IMPACTS OF INTERSECTION TREATMENTS AND TRAFFIC CHARACTERISTICS ON BICYCLIST SAFETY

Final Report

SPR 833

RESEARCH

Oregon Department of Transportation

IMPACTS OF INTERSECTION TREATMENTS AND TRAFFIC CHARACTERISTICS ON BICYCLIST SAFETY

Final Report

SPR 833

by

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16. Abstract: This study assessed the safety impact and performance of three different bicycle-specific intersection treatments (bike boxes, mixing zones, and bicycle signals) using surrogate safety measures (i.e., bicycle-vehicle conflicts and other non-crash measures). To date, limited research had been conducted to analyze how these treatments along with traffic characteristics (e.g., bicycle, pedestrian, and vehicle volumes) impact the frequency and severity bicycle-vehicle conflicts, and research was needed to provide practitioners guidance on when and where to install these treatments. To develop this guidance, this project analyzed data collected from three sources: data reduced from videos at 12 field study sites, microsimulation modeling, and a bicycling simulator experiment. Through estimation of Poisson regression models and other statistical analyses of these data, guidance was developed which provides practitioners information on when and where to consider installation of these treatments based on bicycle, vehicle, and pedestrian volumes, road user speeds, and other bicyclist behavioral characteristics.

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yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
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*SI is the symbol for the International System of Measurement									

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DISCLAIMER

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1.0 INTRODUCTION AND MOTIVATION

Transportation modes converge at intersections resulting in conflicts between bicyclists and motor vehicles. While various geometric and signal control treatments have been used in attempts to mitigate bicycle-vehicle crashes and conflicts, agencies often face questions about optimal treatments and when to use these treatments at intersections. To date, limited research has been conducted to analyze how certain treatments (bike boxes, mixing zones, and bicycle signals) along with traffic characteristics (e.g. bicycle, pedestrian, and vehicle volumes) impact the frequency of bicycle-vehicle conflicts, as well as the severity of such conflicts (i.e. how 'close' a conflict is to resulting in an actual crash). It should also be noted that there are currently no existing crash modification factors (CMFs) for the above mentioned treatments on the Federal Highway Administration (FHWA) CMF Clearinghouse (FHWA, 2020a), reinforcing the need to assess the safety impacts of these treatments using methods other than crash data analysis. Research is needed to ascertain the safety impacts of these different treatments, and to provide practitioners guidance on when and where to install them.

This project aims to help fill the knowledge gap with respect to treatment performance and provide guidance to practitioners using data from three different sources: observations from field-collected video, conflicts collected through microsimulation modeling, and a bicycling simulator experiment. The primary objectives of this project include:

- Determine which factors affect the frequency and/or severity of bicycle vehicle-conflicts at intersection approaches with different bicycle-related treatments: bike boxes, mixing zones, and bicycle signals.

- Provide data-driven guidance as to the efficacy of certain intersection treatments in mitigating vehicle-bicycle conflicts (thereby improving bicyclist safety by this surrogate measure), including consideration of how traffic and site characteristics impact these conflicts.

- Develop guidance to practitioners to assist in countermeasure selection which describes the performance of bicycle-specific intersection treatments (bike boxes, mixing zones, and bicycle signals) under different conditions. This includes providing advantages and disadvantages of different treatments, and descriptions of conditions under which each treatment might be considered, as well as relative time frames and cost for implementation for each treatment.

The remainder of this report is organized in the following way:

- Chapter 2 provides a literature review of relevant publications focused on the treatments considered in this study, as well as use of surrogate safety measures and bicycling simulator experiments to assess bicyclist safety.

- Chapter 3 provides an analysis of both conflict and volume data reduced from field-collected video at 12 study sites in Oregon. Factors associated with field-observed bicycle-vehicle conflict frequency and severity are analyzed.

- Chapter 4 provides information related to the analysis of conflict data generated through development of microsimulation models based on the 12 field study sites including sensitivity analyses to assess the changes in conflict frequency across different traffic volumes.

- Chapter 5 describes the completion of a bicycling simulator experiment conducted with 40 participants. Several different measures are assessed to investigate potential safety impacts of the three study treatments.

- Chapter 6 provides a summary of the study findings, guidance for practitioners related to countermeasure selection based on the study results, and limitations and directions for future research.

2.0 LITERATURE REVIEW

This chapter documents previous research related to the topic of this project: bicyclist safety at signalized intersections. A review of relevant journal articles, reports, and other public- and private-sector publications and guidance documents was conducted. The review is focused on previous research analyzing specific bicycle-oriented intersection treatments, as well as methods for analyzing bicyclist safety at these locations including the use of surrogate measures of safety (e.g. conflicts), microsimulation (incorporating the Surrogate Safety Assessment Model), and bicycling simulators.

2.1 BICYCLE-FOCUSED INTERSECTION TREATMENTS

This section of the literature review focuses on research related to the efficacy of several intersection treatments in improving bicyclist safety as well as their effects on road user behavior. The treatments contained in this section do not represent a comprehensive list of every possible intersection treatment, but rather those discussed the SPR 833 scope of work, which could benefit from data driven guidance as to conditions when they should be considered/applied, and that are either existing in Oregon or might be considered for use by ODOT or other agencies in Oregon. The treatments discussed in this section include bike lanes, bike boxes, mixing zones, and bicycle signals. It's important to note that bicycle-specific treatments at intersections may have impacts on delay for different road users at these intersections, and relative construction and maintenance costs would be considerations for agencies applying these types of treatments; however, this literature review is focused specifically on the potential safety impacts.

2.1.1 Bike Lanes

Bike lanes are a portion of the roadway designated by pavement markings and signs for the preferential or exclusive use of bicyclists (NACTO, 2014; Schultheiss et al., 2019). According to Oregon law (Oregon Revised Statutes 801.155), bike lanes are legally defined in the following way: a bicycle lane "means that part of the highway, adjacent to the roadway, designated by official signs or markings for use by persons riding bicycles except as otherwise specifically provided by law." A bicycle lane exists in an intersection if the bicycle lane is marked on opposite sides of the intersection in the same direction of travel. Bike lanes may allow bicyclists to ride at their preferred speed without interference from motor vehicle traffic and facilitate more predictable behavior and interactions between bicyclists and motor vehicles (NACTO, 2014). Bike lanes may be one of several types including (MassDOT, 2015; NACTO, 2014)

- Conventional bike lanes (located adjacent to motor vehicle traffic)
- Buffered bike lanes (conventional bike lanes paired with a designated buffer space separating the bike lane from adjacent motor vehicle traffic and/or parking lanes)

- Separated/protected bike lane (a bike lane along or within a roadway that is physically separated from motor vehicles by vertical and horizontal elements)

Examples and descriptions of different types of bike lanes can be found in (MassDOT, 2015; NACTO, 2014; Schultheiss et al., 2019).

While bike lanes themselves are not a primary intersection treatment, the presence and type of bike lanes at intersections (particularly striping through the intersection) may have an impact on safety and operations, as well as the choice of bicycle-specific intersection treatment(s). Research has generally shown bike lanes to improve safety by reducing conflicts, reducing crashes, and/or positioning bikes away from parked vehicles (DiGioia et al., 2017; Rothenberg et al., 2016; Schultheiss et al., 2019), though these effects may vary by bike lane type. It should be noted that there are several existing crash modification factors (CMFs) for installation of different types of bike lanes in different scenarios existing on the Federal Highway Administration CMF Clearinghouse (FHWA, 2020a). However the CMFs provided show mixed results (i.e. some indicate increases in crashes while some indicate decreases in crashes after bike lane installation), and there are very few CMFs with a high star rating (FHWA, 2020a). Past research has also shown installation of bike lanes (specifically separated bike lanes) to increase bicycle volumes, encourage a mode shift to bicycling, and motivate people to bicycle more in general (Monsere et al., 2014). While the installation of bike lanes provided generally positive effects, the choice of intersection treatment(s) on roadways with bike lanes has important safety implications, and potential intersection treatments are discussed in subsequent sections 2.1.2-2.1.4.

2.1.2 Bike Boxes

Bike boxes are designated areas at the head of a traffic lane intended to provide bicyclists with a safe and visible way to get in front of queued motor vehicle traffic during red traffic signal phases (NACTO, 2014). Bike boxes may provide several benefits including (NACTO, 2014):

- Increased visibility of the potential presence of bicyclists. This may be due presence of a bicycle stencil ahead of the stop bar, colored pavement markings, and/or position of the bicyclist ahead of the stop line.
- Mitigation of right hook conflicts at the start of green signal indication due to the position of bicyclists ahead of motor vehicles.
- Grouping of bicyclists together to clear an intersection quicker when there is a high volume of bikes for long signal cycles.
- Benefits to pedestrians by preventing motor vehicle encroachment into crosswalks.

Typical applications of bike boxes include locations with high bicycle and/or vehicle volumes (especially at locations with high volumes of left-turning bicycles and/or motor vehicle right-turns), locations where there is a desire to better accommodate left-turning bicycles, or locations where a bicyclist left-turn is required to follow a designated bike route, among others (NACTO, 2014). Note there are other treatments that can accommodate left turning bicycles such as a two-stage turn queue box, though this treatment is not assessed as part of SPR 833. Bike boxes are also a relatively cheap alternative; a previous study found the average cost to be $5,000 per bike box (Weigand et al., 2013). An example of a hypothetical bike box with green paint application is shown in Figure 2.1.

There are some previous studies found in the literature regarding the safety, behavior impacts, and perceptions of bike boxes. Johnson et al. examined versions of bike boxes wherein the storage box was installed either in front of a left turn lane or in front of a center through lane using video data recorded in Melbourne, Australia (Johnson et al., 2010). Driver and bicyclist compliance were examined at each site, with driver compliance defined as stopping before the edge of the bike box, and bicyclist compliance defined as the entering the bike storage box with at least one wheel in the box. The results showed that 64.9% of bicyclists and 49.8% of vehicles were compliant at left turn lane bike boxes, while 53% of bicyclists and 49.6% of vehicles were compliant at center though lane bike boxes (Johnson et al., 2010). It’s noteworthy that over half of motor vehicle drivers were non-compliant at either bike box location.

Figure 2.1: Example of a hypothetical bike box application with green paint (NACTO, 2014)

Dill et al. conducted a before-after study of encroachments and conflicts at 10 locations where bike boxes were installed (7 with green painted bike boxes and 3 with uncolored bike boxes), and also conducted a survey of bicyclists to assess perception of bike boxes (Dill et al., 2012). Overall, it was observed that most road users understood how to use bike boxes properly, and that conflicts between bicycles and motor vehicles decreased after bike box installation, even with a marked increase in bicycle volume. Encroachments into the crosswalk were significantly reduced after bike box installation, however there were mixed results with respect to encroachments of motor vehicles into the bike lane. It should be noted that findings with respect to the colored vs. uncolored bike boxes were not conclusive. Finally, the results of the survey indicated 77% of bicyclists thought the bike boxes made intersections safer while only 2% thought they made intersections more dangerous (Dill et al., 2012). Loskorn et al. analyzed behavior at 2 bike boxes in Austin, TX (both with 'no right turn on red' signs posted) in three stages: before installation, after application of uncolored bike boxes, and after green color was added to the bike boxes (Loskorn et al., 2013). The results showed that only 9%-25% of bicyclists stopped in the box portion in front of the lanes, but 92% did stop in front of motorists in the colored area. Additionally, results were mixed with respect to vehicle encroachments into the bike lane, with no change observed at one site, and decreases and increases observed at the other site depending on the stage (decreased at uncolored bike box but increased marginally at green colored bike box) (Loskorn et al., 2013).

