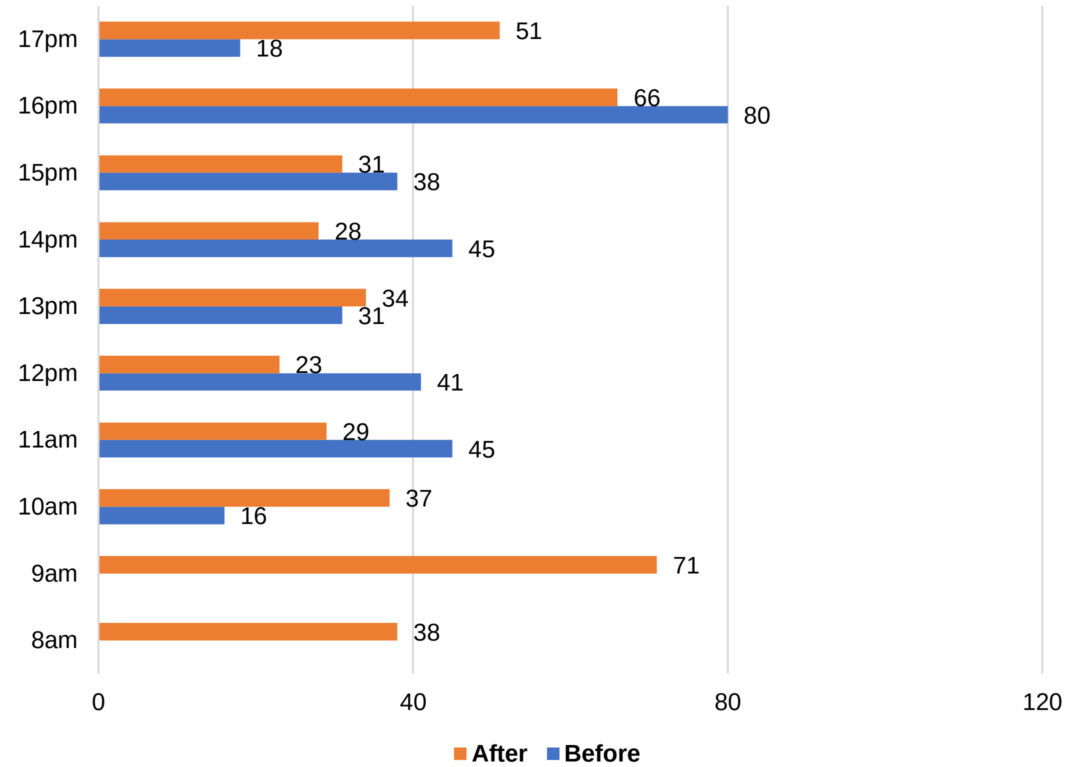



**Figure 15: Number of cyclists arriving at SE Salmon & SE 20th Ave.**

### *5.1.3 <u>Holman and NE 33rd Ave.</u>*

Though this site recorded low volumes of bicycle traffic, the figure also showed the pattern depicted by the other two sites. Highest number of cyclists arrivals at the intersection were during the evening peak with 15 and 18 times for both before and after respectively with the corresponding number of bicyclists also being 15 and 22 cyclists. Substantive variations in traffic were observed during the other times of the day for both before and after. Bicycle traffic arriving at intersection averagely ranged from as low as 2 at 11am to 18.

**Table 9: Number of cyclists arriving at Holman & 33rd Ave.**

| No. of cyclists arriving at intersection | | |
|---|---|---|
| Time of day | Tuesday, 10/4/2016. (Before) | Wednesday, 09/27/2017. (After) |
| 7:00 am | 2 | - |
| 8:00 am | 13 | - |
| 9:00 am | 3 | - |
| 10:00 am | 8 | - |
| 11:00 am | 5 | 2 |
| 12:00 pm | 5 | 6 |
| 13:00 pm | 3 | 12 |
| 14:00 pm | 5 | 18 |
| 15:00 pm | 15 | 18 |
| 16:00pm | 12 | 22 |
| 17:00 pm | 8 | 17 |
| 18:00 pm | 4 | 1 |