Lahrmann et al. used video data from seven locations in Denmark to examine conflicts before and after bike box installation using the Swedish Conflict Technique. The results were mixed with conflict rates between through bicycles and right turning vehicles increasing after bike box installation at 3 locations and decreasing at 4 locations, and the authors stated that no conclusive safety effect could be identified (Lahrmann et al., 2018). It should be noted that according to the Swedish Conflict Technique, a collision course is a necessary condition for a conflict and the severity of a conflict is based on two indicators: time-to-accident and conflicting speed (Laureshyn & Várhelyi, 2018).

Another study of two bike boxes at one intersection in Charlottesville, VA examined bicycle-related conflicts and bicyclist proper/improper use before and after bike box installation (Ohlms & Kweon, 2019). The results indicated that the two bike boxes were used properly/improperly by 46%/40% and 24%/10% of approaching bicyclists at the two respective locations (the authors note these percentages to not add to 100 at each site due to discrepancies in automated counting of total bicyclists). Results were also mixed with respect to traffic violations and conflicts; some types of violations increased while some decreased, and conflicts per potential conflicting road users increased at one bike box location but decreased at another (Ohlms & Kweon, 2019).

Casello et al. used video to analyze bicyclist left turn behavior at signalized intersections in Toronto, Canada with different treatments, including two locations with bike boxes (Casello et al., 2017). The results indicated that compliance rates for bicyclists turning left were relatively high at the bike box locations, with the highest compliance rate (ranging from 58% with low traffic volume to 70% with high traffic volume) at a location with a bike box and an advanced green left turn signal (Casello et al., 2017).

In another study, Abdul Rahimi et al. conducted an experimental study wherein human subjects (both motorists and bicyclists) traveled through specific locations (including a bike box location) and both video observations and surveys were used to assess treatment performance (Abdul Rahimi et al., 2013). Results from the bike box location showed a relatively small proportion of near conflicts compared with other treatments, however the surveys indicated some bicyclists felt unsafe in bike boxes at the onset of the green traffic signal due the difficulty of bicyclists to see the motor vehicles that were positioned behind them (Abdul Rahimi et al., 2013).

Christopha et al. used a driving simulator and participant questionnaires to assess motor vehicle driver behavior at intersections with bicycle-focused treatments to determine whether patterns or causalities exist between driver behavior and infrastructure treatments (Christopha et al., 2017). The analysis of bike box treatments showed promising results with 73.6% of participants yielding properly behind the stop bar, however this means that the remaining 26.4% did not yield correctly. The questionnaire results indicated that participants who responded that they were unfamiliar with bike boxes were least likely to yield correctly; this effect can be seen in Figure 2.2, which shows drivers stopping position with respect to the stop bar by their familiarity with bike boxes.

Overall, previous research has shown promising results with respect to bike box applications, though some research did show mixed results.

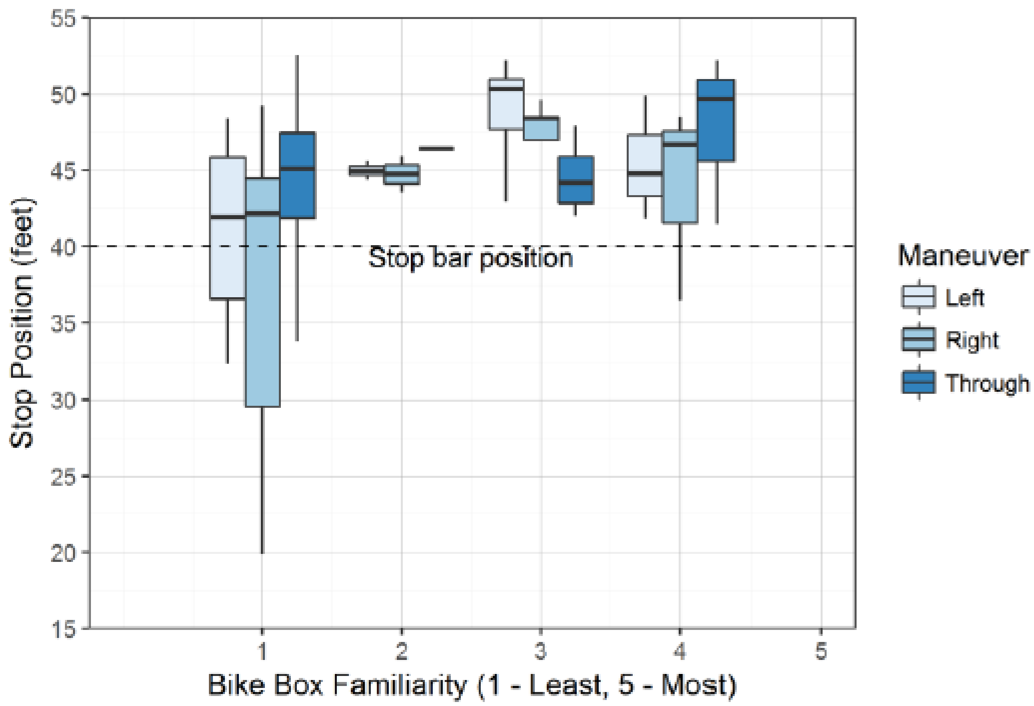


Figure 2.2: Driver stopping position at bike boxes by familiarity (Christopha et al., 2017)

2.1.3 Mixing Zones

Mixing zones are treatments applied in the presence of a combined one-way bike lane and vehicle turn lane, and are intended to minimize bicyclist conflicts with turning vehicles, which in turn may reduce the risk of a right hook crash (NACTO, 2014). At mixing zone locations, vehicles are expected to yield and cross paths with a bicyclist in advance of the intersection, and they should also be designed to reduce motor vehicle speeds and minimize the area of exposure for bicyclists (MassDOT, 2015). The Massachusetts Department of Transportation recommends placing the merge point where the speed of motor vehicles will be 20 miles per hour (mph) or less and as close as practical to the intersection, and also recommends that the length of the merge area should be between 50 and 100 feet (MassDOT, 2015). Additionally, NACTO recommends that the combined lane should be between 9 to 13 feet wide (NACTO, 2014) Agencies may choose to apply mixing zones as a treatment to minimize impacts to traffic operations and site geometry while providing a potential safety benefit, and typically may be 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/left-turn lane is present with a bike lane but there is risk of conflicts between turning vehicles and bicyclists. Figure 2.3 shows an example of a hypothetical mixing treatment.

Figure 2.3: Example of a hypothetical mixing zone application (NACTO, 2014)

There has been quite limited research with respect to the safety performance of existing mixing zones. In a 2015 study, Monsere et al. used both survey and video data to assess the perception and performance of three mixing zones (one in Portland, OR and two in San Francisco, CA) (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 positioned themselves within the mixing zone. Additionally, their findings also revealed that 1%-18% of vehicles at mixing zones also turned from the wrong lane. With respect to bicyclist perception, it was found that roughly 88% of bicyclists surveyed felt that they either somewhat or strongly agreed that they generally felt safe when bicycling through mixing zones, and that the perception of safety for cyclists appeared to be more heavily influenced by the volume of turning motor vehicle traffic than the correct turning movements of motorists (Monsere et al., 2015).

In another study, Kothuri et al. analyzed the performance of two mixing zones (one in Portland, OR and one in New York NY) using conflicts (measured with post-encroachment time (PET)) obtained from video (Kothuri et al., 2018). It should be noted that PET defined as “the time between the moment when the first road user leaves the path of the second and the moment when the second reaches the path of the first” (Johnsson et al., 2018), and further details are provided in Section 2.2.2. The analyses indicated that 22% of observed bicyclists were involved in an incident (defined as a conflict with PET of 5 seconds (sec) or less) at the Portland, OR mixing zone, while 18% were involved in an incident at the New York, NY mixing zone. Of the incidents observed at each site, 28.9% and 37.5% were classified as 'very dangerous interactions' (PET ≤ 1.5 sec) at the Portland, OR and New York, NY sites, respectively. The study also found that significant confusion was exhibited by both cyclists and drivers, with respect to the correct action to be taken at mixing zones, and that a significant percentage of the vehicles merged into the mixing zone at the very last second, thus adding to the confusion (Kothuri et al., 2018).

Another study building off the work of (Kothuri et al., 2018) analyzed factors associated with the frequency and severity of conflicts at three mixing zones (one in Portland, OR and two in New York, NY) (Russo, Kothuri, et al., 2020). A negative binomial model was estimated to assess conflict frequency, and it was found (as expected) that the volume of through bicycles and turning vehicles were statistically significantly associated with conflict frequency (defined as an incident where PET ≤ 5 sec). It was also found that as compared to sites with bicycle signals (operating with a leading bicycle interval) the sites with mixing zones experienced a lower frequency of conflicts, all else being equal (Russo, Kothuri, et al., 2020). Conflict severity was also examined through development of an ordered logit model, and it was found that conflicts were generally less severe at mixing zone sites (compared to sites with leading bicycle signal intervals) and were more severe during the PM peak hour (3-6pm) (Russo, Kothuri, et al., 2020).

A few studies have also investigated the safety performance of mixing zones using crash data, though sample sizes are generally quite limited so it's difficult to make strong conclusions. Bryant et al. found that the number of bicyclist injuries per million bike miles was 42% higher at a site with a cycle track mixing zone in New York, NY compared to a similar site without a mixing zone (but with a bicycle signal), however this finding is only based on one site and the authors note that further analysis would be needed for a complete picture (Bryant et al., 2016). Rothenberg et al. investigated several intersection treatments at sites with separated bike lanes including three sites with mixing zones. The before/after crash analysis found a 100% bicycle crash reduction, however this finding is again based on a very small sample with the mixing zones sites averaging only 2.1 bicycle crashes per year before mixing zone installation, and changes in bicycle volumes were not accounted for (Rothenberg et al., 2016). Perhaps the most comprehensive analysis of crashes at mixing zones was conducted by Sundstrom et al. and included analysis of 126 mixing zones sites (including older generation mixing zones with longer lengths and newer generation mixing zones with shorter lengths) with protected bike lanes (Sundstrom et al., 2019). The analyses indicated that the bicycle crash rate decreased by 21% and 27% after protected bike lanes with older generation mixing zones and newer generation mixing zones were installed, respectively. The authors noted that mixing zones are a reasonable treatment, especially at higher turn volume locations (Sundstrom et al., 2019). Overall, previous research with respect to mixing zones has generally indicated improvements in safety, though there have been some mixed results and further research is warranted.

2.1.4 Bicycle Signals

Bicycle signals are " electrically powered traffic control devices that should only be used in combination with existing conventional traffic signals…" (NACTO, 2014). Bicycle signals provide bicyclists with their own traffic signal head, often with a bicyclist symbol in each signal face as shown in Figure 2.4. Bicycle signals are typically used to improve identified safety or operational problems involving bicycle facilities, and typical applications include locations where a predominant bicycle movement conflicts with a main motor vehicle movement, locations where a bicycle facility transitions from a cycle track to a bicycle lane, or locations where it's desired to give bicyclists an advanced green indication, among others (NACTO, 2014). Bicycle signals may provide potential safety benefits including providing priority to bicycle movements, separating bicycle movements from conflicting motor vehicle traffic, and generally reducing conflicts between all modes, (NACTO, 2014), as well as providing more appropriate information to bicyclists as compared with pedestrian signals. A 'Bicycle Signal' plaque is required at bicycle signals, and optional features such as passive actuation (e.g., bicyclist do not need to press a button to be recognized) of the bicycle signals (recommended), installation of near-sided bicycle signals, visual differentiation of the bicycle signal housing from vehicle signal housings, and application of a leading bike interval to give bicyclists a head start in front of turning vehicles, and others may also be available (NACTO, 2014). It should also be noted that the average cost of a complete bicycle signal retrofit has been found to cost approximately $52,000 (Weigand et al., 2013).

Figure 2.4: Example of a bicycle signal with bicycle symbol in signal face (NACTO, 2014)

The Federal Highway Administration provided interim approval for the use of bicycle signal faces in 2013 (FHWA, 2013) and then provided clarification that bicycle signals with bicycle symbols in their signal faces are limited to use when the bicycle movement is protected from any simultaneous motor vehicle movement (FHWA, 2014). Since then, the use of bicycle signals in the United States has increased significantly. A recent report documented an inventory of existing bicycle signals (with the bicycle symbol in the face) in the United States and found over 511 intersections with this application, including 33 in Oregon (Monsere et al., 2019). The locations of those bicycle signals can be found in an interactive online map located here: http://web.cecs.pdx.edu/~monserec/bicycle_signals.htm. This report also provided the number of bicycle signal installations per year (for those locations where installation date was known), and a significant increase in installations was found in recent years as shown in Figure 2.5 (Monsere et al., 2019). In addition, this report identified gaps in the research literature with respect to bicycle signals including optimal methods to communicate allowable, protected, or permissive movements to bicyclists, and the effects of bicycle signal size, placement, and orientation on road user comprehension and compliance, among others (Monsere et al., 2019).

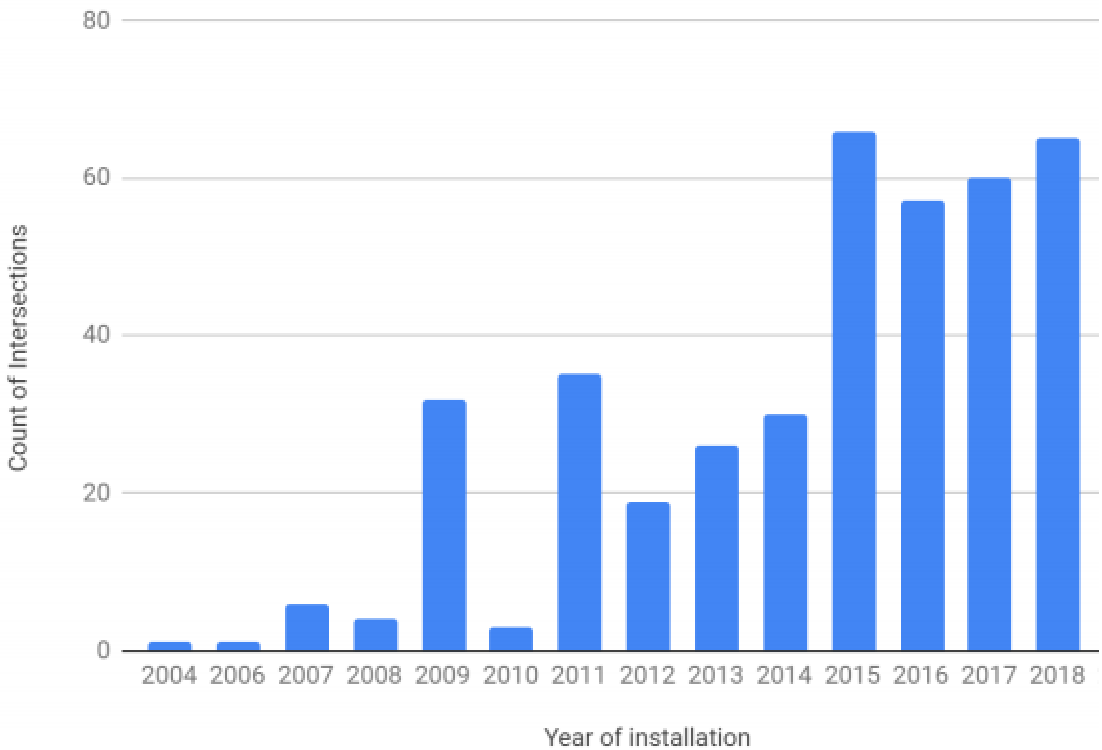


Figure 2.5: Bicycle signal installation by year in the US (Monsere et al., 2019)

There are several options in terms of bicycle signal operations, including several different phasing strategies, such as (MassDOT, 2015; NACTO, 2014):

- Concurrent bike phase which essentially operates concurrently with motor vehicle signals and allows motor vehicles to make turns permissively.
- Leading bike interval (LBI) which gives bicyclists a 'head start' (3 to 7 seconds) in front of turning vehicles, similar in concept to the leading pedestrian interval.
- Split LBI wherein through moving vehicles are allowed start at the same time as parallel bike lanes while turning motor vehicles receive a flashing yellow arrow turn phase after the lead interval.

- Protected bicycle signal which provides a green bike phase during a motor vehicle red turn arrow, followed by a motor vehicle turn phase with an accompanied red bicycle signal. This option is most applicable when motor vehicle turn volumes exceed 150 per hour (NACTO, 2014), though it is not clear exactly how this guidance was derived.

- Bike scramble which gives a green indication to all bicycle movements at once.

Guidance with respect to the choice of phasing schemes is primarily general in nature and includes an engineering judgement component. However, the Massachusetts Department of Transportation does provide specific guidance on when to consider providing time-separated bicycle movements at bicycle signals as shown in Figure 2.6 (MassDOT, 2015), however it was determined that these values are primarily based on engineering judgement and not entirely on data driven research. The British Columbia Ministry of Transportation and Infrastructure (MOTI, 2019) also provides similar guidance on when to provide time separation. This guidance recommends time separation between bicyclists and right-turning vehicles on two-way streets with a uni-directional bike lane when turning vehicle volumes exceed 100 vph on high speed streets (>50 km/hr) and 250 vph on low speed streets (50 km/hr and below), though it's not clear from this guidance exactly how these thresholds were derived (MOTI, 2019).

Separated Bike Lane Operation	Motor Vehicles per Hour Turning across Separated Bike Lane			
	Two-way Street			One-way Street
	Right Turn	Left Turn across One Lane	Left Turn across Two Lanes	Right or Left Turn
One-way	150	100	50	150
Two-way	100	50	0	100

Figure 2.6: Considerations for time-separated bicycle movements at bicycle signals (MassDOT, 2015)

Existing research literature with respect to the safety impacts of bicycle signal installation in general is quite sparse. An experimental study where participants traveled through study locations was conducted in Japan that included an approach with a bicycle signal, and the results indicated lower conflicts per green time as compared with other treatments (including bike boxes and advanced stop lines) (Abdul Rahimi et al., 2013). The results from a survey of participants in this study indicated that they generally felt comfortable at bicycle signal locations, although some participants indicated confusion by not looking at the correct signal (Abdul Rahimi et al., 2013). Rothenberg et al. investigated several intersection treatments at sites with separated bike lanes including 9 sites with bicycle signals (combined with other treatments). The before/after crash analysis found an 30.8% increase in bicycle crashes (8.61/yr before and 11.27/yr after), however changes in bicycle volumes were not accounted for (Rothenberg et al., 2016).

Kothuri et al. analyzed performance in terms of conflicts at a bicycle signal in New York, NY with traditional concurrent timing (although there was a leading pedestrian interval present) and found that 22.2% of observed bicyclists were involved in an incident (i.e. a conflict with PET ≤ 5 sec), and of these incidents, 32.1% were categorized as 'very dangerous interactions' (i.e., a conflict with PET ≤ 1.5 sec) (Kothuri et al., 2018). Additionally, it was found that several observed bicyclists used the lead interval provided by pedestrians even though there was no leading bike interval present (Kothuri et al., 2018).

In terms of bicyclist compliance at bicycle signals in general, there is limited existing research. Monsere et al. noted that compliance of cyclists at bike-specific signals is likely related to overall cyclist compliance with all traffic indications, especially signalization at intersections (Monsere et al., 2013). The authors discussed previous studies of bicyclist compliance with signals at intersections (Johnson et al., 2011; C. Wu et al., 2012) and found non-compliance rates for bicyclists ranging from 7%-50%, and that most non-compliant bicyclists violated either during the very beginning or very end of the red phase. Monsere et al. also collected data (2,617 bicyclist observations) to compare compliance at regular vs. bicycle specific signals and found that compliance was marginally (but statistically significantly) higher at locations with a bicycle signal vs no bicycle signal (89.8% compliant and 88.9% compliant, respectively) (Monsere et al., 2013). Monsere et al. also noted that there are major gaps in the research literature with respect to safety and compliance at bicycle signals with very few documented studies (Monsere et al., 2013), and this is generally still the case.

2.2 SURROGATE MEASURES OF BICYCLIST SAFETY

Traditionally, traffic safety analyses have relied primarily on historical police-reported crash data to assess safety performance and evaluate the effectiveness of safety countermeasures. These crash data, while a critical tool in traffic safety analyses, may suffer from several shortcomings such as poor data quality and availability, differences in crash reporting thresholds between jurisdictions, or differences in data collection methods between jurisdictions (AASHTO, 2010). Furthermore, crash data are often not immediately available and need to be aggregated over several years to obtain practical results when conducting safety analyses. Additionally, many minor or non-injury crashes may not be reported though these low severity events may contain important information for safety analyses (AASHTO, 2010). Furthermore, it is practically not possible to use crash data to analyze the safety performance of new or alternative treatments that do not yet exist in the field, or only exist in a very limited number of locations.

To overcome these crash data limitations, surrogate measures of safety (also known as indirect safety measures) which are non-crash measures of safety that may be used to assess the safety performance of design features, have become popular in recent years. Potential surrogate measures of safety include but are not limited to (AASHTO, 2010):

- Encroachment time (ET) – Time duration during which a turning vehicle infringes upon the right of way of a through vehicle.
- Deceleration rate (DR) – Rate at which a vehicle needs to decelerate to avoid a crash.

- Proportion of stopping sight distance (PSD) – Ratio of distance available to maneuver to the distance remaining to the projected location of a crash.

- Post-encroachment time (PET) – Time lapse between end of encroachment of a vehicle and time that the conflicting vehicle actually arrives at the potential point of crash (e.g., conflict point).