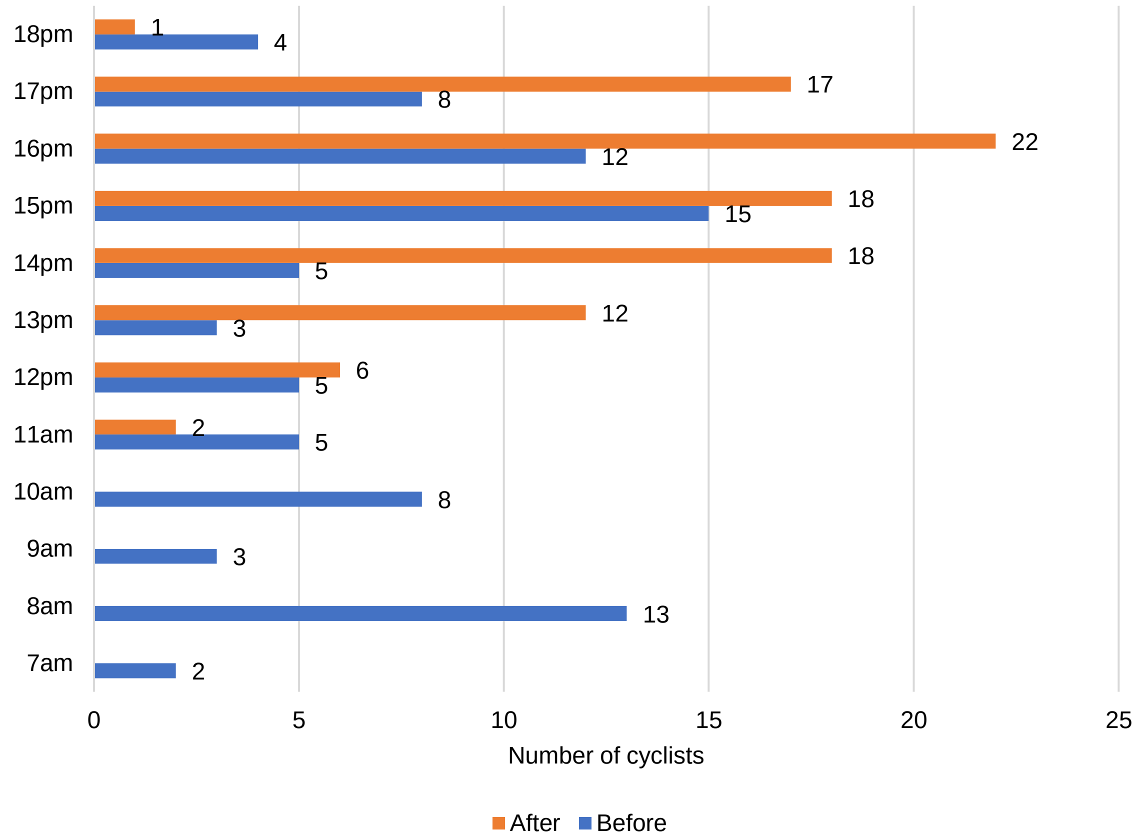



**Figure 16: Number of cyclists arriving at Holman & NE 33rd Ave.**

### *5.1.4 Findings*

The results of the data for the arrival of cyclists at the intersection show that, cyclists' arrival at the sites vary throughout the times of the day. Like motor vehicle traffic, the bicycle traffic also exhibited typical morning and evening peak as shown in all the figures for the various sites. This suggests most bicyclists commute to work by bicycle. The morning peak hours showed considerable differences in bicycle traffic which ranged from as low as 2 cyclists to about 50 cyclists. The evening peak hours did show higher bicycle volumes. Volumes ranged from 35 cyclists to 120. It is worth noting that NE Going and

NE 15th recorded high bicycle traffic. One reason for this could be the fact that NE 15th has been prioritized for bicycle traffic.

The reasonably good number of bicycles that arrived at the intersections during the study period presented the opportunity to obtain adequate data on bicycle performance as well as motorists yielding behavior towards bicyclists at crossings. This formed the basis of the analysis of the effectiveness of the cross-bike markings.

### 5.2 Motorists Yielding Analysis (Type 1 Interaction – Car yields to bicyclists)

Motorists yielding rates by location are presented in table 9. For this study, the bicycle crossing events was categorized into three different types namely, *Type 1, Type 2, and Type 3*. Type1 refers to instances where a motorist stops for waiting bicyclists to cross the street. Type 2 is when bicyclists waits for all the vehicles to clear the intersection before crossing. Type 3 is where cyclists are able to cross the intersection without any car being present at the time of crossing. Overall, the driver yielding rates to bicyclists increased for both near and far sides after the installation of the cross-bike pavement markings. NE Going and NE 15th Ave had a statistically significant increase in motorist yielding rates from 48% and 61% for the before condition to 91% and 95% for near and far sides respectively after the installation of cross bike markings. SE Salmon & 20th doubled the yielding rates for near side for before cross bike (21% to 40%). The far side rate increased by almost three times after the installation (11% to 33%). Holman and NE 33rd realized an improved motorist yielding behavior with driver yielding increasing from 38% near side and 36% far side for before cross-bike pavement markings to 77% near side and 82% far side after the treatment. It is worth noting that the far side yielding rates were always higher than near sides for before and after installation.  The table below gives details of the yielding rates for the before and after cross bike installation. Also, worth stating that these rates are instances where motorists yielded because a bicyclist was waiting for a gap to cross the street. For instances where motorists yielded because of the presence of both cyclists and pedestrians accounted for less than 1% for each site. The rates presented here represent motorists yielding due to the presence of bicyclists only.

**Table 10: Sample size and motorists yielding rates by sites- Before and After Cross-bike.**

| Car Yielding Type | Sample Size (n) by Site | | | | | |
|---|---|---|---|---|---|---|
| | NE Going & NE 15th Ave | | SE Salmon & SE 20th Ave | | Holman & NE 33rd | |
| | Near Side | Far Side | Near Side | Far Side | Near Side | Far Side |
| ****1** | **100** | **170** | **13** | **8** | **19** | **22** |
| 2 | 109 | 108 | 50 | 66 | 31 | 39 |
| 3 | 328 | 259 | 190 | 179 | 32 | 21 |

| Car Yielding Type | Motorists Yielding Rates (%) | | | | | |
|---|---|---|---|---|---|---|
| | NE Going & NE 15th Ave | | SE Salmon & SE 20th Ave | | Holman & NE 33rd | |
| | Near Side | Far Side | Near Side | Far Side | Near Side | Far Side |
| ****1** | **48** | **61** | **21** | **11** | **38** | **36** |
| 2 | 52 | 39 | 79 | 89 | 62 | 64 |
| 3 | – | – | – | – | – | – |

**Notes:  ** Type 1 yielding rate, – no observations**

After Installation of Cross bike

| Car Yielding Type | Sample Size (n) by Site | | | | | |
|---|---|---|---|---|---|---|
| | NE Going & NE 15th Ave | | SE Salmon & SE 20th Ave | | Holman & NE 33rd | |
| | Near Side | Far Side | Near Side | Far Side | Near Side | Far Side |
| ****1** | **153** | **181** | **33** | **27** | **35** | **48** |
| 2 | 16 | 9 | 49 | 55 | 11 | 11 |
| 3 | 304 | 283 | 247 | 247 | 35 | 22 |

| Car Yielding Type | Motorists Yielding Rates (%) | | | | | |
|---|---|---|---|---|---|---|
| | NE Going & NE 15th Ave | | SE Salmon & SE 20th Ave | | Holman & NE 33rd | |
| | Near Side | Far Side | Near Side | Far Side | Near Side | Far Side |
| ****1** | **91** | **95** | **40** | **33** | **76** | **81** |
| 2 | 9 | 5 | 60 | 67 | 24 | 19 |
| 3 | – | – | – | – | – | – |

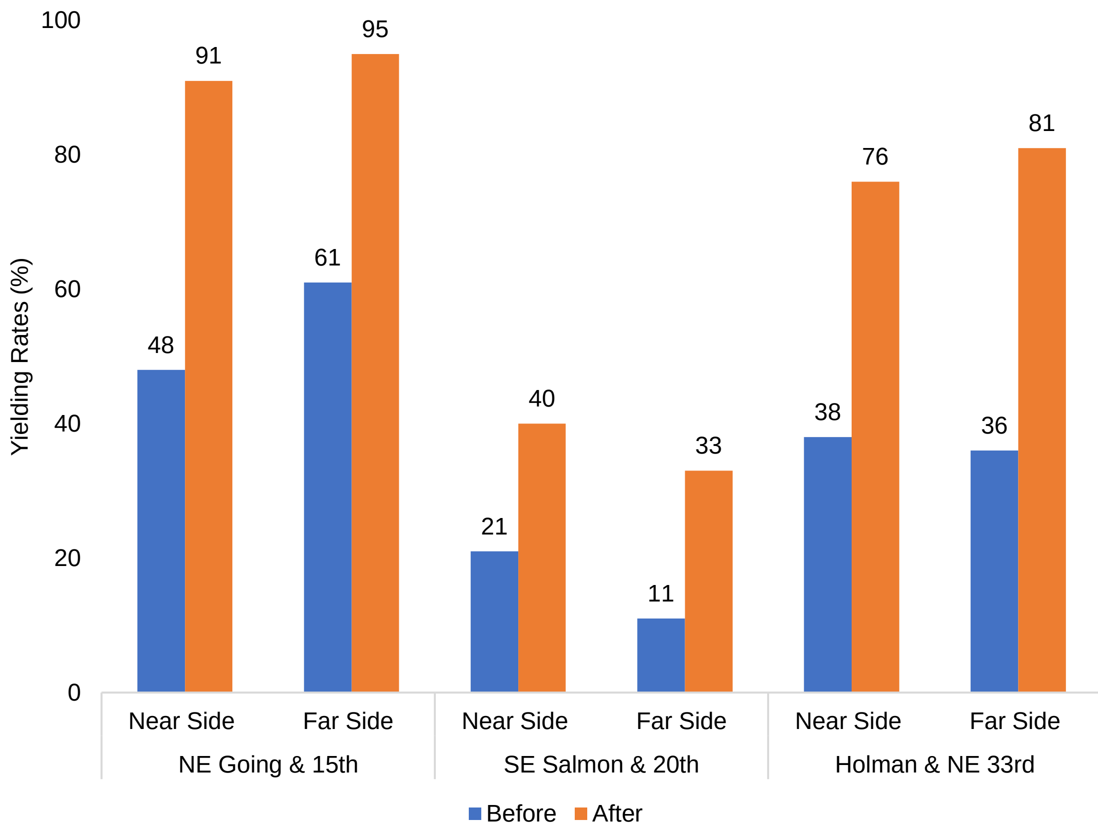



**Figure 17: Motorists yielding rates to bicyclists by site.**

### *5.2.1 Comparison of Yielding Rates among Sites*

Motorists yielding rates among the sites were compared to find out if there are any substantial differences in driver yielding behavior. The existing conditions at the sites differed in characteristics. SE Salmon and SE 20$^{th}$ was adopted to be the base model for which the other two sites were compared to. This site was assumed to be the base model because the existing site characteristics consisted of only two-way road with no marked crosswalk and median as compared with the other two sites. The before condition revealed that the rate at which motorists stopped for bicyclists were higher at NE Going and NE 15$^{th}$ Ave as well as Holman and NE 33$^{rd}$ as detailed in the table 10 below for near and far side.

Part of the reason for these higher rates of yielding could be the combined effect of marked crosswalk and median islands at these sites. Similar trend of higher yielding rates were observed after installing cross-bike at the intersection.

The review of the crash history showed that SE Salmon and 20$^{th}$ recorded the highest number of crashes with 12 of the crashes being angle. The low yielding rates prior to the cross-bike suggests that this treatment may enhance the safety of bicycles.

### *5.2.2 STATISTICAL ANALYSIS*

Statistical tests were conducted to compare the proportions of yielding for near and far-side drivers within each site category between the before and after cross-bike treatment. The results show that difference in yielding rates observed after installation of cross bike markings are statistically significant at the 99$^{th}$ percentage confidence level. This leads to the rejection of the null hypothesis and to accept the alternative hypothesis that increasing the visibility of intersection as bicycle crossing will enhance or improve the rate at which motorists stop for bicyclists although motorists are not required to yield for bicyclists at intersection with cross-bike installation. The details of the test of proportions for each site is shown in the table below.

**Table 11: Results of proportion tests for differences in before and after yielding rates.**

| Site | Near Side | | | | | Far Side | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Before | | After | | | Before | | After | | |
| | Yielding **(n)** | Not Yielding **(n)** | Yielding **(n)** | Not Yielding **(n)** | p-value | Yielding **(n)** | Not Yielding **(n)** | Yielding **(n)** | Not Yielding **(n)** | p-value |
| NE Going & NE 15th | 100 | 109 | 160 | 17 | **0.00*** | 170 | 108 | 191 | 1 | **0.00*** |
| SE Salmon & SE 20th | 13 | 50 | 23 | 44 | **0.01***| 8 | 66 | 33 | 57 | **0.00*** |
| Holman & NE 33rd | 19 | 31 | 35 | 11 | **0.00*** | 22 | 39 | 48 | 11 | **0.00*** |

**Note**: *statistically significant at the 95% confidence level.

## 5.3 Bicyclists Waiting Analysis (Type 2 – Bicyclists waits for safe gap to cross)

Another metric that can be used to assess the effectiveness of the cross-bike markings is the rate at which cyclists wait for safe gap at intersection to cross. Waiting rate is the frequency at which bicyclists had to wait for vehicles that did not yield to clear intersection before they could cross. The analysis of the data shows that after the installation of the treatment, the frequency or rate at which bicycles wait for cars to clear the intersection before crossing reduced. This implies that cyclists time and effort spent scanning for a safe gap to cross are minimized. For instance, at NE Going and NE 15th Ave there was a drastic reduction in the rate at which cyclists wait for cars to clear the intersection. The rates of cyclists waiting reduced from 52% to 9% for near side and 39% to 5% on the far side at NE Going and NE 15th Ave. This improvement in the cyclists waiting rates is reflected in the motorists' yielding results that saw their yielding rates increasing from 48% to 91% for nearside and 61% to 95%. SE Salmon and SE 20th also had a considerable improvement in bicycles waiting for cars to clear the intersection before crossing. (79% to 60% near side and 89% to 67% far side).