- Time to collision (TTC) – Expected time for two vehicles to collide if they remain at their present and on the same path.

These surrogate measures are most commonly collected through the manual transcription of high-resolution video data captured in the field. Of these surrogate measures of safety, PET and TTC seem to be the most commonly used, likely because they are relatively easier to calculate, and provide a quantitative, objective method to assess both the frequency and severity of conflicts between road users. Further details regarding PET and TTC are provided in subsequent sections.

The basic concept of surrogate safety measures assumes that “all traffic events involving nearness of some kind between two or more road users are related to safety, and that these events differ in their degree of severity” (Johnsson et al., 2018). The degree of severity of interaction between road users may vary from very minor conflicts (less severe events) where there is very minimal chance of a crash, to severe conflicts (severe events) where a crash is close to occurring (e.g., near-miss), all the way up through property damage only, injury, or fatal crashes, as shown in Figure 2.7. If a roadway treatment helps to mitigate severe conflicts (e.g., severe events) between road users at a certain location, it stands to reason that the probability of crashes occurring would be reduced. Although an exact quantitative relationship between conflicts and crashes has not been established, several previous studies have validated a relationship between conflicts and crashes, including at least 5 studies using TTC and at least 8 using PET, and some of these studies are documented and summarized by (Johnsson et al., 2018) and (Tarko, 2020c).

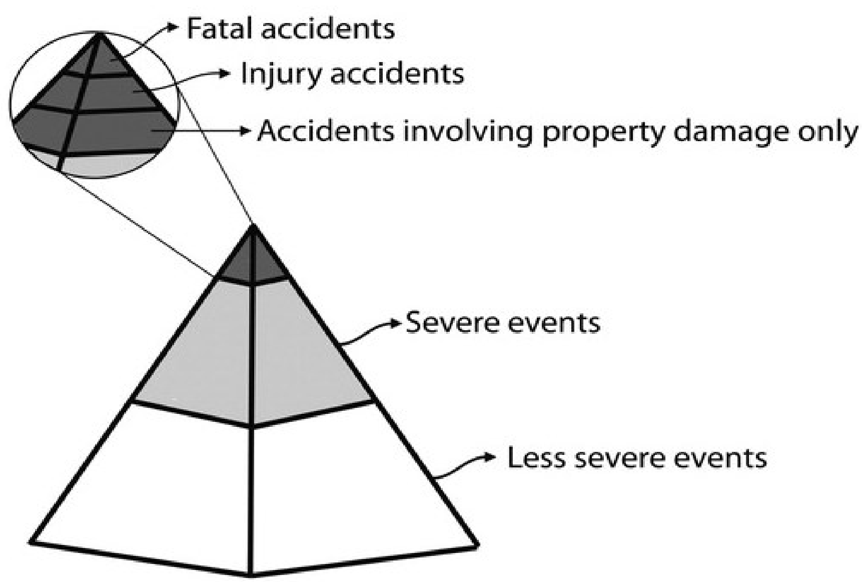


Figure 2.7: Severity levels of traffic events (Johnsson et al., 2018)

Surrogate safety measures may be especially useful to assess safety for bicyclists given the lack of crash data as compared with motor-vehicle crashes, and it should be noted that none of the treatments discussed in Sections 2.1.2-2.1.4 have associated crash modification factors listed on the Federal Highway Administration Crash Modification Factors (CMF) Clearinghouse (FHWA, 2020a). Numerous previous studies have successfully used surrogate safety measures (TTC and/or PET) to assess bicyclist safety in some context (though not necessarily with respect to the specific treatments discussed previously in this literature review), and the threshold to define a 'conflict' for these measures (TTC or PET) is generally 2 to 5 sec, with a conflict closer to zero seconds considered more severe (Fleskes & Hurwitz, 2019; Hurwitz et al., 2015; Johnsson et al., 2018; Kassim et al., 2014; Kothuri et al., 2018; Lahrmann et al., 2018; Ledezma-Navarro et al., 2018; Madsen & Lahrmann, 2017; Russo, Kothuri, et al., 2020; Zangenehpour et al., 2016). For example, Russo et al. developed a negative binomial bike-vehicle conflict prediction model (with a conflict definition of $PET \leq 5$ sec) using field observed conflicts and volumes from sites with mixing zones and split LBIs (Russo, Kothuri, et al., 2020). These models were then used to predict conflict frequency across a range of different vehicle and bicycle volumes.

2.2.1 Time to Collision (TTC)

Time to collision is a surrogate safety measure "that calculates the time remaining before the collision if the involved road users continue with their respective speeds and trajectories." (Johnsson et al., 2018). In other words, TTC represents the time remaining before a collision would occur if no evasive maneuver is taken, and the closer to TTC=0 sec, the closer those road users were to colliding (i.e., more 'severe' conflict), with TTC=0 sec indicating a collision. Figure 2.8 shows an example of the concept of TTC. Although TTC has been a widely used surrogate safety measure since its introduction by (Hayward, 1971), there are a few potential drawbacks: 1) it can only be measured when two road users are on a collision course (otherwise it's undefined), and 2) it may be difficult to calculate manually using field-collected videos because road user trajectories and speeds are required. That being said, there are more advanced automated methods to calculate TTC using field observed video (Tarko, 2020b), and it can also be obtained using microsimulation models (Gettman et al., 2008), as discussed in subsequent Section 2.3.

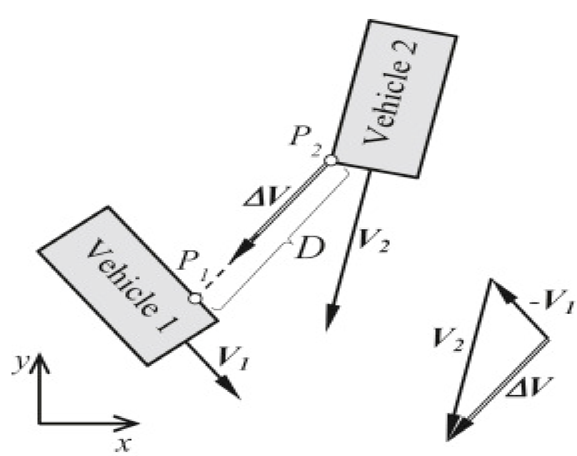


Figure 2.8: Example showing the concept of TTC ($TTC = D/||\Delta V||$, and P_1 and P_2 represent potential collision points for each vehicle) (Hayward, 1971; Tarko, 2020c)

2.2.2 Post Encroachment Time (PET)

Post encroachment time was originally introduced by Allen et al. (Allen et al., 1978), and is defined as "the time between the moment when the first road user leaves the path of the second and the moment when the second reaches the path of the first (i.e. the PET indicates the extent to which they miss each other)" (Johnsson et al., 2018). Essentially, PET is a measure of how close two road users are to occupying the same space at the same time, and closer a conflict is to PET=0 sec, the closer those road users were to colliding (i.e. more 'severe' conflict), with PET=0 sec indicating a collision. Figure 2.9 shows an example of the concept of PET. Use of PET as a surrogate safety measure offers two potential advantages compared to TTC: 1) the road users do not necessarily need to be on a collision course to calculate PET, and 2) it is relatively easy to measure manually using field-collected videos by defining the conflict point and simply recording time stamps for different road users to calculate PET. Similar to TTC, PET may also be calculated using more advanced automated techniques and/or microsimulation (Gettman et al., 2008; Tarko, 2020b)

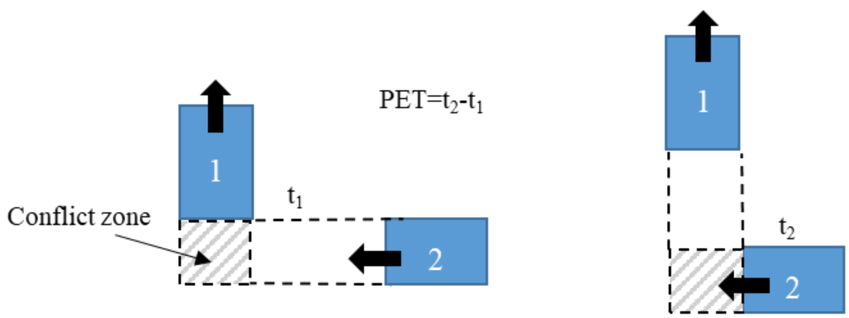


Figure 2.9: Example showing concept of PET (Russo, Lemcke, et al., 2020)

2.3 USE OF MICROSIMULATION AND SURROGATE SAFETY ASSESSMENT MODEL TO ASSESS BICYCLIST SAFETY

The use of traffic microsimulation software has been an invaluable tool for analysis of operational performance at signalized intersections (as well as roadway segments and interchanges) in recent decades. Microsimulation also offers opportunities to examine the safety performance of a roadway or intersection through analysis of surrogate measures of safety such as conflicts identified using PET or TTC. These surrogate safety parameters can be extracted using vehicle, bicycle, and/or pedestrian trajectories obtained from microsimulation software (e.g., VISSIM (PTV Group, 2020) using the Surrogate Safety Assessment Model (SSAM) available from the United States Federal Highway Administration (SSAM, 2020). The primary advantage of the use of microsimulation with surrogate measures of safety is that it offers opportunities to examine the impact of new or rarely used designs, and the ability to more easily examine the impacts of traffic characteristics and road user behavior on safety performance without the need for conventional police-reported crash data or field observations (although field observations are useful to calibrate microsimulation models if possible).

SSAM uses trajectory files (.trj file extensions) obtained from microsimulation outputs to extract conflict information, as shown in Figure 2.10 (Gettman et al., 2008). For each identified conflict, the following information is provided (among other information) (Gettman et al., 2008):

- PET (including minimum PET)
- TTC (including minimum TTC)
- Max S (the maximum speed of either road user during the conflict)
- Delta S (the difference in road user speeds observed at minimum TTC)
- DR (the initial deceleration rate of the second road user)
- MaxD (the maximum deceleration of the second road user)

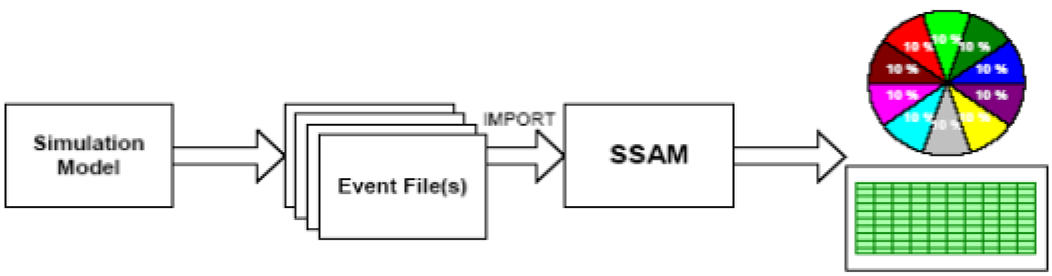


Figure 2.10: Example showing the operational concept SSAM (Gettman et al., 2008)

Several previous studies have utilized microsimulation with SSAM to assess traffic safety. Shahdah et al. used conflicts (TTC) extracted from microsimulation/SSAM at 53 modeled intersections in Toronto and found a strong correlation between crash analyses conducted at these intersections and conflicts (Shahdah et al., 2015). Several other previous works have assessed safety through use of conflicts between vehicles (Gettman & Head, 2003; Huang et al., 2013; Vasconcelos et al., 2014; Wang & Stamatiadis, 2014) and conflicts between vehicles and pedestrians (Muley et al., 2018; J. Wu et al., 2017) using microsimulation/SSAM.