**Table 12: Bicyclists waiting rates by site.**

| Bicyclists Waiting Rates | | | | | | |
|---|---|---|---|---|---|---|
| Type 2 - Interaction | NE Going & NE 15th Ave | | SE Salmon & 20th Ave | | Holman & NE 33rd | |
| | Near Side | Far Side | Near Side | Far Side | Near Side | Far Side |
| Before | 52 | 39 | 79 | 89 | 62 | 64 |
| After | 9 | 5 | 60 | 67 | 23 | 19 |

**Notes: Type 2 -Interaction: Bicyclists wait for safe gap to cross**

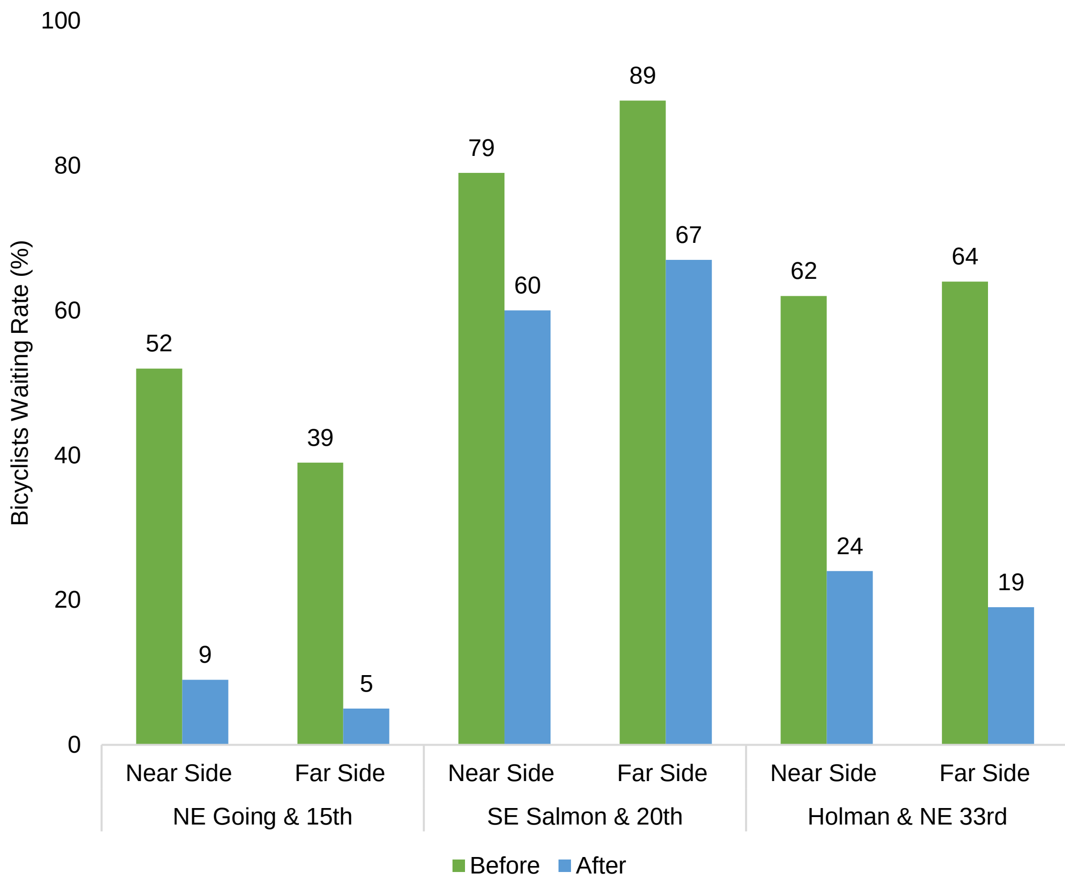



**Figure 18: Bicycle waiting rates analysis by site.**

### *5.3.1 <u>Findings</u>*

One key question that this study seek to address is whether the cross-bike markings influence cars yielding for bicyclists at unsignalized crossings. To evaluate the effectiveness, the rate of motorists yielding for bicycles were analyzed. The data analyzed reveals that installing the cross bike has improved driver yielding for cyclists. This difference in the rate of motorists yielding is statistically significant at the 99$^{th}$ percentile confidence level. Data results strengthen the hypothesis that improving the visibility of intersections as bicycle crossings help to modify motorists yielding to cyclists.

Another approach used to explore the effectiveness of the treatment was to assess the rate at which the bicycles also wait for motor vehicles to clear intersection before crossing. Just as the rate of motorists yielding saw a statistically significant increase, the bicycle rate of waiting for cars to clear the intersection also reduced significantly after the treatment. This implies that cyclists no longer had to wait for long to seek for a safe gap to cross street.

For instance, SE Salmon & SE 20$^{th}$ recorded very low motorists yielding rates of 21% and 11% for the before cross-bike marking treatment. However, after installing the markings the yielding rates doubled for the near side and tripled for far side. The improvement in motorists yielding behavior was also reflected in the rate of bicyclists waiting. In that, there was a reduction in the rate at which cyclists used to wait for cars to clear the intersection before crossing. This has improved the overall operational efficiency of the crossing as well as safety. Additionally, the crash history at this site was frightening and therefore with the installation of cross-bike and other enhancements, the safety of this intersection will be improved magnificently.

## 5.4 Average Bicyclists Wait Time

### *5.4.1 <u>By Car Yielding Type</u>*

The operational efficiency of crossings helps improve safety and increase bicycle ridership. Excessive delays at crossings tend to discourage many people from biking because of the fear of getting to their destinations late. The cyclists' wait time was assessed to investigate if there were any improvements in terms of reduction in the average amount of time bicyclists spend at intersection before they could cross. After analyzing the empirical data, the average cyclists wait time are presented below by the type of car yielding. Intuitively, Type 3 is expected to have lower wait times since cyclists are not expected to wait for any passing vehicles. The overall wait time reduced after the treatment was installed. The table below details the average wait times at each intersection by the type of yielding.

**Table 13: Average Bicyclists Wait Time at Intersection by Site.**

| Car Yielding Type | Average Bicyclists Wait Time at Intersection (Sec) | | | | | |
|---|---|---|---|---|---|---|
| | NE Going & 15th | | SE Salmon & 20th | | Holman & NE 33rd | |
| | Before | After | Before | After | Before | After |
| 1 | 7 | 6 | 13 | 8 | 9 | 7 |
| 2 | 8 | 7 | 18 | 11 | 10 | 6 |
| 3 | 5 | 5 | 7 | 3 | 7 | 6 |

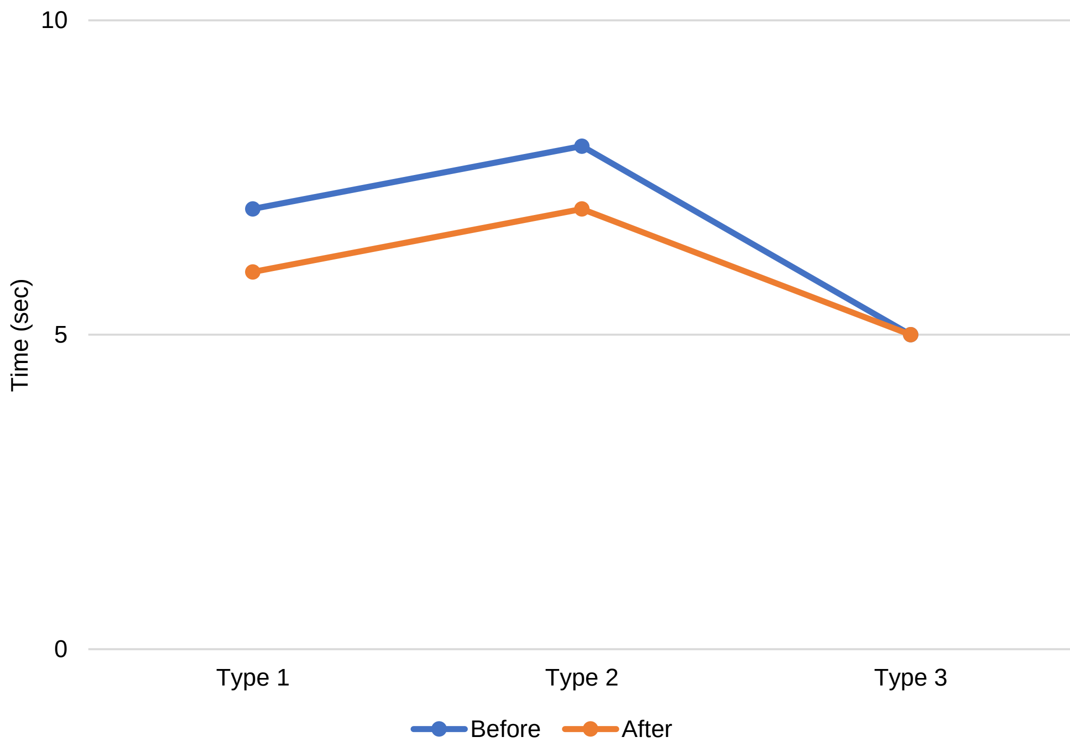



Figure 19: Average cyclists wait time by bicycle crossing type. (NE Going & NE15th Ave).