Several previous studies have used microsimulation of bicycle-focused treatments to assess operations at intersections (e.g., delay) (Jayankura, 2015; Kothuri et al., 2018; Stanek & Alexander, 2016), and some have also used microsimulation with SSAM to assess bicyclist safety. In one bicycle-focused study, an intersection in Charlotte, NC was used to develop a microsimulation model for both existing conditions and a proposed protected design, and the safety impacts were assessed using conflicts obtained from SSAM (Preston, 2019). As mentioned in a previous section, Ledezman-Navarro et al. assessed the safety impacts of three different bicycle signal treatments: a leading phase, a partially protected design, and a partially protected with protected turn phase. These treatments were compared to a base case (standard concurrent signal phasing) using conflicts obtained from microsimulation/SSAM, and relative safety impacts of each treatment were discussed in terms of conflicts (PET) (Ledezma-Navarro et al., 2018).

It should be noted that when using microsimulation to assess operations or safety, it's important to calibrate the models to obtain accurate and practical results. Previous studies have examined the importance of calibration of microsimulation models and have assessed the relative importance of different model parameters (Habtemichael & Picado-Santos, 2013; Maheshwary et al., 2020), and Huang et al. proposed a two-stage calibration procedure for VISSIM/SSAM which improved the goodness of fit between simulated and real-world observed conflicts (Huang et al., 2013). With respect to microsimulation of bicyclists specifically, Russo et al. performed a parameter sensitivity analysis to assess the impacts of different microsimulation parameters on bicycle-vehicle conflicts using VISSIM/SSAM (Russo, Lemcke, et al., 2020). The results indicated some parameters had no effect on conflict outputs, while others (such as 'average standstill distance') had a significant impact on conflict (PET) outputs and may be more important in terms of calibration as shown in Figure 2.11 (Russo, Lemcke, et al., 2020).

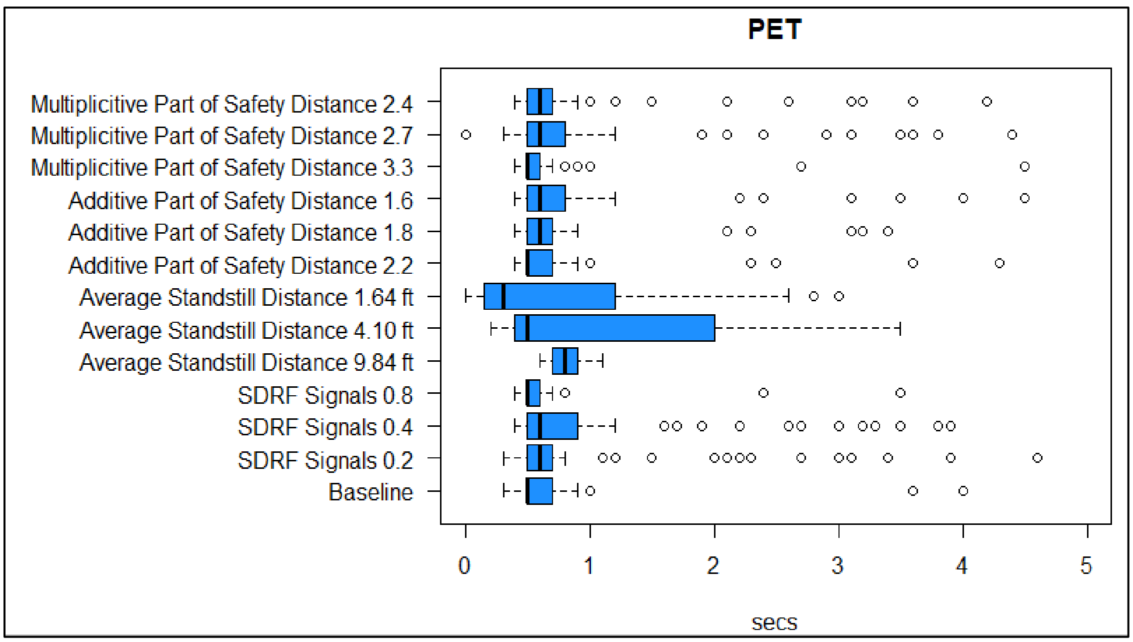


Figure 2.11: Boxplots of average PET for bicycle-vehicle conflicts by parameter tested (Russo, Lemcke, et al., 2020)

2.4 USE OF BICYCLING SIMULATOR TO ASSESS BICYCLIST SAFETY

As previously stated, assessing bicyclist safety impacts of new or innovative treatments, or in situations with a lack of adequate crash data requires the use of surrogate measures of safety. Another method to examine these surrogate measures is through the use of a bicycling simulator. While several studies have examined impacts on bicyclist safety through the use of motor vehicle driving simulators (Christopha et al., 2017; Fleskes & Hurwitz, 2019; Jannat et al., 2018; Jannat et al., 2020), for example), the use of a bicycling simulator presents a unique opportunity to assess safety and behavior from the bicyclists perspective. An example of the components of a bicycling simulator laboratory existing at Oregon State University are shown in Figure 2.12. In addition to traditional surrogate safety metrics, use of bicycling simulators also allows for examination of bicyclist stress and eye glance characteristics as they travel through different simulation environments.

Figure 2.12: Example showing views from (a) Oregon State University bicycling simulator, (b) Operator workstation, and (c) Simulated environment (Ghodrat Abadi et al., 2019)

There are several examples of the use of bicycling simulators to assess safety, behavior, skill, or preference of bicyclists in the research literature:

- Ghodrat Adabi and Hurwitz used a bicycling simulator to assess the operational impacts (and impacts on conflicts) of protected-permitted right-turn signal indications with different pavement marking treatments. The authors concluded signal indications and pavement markings did have a significant effect on bicyclist velocity and lateral position using the bicycling simulator (Ghodrat Abadi & Hurwitz, 2019).

- Ghodrat Abadi et al. used a bicycling simulator to analyze bicyclist behavior near commercial vehicle loading zones with different combinations of pavement markings, signage, and truck maneuvers. The results indicated that truck presence had an effect on bicyclist behavior and that effect varied among the different truck maneuvers and different pavement marking and signage designs (Ghodrat Abadi et al., 2019).

- Grechkin et al. used a bicycling simulator to assess bicyclist behavior and preferences when crossing intersections with continuous cross traffic from opposing directions (Grechkin et al., 2013).

- Sun and Qing discussed the development of a bicycling simulator (including tradeoffs between design decisions) and presented results of a sample application analyzing the impacts of different wayfinding markings/signage in environments with shared lanes, bike lanes, shared paths, and bike routes (Sun & Qing, 2018).

Overall, past research indicates bicycling simulators are a viable option to assess bicyclist safety and other performance measures for some applications.

2.5 LITERATURE REVIEW SUMMARY

This literature review presented an examination of relevant journal articles, reports, and other public- and private-sector publications and guidance documents focused on previous research analyzing specific bicycle-oriented intersection treatments, as well as methods for analyzing bicyclist safety at these locations including the use of surrogate measures of safety, microsimulation (incorporating the Surrogate Safety Assessment Model), and bicycling simulators. The primary findings and conclusions of the literature review include:

- With respect to the safety impacts specifically of bike boxes, mixing zones, and bicycle signals, there is a relatively sparse number of publications found in the research literature.
    - Based on the existing studies, most treatments have shown generally positive safety impacts, though there have been some mixed results.
- Almost all previous studies utilized violations/encroachments and/or conflicts to assess treatment performance.
- There is a lack of data driven guidance as to the efficacy of these treatments in terms of how they perform under different traffic conditions (considering vehicle, pedestrian, and bicyclist volumes) and geometric conditions.
- Surrogate measures of safety (specifically PET and TTC) are commonly used to assess traffic safety in the absence of adequate crash data.
- Surrogate measures that have been used to assess traffic safety (including bicyclist safety) have been obtained from three different sources in previous work:
    - Field-observed conflicts (usually collected by video). Field observations can also be used to analyze violations/encroachments.
    - Conflicts obtained from microsimulation models with SSAM. Microsimulation/SSAM may be particularly useful to assess treatments that don’t yet exist in the field and/or to observe the impacts of different traffic and/or geometric characteristics that are not easily observable in the field.
    - Measures obtained using bicycling simulators. Bicycling simulators can also be used to analyze violations/encroachments and may also be used to assess treatments that do not yet exist in the field.

3.0 FIELD DATA COLLECTION AND ANALYSIS

This Chapter provides information related to the collection and analysis of data extracted from field-collected videos at 12 study sites in Oregon. The primary goal of the field data analysis was to examine factors associated with the frequency or severity of bicycle-vehicle conflicts (measured using PET), including how these conflicts vary with vehicle volumes, bike volumes, and other characteristics, as well as between the different study treatments.

3.1 VIDEO DATA COLLECTION

For this project, 12 study intersections were identified for data collection 3 with bike boxes, 3 with mixing zones, 3 with bicycle signals, and 3 control sites with no specific bicycle treatment aside from bike lanes) in consultation with the SPR833 TAC. It should be noted that control sites were chosen among approaches with a bike lane located to the right of the furthest right travel lane and that were expected have a reasonable bicycle volume for analysis. At each of the 12 intersections, one study approach with the treatment of interest was identified for data collection. Quality Counts LLC (QC) collected 12 hours of video (7am-7pm) at each of the 12 study sites. As described in Amendment 1 to SPR833, Street Simplified (SS) was contracted by ODOT to conduct a separate analysis at the study intersections, and as such, SS cameras were used at all 12 sites (along with QC cameras at select sites where additional angles were requested by the SPR833 research team). SS required 4 camera angles at each site, while the research team requested up to 2 additional QC cameras at select sites as needed. There is no practical difference between the two video types in terms of their use for SPR833; the QC videos were provided as one 12-hour MP4 file, while the SS videos were provided in ~17-minute MP4 files (the separate SS video files that represent 7am-7pm were identified for use in SPR833).

Videos were collected between August 6, 2020, and September 1, 2020, and video files from QC were provided directly to the research team and uploaded to a password protected project folder on Box.com, while SS videos were provided via a Google drive link, and then downloaded for use by the research team. Table 3.1 provides a summary of the video data collection including the site ID, treatment, intersection crossroads (with the study approach direction indicated in the Road 1 column), date of video collection, and whether SS and QC or just SS video were collected.

Table 3.1: Summary of Video Data Collection

Site ID	Treatment	Road 1	Road 2	Data Collection Date (7am-7pm)	Cameras
1	Bike Box	NW Broadway (SB)	NW Hoyt	8/27/2020	SS+QC
2	Bike Box	SE 7th Ave (SB)	SE Madison St.	9/1/2020	SS+QC
3	Bike Box	SE Gladstone (WB)	SE Cesar E. Chavez	8/11/2020	SS
4	Mixing Zone	NE Multnomah (EB)	NE 9th Ave	8/6/2020	SS
5	Mixing Zone	NE Multnomah (EB)	NE 16th Ave	8/11/2020	SS
6	Mixing Zone	NE Multnomah (WB)	NE Grand Ave	8/18/20	SS
7	Bicycle Signal	N Broadway (WB)	N Williams	8/13/2020	SS+QC
8	Bicycle Signal	N Rosa Parks (EB)	N Greeley Ave	8/27/2020	SS+QC
9	Bicycle Signal	NE Halsey (EB)	NE 102nd Ave	8/6/2020	SS
10	Control	SE 7th Ave (NB)	SE Clay Ave	9/1/2020	SS+QC
11	Control	NE Weidler (EB)	NE 9th Ave	8/13/2020	SS
12	Control	E Burnside (EB)	E 8th Ave	8/18/2020	SS+QC

Note: SS = Streets Simplified camera, QC = Quality Counts LLC camera

3.1.1 Road User Volume Data Reduction

After videos were collected at each of the study sites, road user volumes were extracted for the study approach at each intersection. These volumes were used both to explore correlations with conflict frequency and for development of microsimulation models presented in Chapter 4.0. Road user volumes were extracted manually from the videos in an office setting and the following information was recorded in 15-minute bins over the full 12-hour period (7am-7pm) at each study approach:

- Bicycles: all bicyclists in the bicycle lane or on the roadway were counted by their turning movement (i.e., left, thru, or right) at the study approach.
- Passenger Vehicles: cars, pickup trucks, vans, and SUVs, etc. were counted by lane and turning movement at the study approach.
- Heavy Vehicles: buses, semi-trucks, package trucks, firetrucks, and RVs were counted by lane and turning movement at the study approach.
- Pedestrians: pedestrians walking through or near crosswalks, including skateboarders, non-powered scooters, and skaters were counted for both the crosswalk perpendicular to the study approach and parallel (to the right side) of the study approach.
- Pedestrians Using Mobility Devices: pedestrians in a wheelchair using another visible mobility device were counted for both the crosswalk perpendicular to the study approach and parallel (to the right side) of the study approach.
- Scooters: powered scooters either in the street or on the sidewalk were counted on the study approach.

Additionally, bike queues were collected at the start of each cycle at the bike box locations. Finally, research team members also provided notes for any atypical behavior observed during data collection. Appendix A shows the instructions for road user volume data reduction used by the research team, and Appendix B shows a sample road user volume data reduction spreadsheet. To ensure consistency, before official volume data reduction began, the three research team members involved in this task counted volumes for two test videos, and volume counts were very consistent (within +/- ~0.5-1.9% of each other). Table 3.2 provides a high-level summary of average hourly bicycle and vehicle volumes by turning movement at each study approach, along with average hourly pedestrian volumes crossing the right-side parallel crosswalk. Note that the values in Table 3.2 represent averages across all 12 hours (7am-7pm) at each site and detailed disaggregate (15-minute bin) volume counts for all road user/vehicle types at each site were provided separately to the SPR833 Research Coordinator.

Table 3.2: Summary of Average Hourly Volumes at Study Approaches

Site ID	Treatment	Avg. Hourly Bike Volumes				Avg. Hourly Vehicle Volumes				Avg. Hourly Parallel Pedestrian Volumes
		Left	Thru	Right	Total	Left	Thru	Right	Total	
1	Bike Box	0.1	21.5	4.5	26.1	5.2	374.0	53.5	432.7	24.7
2	Bike Box	0.0	9.0	10.0	19.0	0.0	248.3	37.9	286.2	4.2
3	Bike Box	0.0	9.2	0.0	9.2	5.1	24.8	8.3	38.2	15.0
4	Mixing Zone	0.4	7.3	0.4	8.1	12.4	50.6	32.1	95.1	25.1
5	Mixing Zone	2.3	12.0	0.0	14.3	74.0	92.8	3.4	170.2	9.9
6	Mixing Zone	0.2	11.5	0.3	12.0	0.0	64.8	58.7	123.5	11.9
7	Bicycle Signal	0.0	16.6	3.7	20.3	0.0	684.3	786.3	1470.6	4.8
8	Bicycle Signal	0.2	13.5	1.2	14.9	9.2	157.3	271.8	438.3	7.0
9	Bicycle Signal	0.1	1.2	0.1	1.4	129.3	564.3	135.5	829.1	15.2
10	Control	0.2	5.0	0.3	5.5	17.6	119.8	2.6	140.0	5.5
11	Control	0.3	12.1	0.8	13.2	37.3	838.2	57.6	933.1	17.6
12	Control	0.1	6.4	0.8	7.3	15.8	544.3	24.2	584.3	31.6

3.1.2 Bicycle-Vehicle Conflict Data Reduction

After volume data reduction, bicycle-vehicle conflicts on the study approach for each site were manually reduced from the field-collected videos. The conflicts were measured using post-encroachment time (PET), and only conflicts with a PET of 5 sec or less were included in this study based on previous research in this area (Russo, Kothuri, et al., 2020; Zangenehpour et al., 2016). It should be noted that details regarding the use of PET to assess conflicts was provided previously in Section 2.2.2 of this report. In addition to PET, the speed of conflict-involved units was measured near the conflict area using measured distances between landmarks and time differences, and the unit which occupied the conflict area first (e.g., bike or vehicle) was noted. To assist research team members in reducing conflict data uniformly, a set of instructions was created along with a conflict data collection template spreadsheet.

Before conflict and speed data were reduced at each site, an annotated figure showing the conflict area (determined after assessing where the paths of turning vehicles and bicyclists generally intersect) and landmarks used to measure speed was created. An example of an annotated figure for conflict data collection at Burnside and 8th (control site) is presented in Figure 3.1. The distance between landmarks used to determine speed were then measured using Google earth before speed and conflict data were reduced. Essentially, this data reduction effort entailed transcribing a series of time stamps when interactions involving bicycles and vehicles are observed, and these time stamps are then used to calculate conflict PET and speed at specified locations. It should be noted that research team members could advance (or reverse) the video frame by frame, and time stamps are recorded to hundredths of a second precision. Similar to the road user volume data reduction, before official data reduction began, research team members first reduced data from a test video and results were compared to ensure consistency. The results of test video data reduction were consistent after some clarifications/iterations to the method were made. Appendix C shows the instructions for speed and conflict data reduction, while Appendix D shows an example template spreadsheet for this data reduction.

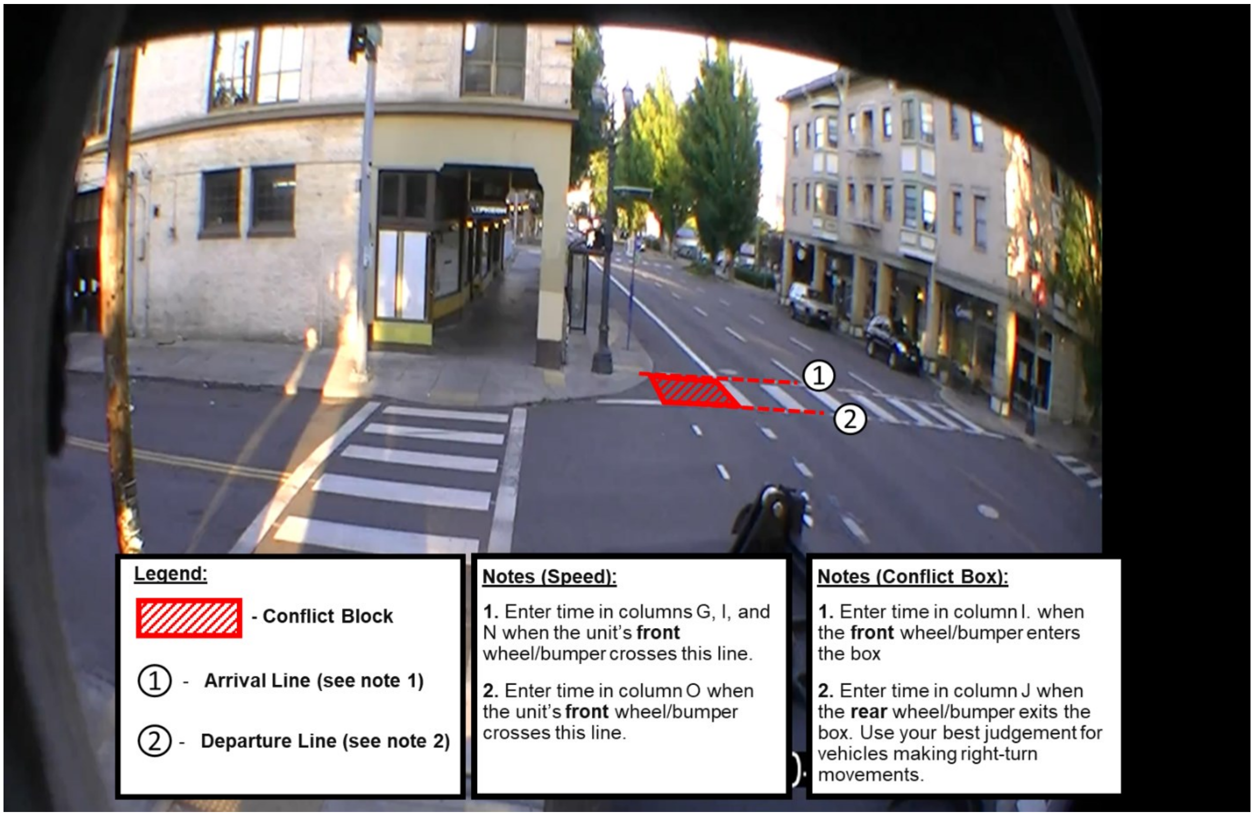


Figure 3.1: Example annotated figure for speed and conflict data reduction

Figure 3.2 shows an example of two screenshots constituting an observed vehicle conflict at Burnside and 8th (control site). In the top image, a pickup truck is leaving the conflict area as it turns right with the bicyclist approaching in the background, and in the bottom image, the bicyclist arrives to the conflict area. The difference in time stamps between these two images constitutes the PET value of the conflict which in this example, was 1.52 sec. Additionally, the example shown in Figure 3.2 is an example of a conflict where the vehicle arrived at the conflict area first (as opposed to the bicycle arriving first).

Figure 3.2: Example of observed bicycle-vehicle conflict

Table 3.3 provides a summary of the observed bicycle-vehicle conflicts over the full 12 hours of video at each study approach including total conflicts and conflicts summarized by different PET severity ranges (lower PET indicates more severe conflict severity). Additionally, since these conflicts involve through bicyclists and right turning vehicles, the average hourly volume of through bicyclists and right turning vehicles is also provided in Table 3.3 for reference. As noted in Table 3.3, there were zero conflicts observed between bicyclists and vehicles who properly used bicycle signals at these study approaches (sites 7-9); an expected result as bicycle and vehicle movements are time-separated at these locations. Although rare instances of vehicles or bicyclists violating signals were observed, conflicts resulting from these observations are not included as those observations do not represent typical operating conditions and are generally a result of a road user's conscious decision to violate the signal. Additionally, no conflicts were observed at site 10 (control site) likely due to very low volumes of both bikes and right-turning vehicles at this study approach.