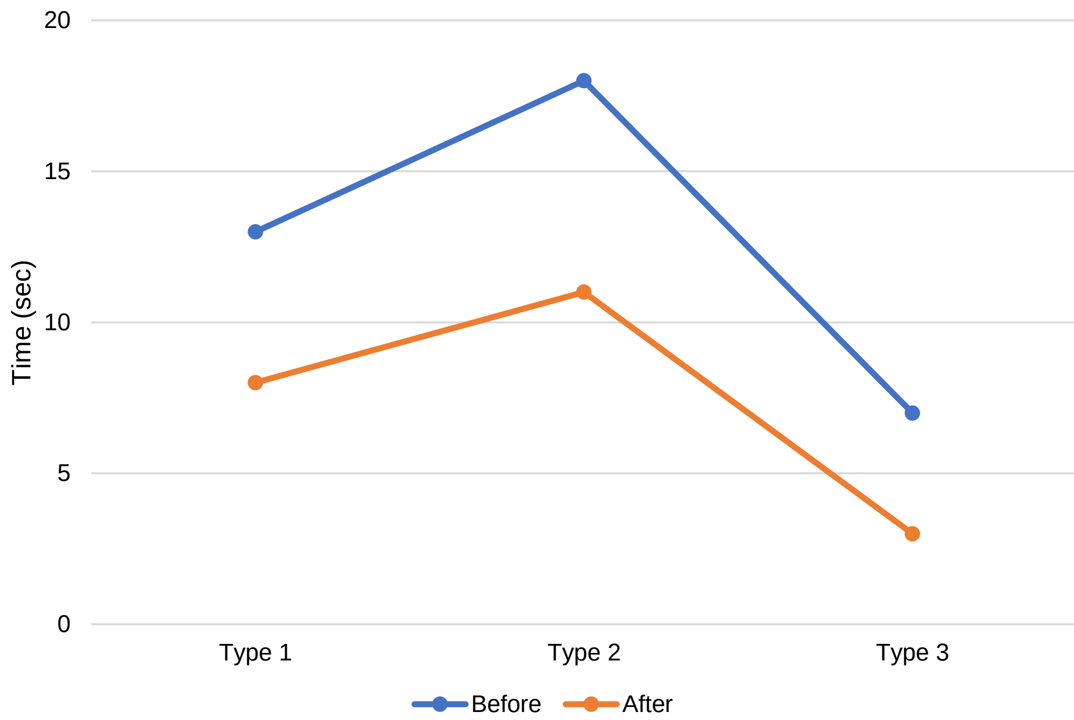



**Figure 20: Average cyclists wait time by bicycle crossing type. (SE Salmon & Se 20th Ave).**

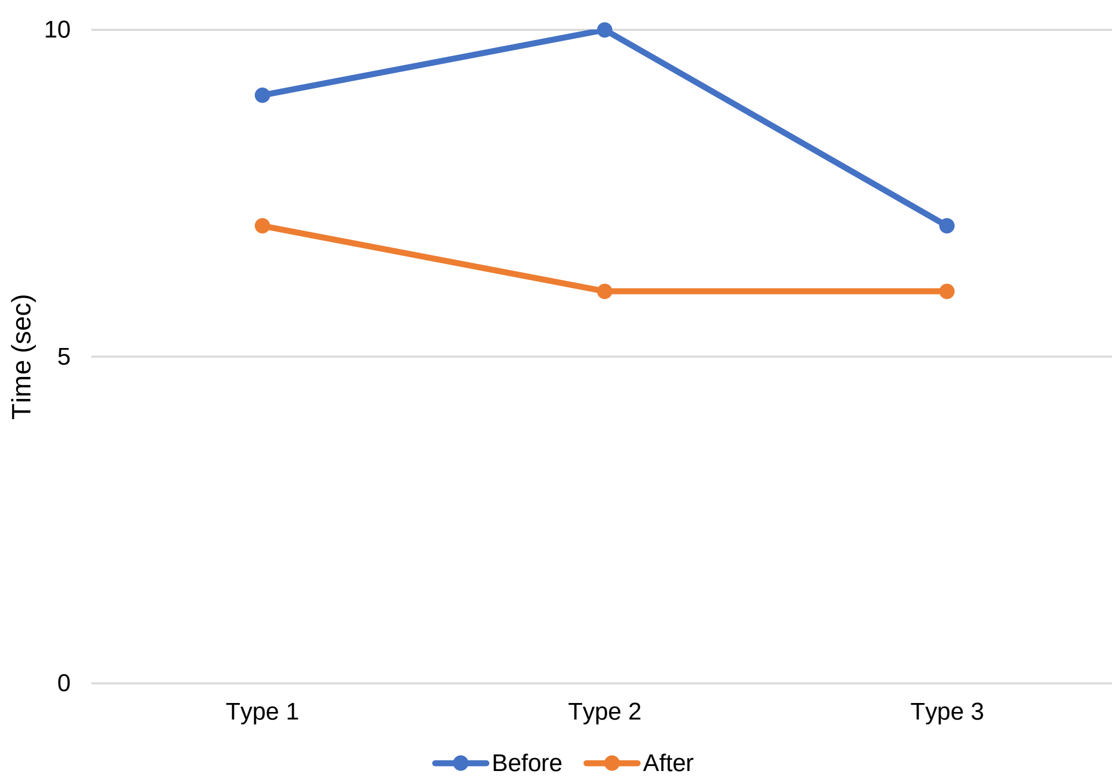



**Figure 21: Average cyclists wait time by bicycle crossing type. (Holman & NE 33rd).**

### *5.4.2 Total Average Wait Time by Site*

The total average cyclists wait time also experienced a considerable reduction in wait times. NE Going & NE 15th maintained a 6sec overall wait time for cyclists crossing before and after the installation of the treatment. Salmon and 20th recorded a substantial reduction from 9sec to 4sec. This indicates an impressive improvement in the operational efficiency of the crossing. The total average wait time depicted the pattern shown in the earlier discussion. Table 15 details the summary of the various wait times by the sites.

**Table 14: Total Average Wait Time by Site.**

| Total Average Bicyclists Wait Time at Intersection (Sec) | | | | | |
|---|---|---|---|---|---|
| NE Going & 15th | | SE Salmon & 20th | | Holman & NE 33rd | |
| Before | After | Before | After | Before | After |
| 6 | 6 | 9 | 4 | 9 | 6 |

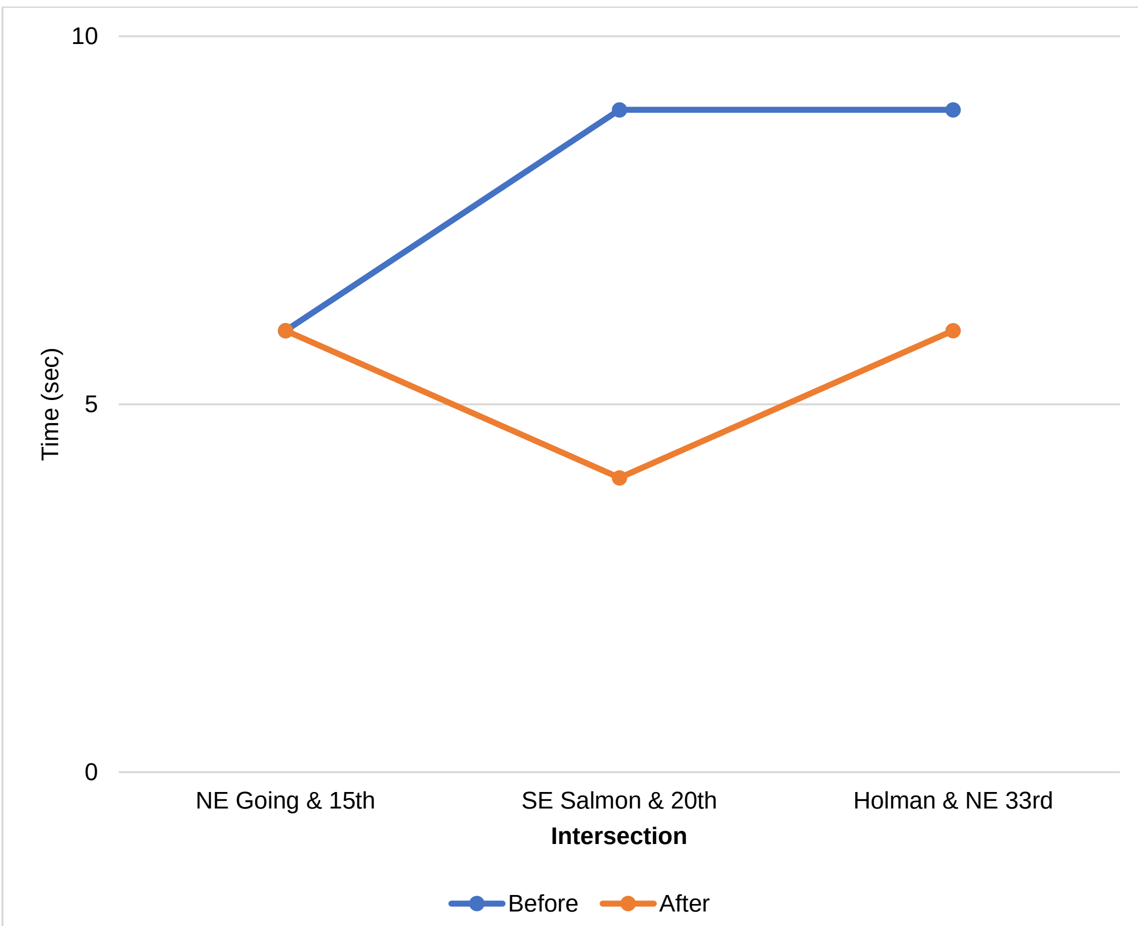



**Figure 22: Total average wait time by site.**

### 5.4.3 ***Findings***

Operational efficiency is a key metric that was used to assess the effectiveness of the markings at the various crossing sites. A study shows that pedestrians engage in risky behavior once their wait times for crossing street exceeds 30sec. In the same vein cyclists, are discouraged to bike if they experience excessive delays at crossings. The data analyzed showed a considerable reduction in cyclists' wait time after the markings have been installed. The wait time by yielding type showed a reasonable reduction from 7sec before treatment to 6secs after for NE Going & 15$^{th}$. Also, the wait time cyclists spend in allowing vehicles to clear intersection before crossing also reduced from 8secs to 7secs. SE Salmon and SE 20$^{th}$ saw a significant reduction in average cyclists wait time. For instances where motorists failed to yield for cyclists at this site, the wait time reduced from 18secs to 11secs. This is because the motorists' yielding rates doubled and almost tripled at the near and far sides respectively after the crossing was marked for cyclists. The overall average total wait time also reduced from 9secs to 6secs for SE Salmon & 20$^{th}$ as well as Holman and NE 33$^{rd}$. NE Going & NE 15$^{th}$ maintained a 6secs wait time for before and after installation. Overall, the treatment improved the intersections' operational efficiency by reducing the average wait times.