It should be noted that the PET thresholds defining high/medium/low severity conflicts are based on existing published research examining bicycle-vehicle conflicts (Russo, Kothuri, et al., 2020; Zangenehpour et al., 2016), and PET values ≤ 1.5 sec are generally considered potentially dangerous interactions. While it is recognized the PET threshold which causes discomfort to a bicyclist may vary between different areas or bicyclist types, the use of PET provides a quantitative measure to assess how close the paths of bicyclists and vehicles intersect in space and time and lower PET conflicts are clearly more critical interactions.

Table 3.3: Summary of Observed Bicycle-Vehicle Conflicts

Site ID	Treatment	Avg. Hourly Right Turn Veh Volume	Avg. Hourly Through Bike Volume	No. of High Severity Conflicts (PET ≤ 1.5 sec)	No. of Medium Severity Conflicts (PET >1.5-3.5 sec)	No. of Low Severity Conflicts (PET >3.5-5 sec)	Total No. of Conflicts (PET ≤ 5 sec)
1	Bike Box	53.5	21.5	24	30	8	62
2	Bike Box	37.9	9.0	8	2	0	10
3	Bike Box	8.3	9.2	8	4	1	13
4	Mixing Zone	32.1	7.3	5	2	1	8
5	Mixing Zone	3.4	12	0	1	1	2
6	Mixing Zone	58.7	11.5	10	7	3	20
7*	Bicycle Signal	786.3	16.6	0	0	0	0
8*	Bicycle Signal	271.8	13.5	0	0	0	0
9*	Bicycle Signal	135.5	1.2	0	0	0	0
10	Control	2.6	5.0	0	0	0	0
11	Control	57.6	12.1	8	15	4	27
12	Control	24.2	6.4	8	4	1	13

*These bicycle signal locations were expected to have very few if any conflicts since vehicle and bike movements are time-separated. These numbers do not include conflicts in which road users (vehicles or bikes) violated a signal.

3.2 ANALYSIS OF FIELD-OBSERVED CONFLICT DATA

This section provides an analysis of factors related to the frequency and severity of bicycle-vehicle conflicts reduced from the field-collected videos. The analyses presented in this section focuses primarily on locations with bike boxes and mixing zones (as well as control sites) as relevant conflicts were not observed at locations with bicycle signals due their time-separated movements.

3.2.1 Analysis of Bicycle-Vehicle Conflict Frequencies

As shown in Table 3.3, site 1 (bike box site) had the highest frequency of observed conflicts, however this site also had the highest average hourly volume of through bicyclists and a relatively high volume of right-turning vehicles. It's important to consider these 'exposure' measures (i.e., through bike and turning vehicle volumes) when assessing whether a particular treatment itself might be associated with an increase or reduction in conflict frequency. To this end, a series of regression models were developed to quantitatively explore the impact of through bike and turning vehicle volumes on the frequency of bicycle-vehicle conflicts, and separate models were developed using data from sites with bike boxes, mixing zones, and no treatment (i.e. control sites) to explore differences between site types.

Given the discrete, non-negative nature of the conflict frequency data (i.e., count data), both Poisson and Negative Binomial (NB) regression were considered for this analysis. This modeling framework is appropriate for this type of data (Washington et al., 2010) and has been employed in previous studies analyzing conflict frequency (Russo, Kothuri, et al., 2020; Sacchi & Sayed, 2015). To prepare the data for this analysis, conflict frequency, turning vehicle volumes, and through bicycle volumes were summarized by hour for each site (note that sites with bicycle signals are excluded from this analysis). Hourly conflict frequency is then modeled as a function of hourly turning vehicle and hourly though bicycle volumes. In Poisson regression and in the context of this analysis, the probability of site i experiencing y_i conflicts during one hour is given by (Washington et al., 2010):

$$\boldsymbol{P(y_i) = \frac{EXP(-\lambda_i)\lambda_i^{y_i}}{y_i!}}$$

(3-1)

where:

> $P(y_i)$ is probability of site i experiencing y_i conflicts during a one-hour period, and
>
> λ_i is the Poisson parameter which is equal to the site's expected number of conflicts per hour, $E[y_i]$.

Poisson Regression models are estimated by specifying λ_i (the expected number of conflicts per hour) as a function of explanatory variables taking the form $\lambda_i = EXP(\beta X_i)$, where X_i is a vector of explanatory variables (e.g. through bike and turning vehicle volumes) and β is a vector of estimable parameters (Washington et al., 2010). The NB model is a generalized form of the

Poisson model which allows the mean and variance to differ, and is specified by modifying λ_i such that $\lambda_i = EXP(\beta X_i + \varepsilon_i)$, where $EXP(\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α (also known as the overdispersion parameter). NB regression modeling is more appropriate for distributions with significant overdispersion (i.e. the variance is greater than the mean), and is very common in modeling crash frequencies (Mannering & Bhat, 2014). Ultimately, both types of models are considered in this study.

3.2.1.1 Analysis of Bicycle-Vehicle Conflict Frequencies Across All Sites

In this subsection, hourly conflict frequency (across all sites combined but excluding bicycle signal sites) is modeled as a function of hourly through bike and turning vehicle volumes. Given that conflicts with PET values ≤ 1.5 sec are considered the most critical interactions, the analysis is focused on the frequency of high severity (i.e. PET ≤ 1.5 sec) conflicts. While this analysis does not assess differences between treatment types, it does provide a general comparison to existing research and guidance with respect to the impact of volumes on conflict frequency. Both Poisson and NB models were developed, and while the model results were almost identical, the Poisson model provided a marginally better model fit based on Akaike's Information Criterion (AIC) so it was selected as the model of choice. The results of the Poisson model analyzing high severity conflict frequencies across all sites is shown in Table 3.4.

Table 3.4: Results of Poisson Model for Conflict Frequency Across All Sites

Parameter	Estimate (β)	Std. Error	P-Value
Intercept	-1.919	0.311	<0.001
Through Bike Volume	0.055	0.014	<0.001
Turning Veh Volume	0.021	0.005	<0.001

Based on the results presented in Table 3.4, both hourly bike through volume and turning vehicle volume are significantly associated with hourly conflict frequency at greater than a 99.9% confidence level (p-values < 0.001). Note that for all statistical models in this report, a p-value of 0.10 or less indicates statistical significance at the 90% confidence level, while a p-value of 0.05 or less indicates statistical significance at the 95% confidence level. The model results can be used to predict hourly conflict frequency across hypothetical ranges of through bike and turning vehicle volumes using the following formula based on the Poisson model results:

$$\textbf{Npredicted\_conflicts} = \exp[-1.919 + (0.055 * \text{ThroughBikeVolume}) + (0.021 * \text{TurningVehVolume})] \quad \textbf{(3-2)}$$

This equation was used to plot predicted hourly conflict frequencies across ranges of 10-50 through bikes per hour and 25-150 turning vehicles per hour (vph), and the results are shown in Figure 3.3. From this figure, it is evident that predicted conflicts increase markedly when hourly turning vehicles exceed 100 vph (and particularly 150 vph). This result is consistent with past research (Russo, Kothuri, et al., 2020), and is in line with guidance from the Massachusetts DOT on when to provide time separation between bicyclists and turning vehicles (MassDOT, 2015).

While these results do not provide information regarding differences between treatment types, they do reinforce findings in previous research and information in existing guidance documents.

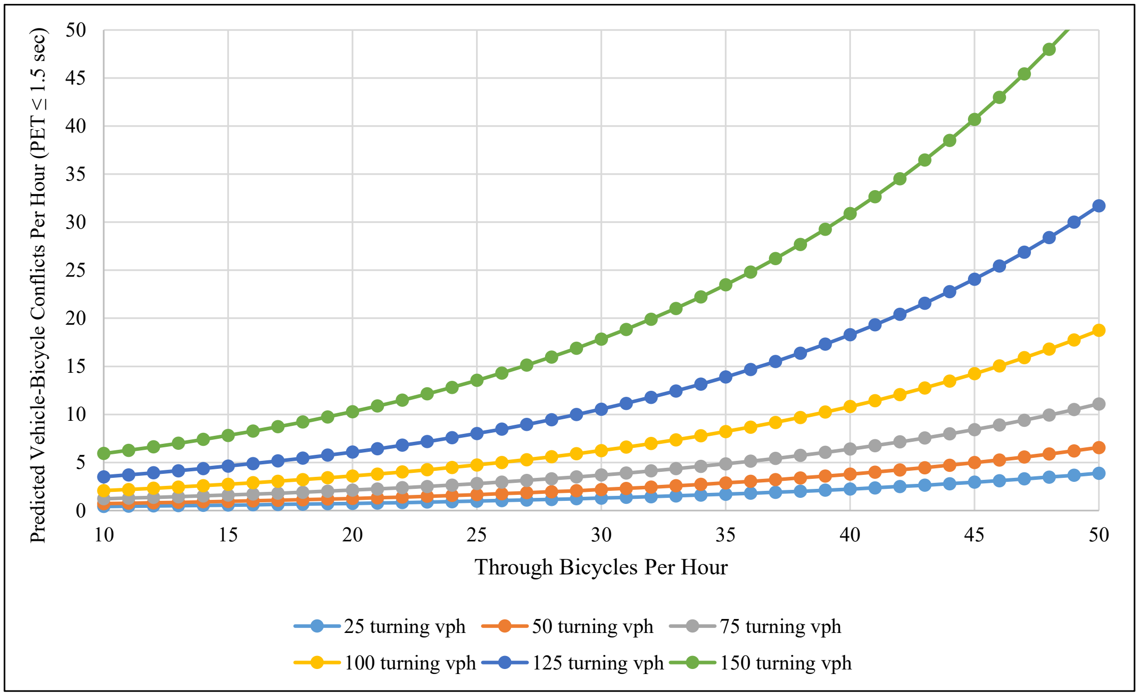


Figure 3.3: Predicted hourly conflict frequency across all sites

3.2.1.2 Analysis of Bicycle-Vehicle Conflict Frequencies by Treatment Type

To assess potential differences in the effects of volumes on conflict frequency across different treatment types, a series of regression models were estimated separately for each treatment in this analysis: Bike box sites, mixing zone sites, and control sites. The modeling framework and process is the same as previously described in section 3.2.1.1, the only difference being separate models are developed for each treatment type. The results of these models are presented in Table 3.5. It should be noted that both Poisson and NB regression models were developed for each site type with the results being nearly identical, however the Poisson model for each site type exhibited a slightly better model fit based on AIC and therefore are retained as the models of choice presented in Table 3.5. Additionally, the predicted percent increase in conflict frequency per unit increase in through bike or turning vehicle volume can be calculated based on parameter estimates by taking [*(e^(β))-1*] and these values are also presented in Table 3.5. It should be noted that two of the variables in Table 3.5 have p-values greater than 0.10, and thus are technically not statistically significant. However, both bike through volume and turning vehicle volume are critical 'exposure' variables to assess conflict frequency and should be included in each model regardless. For example, if bike through volume was excluded as a predictor in the mixing zone model, the results could yield predicted conflicts at a site even with zero bike volume.