## 5.5 Number of Vehicles that Pass Mark before Motorists Yield.

The reduced data took record of the average number of cars that passed the mark before the cyclist gets a car to yield. This data was analyzed for the before and after improvement to evaluate if the treatment had a significant impact on the number of traffic that failed to yield for a waiting cyclist. The earlier discussion established a significant increase in motorists yielding rates after the treatment. However, the subsequent impact on the number of cars that passed the mark before first car yielded was not brought to light by the yielding rates. Evaluating the average number of cars that passed the mark before yielding occurred, it was revealed that each site recorded a substantial decrease in the number of cars that failed to yield. Figure 19 shows the percentage reduction in the number of cars that passed mark before yielding occurred. NE Going & NE 15th recorded a decrease in percentage from 57% and 42% in the near and far side for the before condition to 32% after the cross-bike marking was installed. SE Salmon & 20th also had high percentage of 94% for the number of cars that passed before yielding occurred being reduced to 76 %.

**Table 15: Sample size and number of cars passing before yielding.**

| | Sample Size (n) by Site | | | | | |
|---|---|---|---|---|---|---|
| | NE Going & NE 15th Ave | | SE Salmon & SE 20th Ave | | Holman & NE 33rd | |
| | Near Side | Far Side | Near Side | Far Side | Near Side | Far Side |
| No. of cars yielding | 149 | 355 | 10 | 8 | 32 | 105 |
| No. of cars that passed mark | **198** | **256** | **150** | **132** | **87** | **43** |
| | | | | | | |

| | Percentage of cars passing mark (%) | | | | | |
|---|---|---|---|---|---|---|
| | NE Going & NE 15th Ave | | SE Salmon & SE 20th Ave | | Holman & NE 33rd | |
| | Near Side | Far Side | Near Side | Far Side | Near Side | Far Side |
| No. of cars yielding | 43 | 58 | 6 | 6 | 27 | 29 |
| No. of cars that passed mark | **57** | **42** | **94** | **94** | **73** | **71** |

After

| | Sample Size (n) by Site | | | | | |
|---|---|---|---|---|---|---|
| | NE Going & NE 15th Ave | | SE Salmon & SE 20th Ave | | Holman & NE 33rd | |
| | Near Side | Far Side | Near Side | Far Side | Near Side | Far Side |
| No. of cars yielding | 202 | 116 | 42 | 8 | 36 | 41 |
| **No. of cars that passed mark** | **93** | **249** | **120** | **107** | **89** | **75** |
| | | | | | | |

| | Percentage of cars passing mark (%) | | | | | |
|---|---|---|---|---|---|---|
| | NE Going & NE 15th Ave | | SE Salmon & SE 20th Ave | | Holman & NE 33rd | |
| | Near Side | Far Side | Near Side | Far Side | Near Side | Far Side |
| No. of cars yielding | 68 | 68 | 26 | 24 | 29 | 35 |
| **No. of cars that passed mark** | **32** | **32** | **74** | **76** | **71** | **65** |

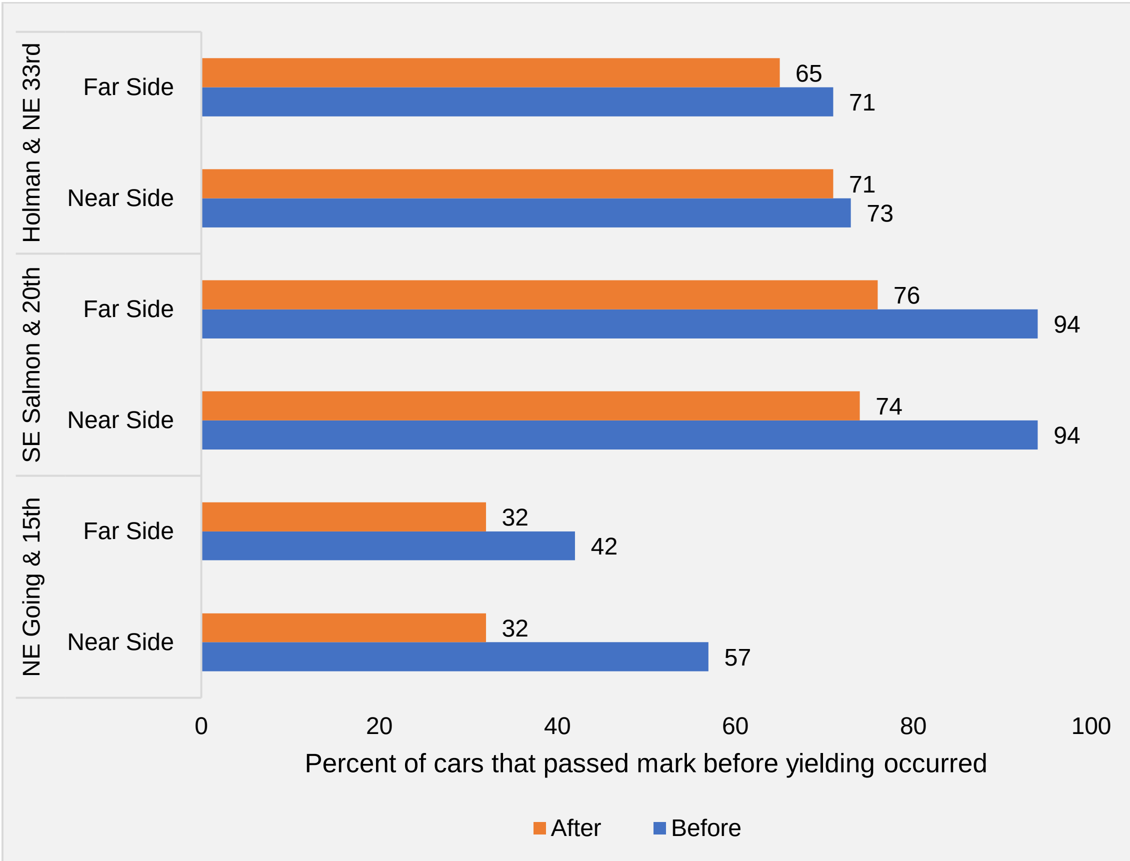



**Figure 23: Percent average number of cars that passed mark before yielding by site.**

## 5.6 Cyclist Position Waiting to Cross

The effectiveness of the treatment was also assessed by how much it assisted bicyclists in locating a suitable waiting position to scan for gap to cross and also provided clear crossing paths for them. Before the cross-bike pavement markings were installed at the crossings, cyclists upon reaching the intersection did not have a designated spot where they could wait and scan for a safe gap to cross the street. In some instances, some cyclists did not really know where best to wait in order to be easily sited by an oncoming vehicle. This led to some delays of cyclists. At NE Going & NE 15$^{th}$ Ave where there was a marked crosswalk before the cross-bike treatment, it was noted that in five instances cyclists had to use the pedestrian crosswalk after being delayed in scanning for a gap at where they were initially positioned. This may have accounted for the high average wait time of 18secs at SE Salmon & SE 20$^{th}$ Ave before the pavement marking treatment. This site had no marked pedestrian crosswalk or median island before the cross-bike pavement was installed. After installing the markings, the average cyclists wait time at the site reduced from 18secs to 11sec. Part of the reason for this improvement is the fact that cyclists could now locate a designated marked area where they could wait for motorists to stop for them to cross. Additionally, the marking was observed to have provided a clear crossing path for cyclists across all the sites.

# 6 CONCLUSIONS

Intersection treatments at crossings of busy roads are the one of the biggest challenges in developing bicycle boulevards and trails. The key question that this thesis sought to answer was to use empirical data to assess and evaluate the effectiveness of improving the visibility of an unsignalized bicycle crossings in Portland, Oregon. Cross-bike marking is a treatment installed at crossings in a similar way as pedestrian crosswalk but marked with green pavement markings. The goal is to improve visibility of the intersection as a bicycle crossing Although motorists are not legally required to stop for cyclists at intersections with such treatment, it was hypothesized that motorist yielding to persons on bicycles would increase. Video data, collected before and after at three intersections, were to be analyzed to evaluate the change in the rate of motorists yielding to bicyclists. The 10-year crash data for the sites shows SE Salmon and 20$^{th}$ had the highest total number of 15 crashes over the period with Holman and 33$^{rd}$ Ave having 5 crashes followed by NE Going and 15$^{th}$ Ave with 4 crashes. SE Salmon and 20$^{th}$ averaged about 2 crashes every year with the remaining sites averaging a crash every year.

Notably, the analysis found that, the installation of the cross-bike improved the driver yielding behavior for cyclists. This change in driver yielding was statistically significant. Driver yielding rates at NE Going & NE 15$^{th}$ Ave was found to be 48% near side and 61% far side before the crossing was marked. These yielding rates improved to 91% near side and 95% far side after the installation of the treatment. This statistically significant difference in yielding behavior of motorists is expected to translate into improved bicycle safety. SE Salmon and SE 20$^{th}$ had lowest yielding rates of 21% and 11% for near and far side respectively before the treatment. Marking the cross-bike doubled (40%) nearside and tripled (33%) far side the rates of motorist stopping for cyclists. Similar improvements in motorists yielding behavior was seen at Holman and 33rd Ave was made at Holman & NE 33rd. All the differences in motorists yielding were statistically significant.

Another way the effectiveness of the facility was assessed was to analyze the rate of cyclists waiting for cars to clear the intersections before crossing. All the three sites experienced a substantial reduction in cyclists waiting rates. NE Going & NE 15th Ave which recorded a significant increase in motorists yielding also recorded a drastic reduction in the rate at which bicyclists stop for cars. Prior to the installation of the treatment, the bicycle waiting rates were 52% and 38% for near and far sides. However, after marking the intersection, the bicycles rates reduced to 10% and 5% at this location.

Also, SE Salmon & 20th recorded a considerable reduction in the rate of cyclists waiting by decreasing from 77% to 56% near side and 88% to 63% far side. This reduction reflected in the motorists yielding rates which doubled and tripled. Overall, yielding behavior of motorists toward bicyclists was significantly modified because of the cross-bike marking installed at the unsignalized intersections.

The analysis further investigated the reason for driver yielding to identify if they did so because of the presence of pedestrian or solely because of bicyclists. NE Going & NE 15th Ave had a marked crosswalk. The number of times motorists yielding occurred was compared with the number of times cyclists cross the street with pedestrians. Results at NE Going showed that out of the 101 counts of motorists yielding, only 3 instances were where there were pedestrians crossing at the same time the bicycles crossed for the near side. The far side recorded 177 counts of motorists yielding out of which 10 counts were when pedestrians crossed simultaneously. The other two sites recorded lower volumes of pedestrians crossing with cyclists. For instances, Holman & NE 33rd recorded no instance of pedestrian crossing at the same time with the bicyclists for the number of times motorists yielded. This shows that about 98% of the driver yielding was because of the cyclists.

The bicycle network increases ridership if the safety and efficiency of the crossings are improved. Excessive delays at busy crossings put off many interested but concerned cyclists. Data was analyzed to investigate whether it improved the operational efficiency of the crossing by reducing the average wait time of bicyclists. The results showed that the average total wait times of cyclists were reduced from 9secs to 6 secs after the cross- bike was marked. SE Salmon which recorded lowest driver yielding rates realized a significant decrease in cyclists wait time from 18 secs to 11secs after improving the visibility of the crossing.

Additionally, the marking was found to have improved the consistency of the waiting location of bicyclist waiting to cross by providing positive guidance for bicyclists crossing. Prior to installation many cyclists had difficulty in identifying good locations to wait for a gap to cross. The installation of the treatment provided a clear guidance for cyclists waiting and scanning for gap to cross. The separation of cyclists from pedestrians also reduced potential conflicts between bikes and pedestrians.

In conclusion, the combined effects of installing cross-bike at unsignalized intersection improves motorists yielding rates and operational efficiency by reducing average wait times and provides positive guidance for bicyclists.

## 6.1 Limitations

The limitations associated with the data analyzed and presented above are discussed hereunder.

- The data analyzed could not account for the effects of existing treatments such as pedestrian crosswalks, and median islands on the yielding behavior of motorists. The video data collection method focused more on the treatment for bicycles with little emphasis or accommodation to account for the effect of other existing treatments on motorists yielding behavior.

- Sites selected for study do not entirely cover the varying differences in intersection types formed by different road functional classes. Results may not be extractable to intersections with high traffic volumes or number of crossing lanes.

## 6.2 Future Research

The future research identified from the above analysis include but not limited to.

- It is imperative to determine the sole effectiveness of cross-bike marking without the effects of other treatments at the intersection. To achieve this, traffic simulation approach should be adopted to model different intersection types and run the simulation in a virtual environment to collect data that can accurately show the effectiveness of the facility.

- The selected intersections were unsignalized and had low volume of motor traffic. A study should be staged to expand the scope to identify the performance of the facility under different conditions.

- Incorporate intercept surveys in data collection methodology to seek user comprehension of the treatment in terms of their perception of safety.

- More detail exploration of near-misses and conflicts before and after cross-bike installation at crossings.

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