Table 3.5: Results of Poisson Models for Conflict Frequency by Site Type

Parameter	Estimate (β)	95% Conf. Lower Limit	95% Conf. Upper Limit	Std. Error	P-Value	Predicted Percent Increase in Conflicts per Unit Increase
Control Site Model						
Intercept	-2.247	-3.462	-1.067	0.602	<0.001	N/A
Bike Through Volume	0.079	-0.009	0.167	0.045	0.078	8.2%
Turning Veh Volume	0.017	-0.006	0.040	0.012	0.138	1.7%
Bike Box Model						
Intercept	-1.092	-1.918	-0.267	0.421	0.010	N/A
Bike Through Volume	0.038	0.004	0.072	0.018	0.030	3.9%
Turning Veh Volume	0.016	-0.001	0.033	0.009	0.062	1.6%
Mixing Zone Model						
Intercept	-2.612	-4.330	-0.895	0.8762	0.003	N/A
Bike Through Volume	0.042	-0.051	0.136	0.0478	0.374	4.3%
Turning Veh Volume	0.031	0.011	0.050	0.0100	0.002	3.1%

Similar to the analysis presented in Section 3.2.1.1, these model results can be used to predict hourly conflict frequency across hypothetical ranges of through bike and turning vehicle volumes for each site type, and these prediction for all three site types are shown in Figure 3.4. This same information is presented in Figure 3.5 but summarized by turning vehicle volumes instead of treatment type. From these figures, it can be seen that for scenarios where there are 75 or less turning vph and 25 or less bikes per hour, the predicted frequency of conflicts is quite similar across all three site types. However, some notable differences appear at different ranges of turning vehicle and through bike volumes.

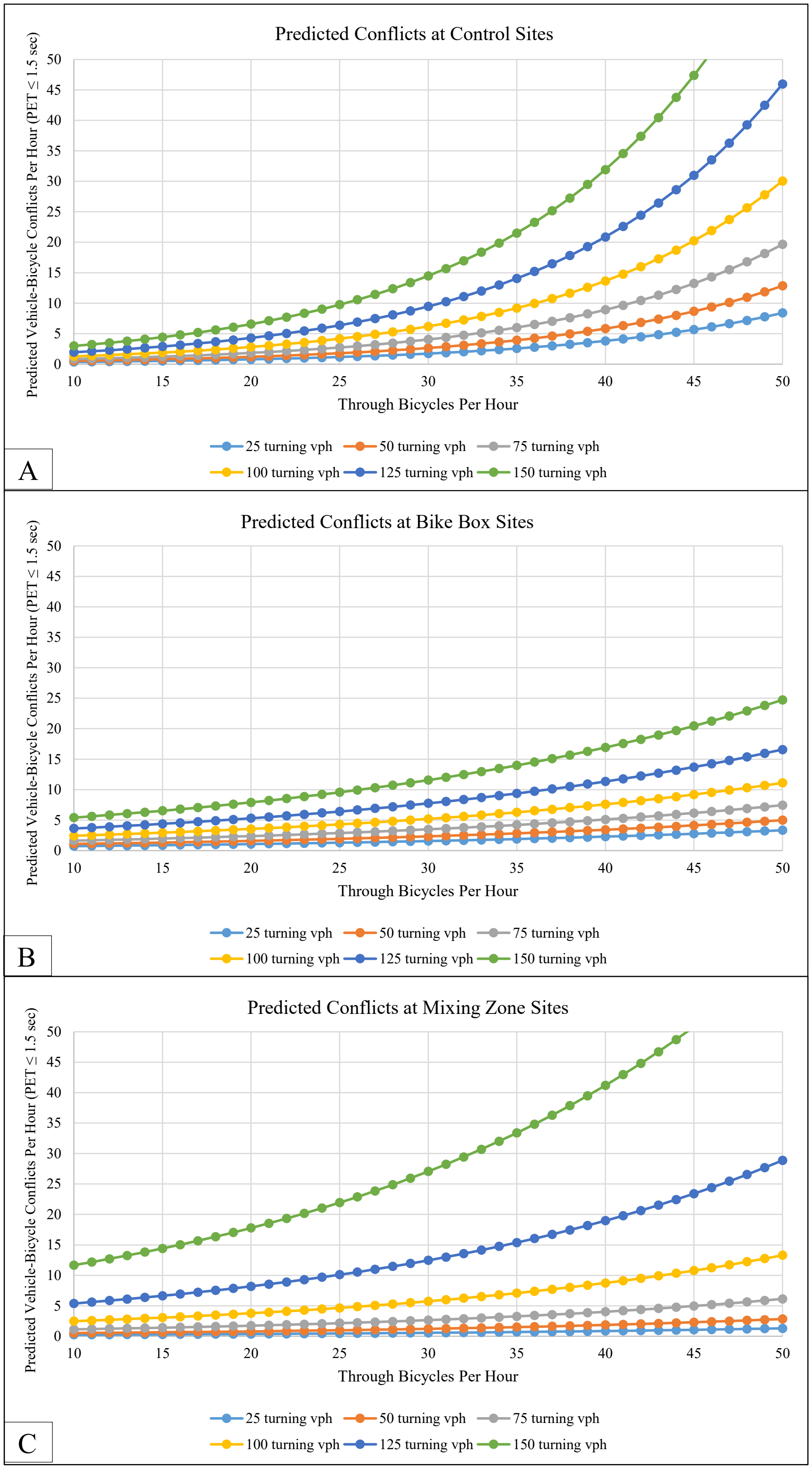


Figure 3.4: Predicted hourly conflict frequency for A) Control sites, B) Bike box sites, and C) Mixing zone sites

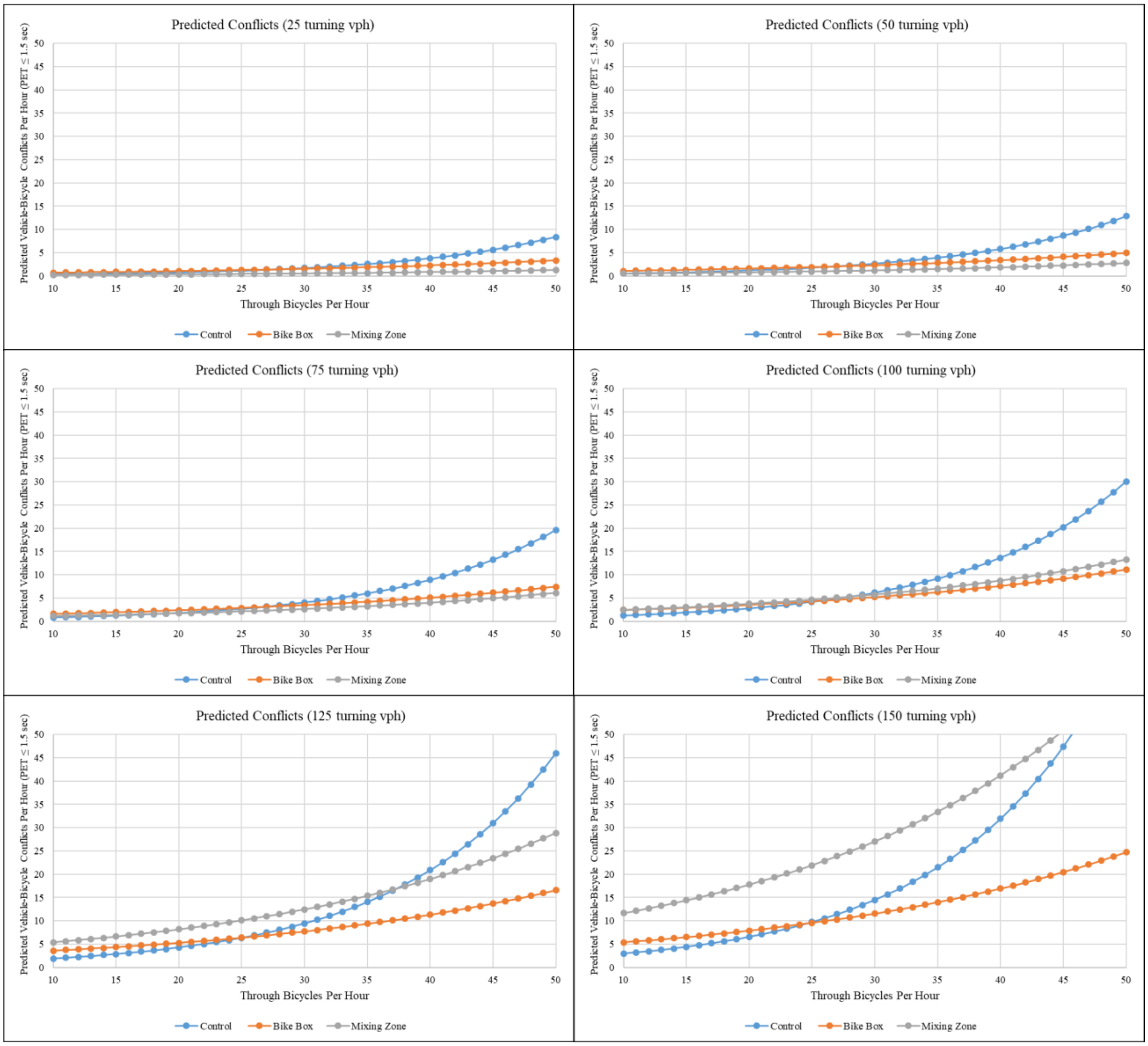


Figure 3.5: Predicted hourly conflict frequency by turning vehicle volume

First, control sites (with no specific bicycle-focused treatment aside from bike lanes) exhibit higher predicted conflict frequencies than bike box or mixing zone locations particularly under conditions with 100 or more turning vph and/or through bike volumes higher than 25 bikes per hour. The one exception to this observation is that for mixing zone sites, when turning vehicle volumes are 125 vph or greater, marked increases (larger than control sites) in predicted conflict frequency are observed. Bike box sites generally exhibit the lowest conflict frequencies across all ranges of turning vehicle and through bike volumes. This is particularly true for the higher ranges of turning vehicle volumes (100 or greater turning vph). These results indicate that for higher ranges of turning vehicle volumes and through bike volumes, both bike boxes and mixing zones seem to provide a benefit (in terms of reduced predicted conflict frequency) compared with control sites, the one exception being that mixing zones do not seem to provide this benefit at higher (>100 vph) turning vehicle volumes.

3.2.1.3 Potential Impacts of Parallel Crossing Pedestrian Volumes

The presence of pedestrians crossing the crosswalk adjacent and parallel to the right-most lane may have an impact on conflict characteristics as right turning vehicles must yield when there is a pedestrian present. This in turn may impact vehicle speeds and slowing/stopping behavior or positioning as they complete the turn. As such, the potential impact of right-side parallel crossing pedestrian volumes on conflict frequencies was investigated by incorporating hourly pedestrian volumes into the Poisson regression models previously presented in Sections 3.2.1.1 and 3.2.1.2. Separate models were estimated for control sites, bike box sites, and mixing zone sites, and the results of these models are presented in Table 3.6.

Table 3.6: Results of Poisson Models for Conflict Frequency by Site Type Considering Pedestrian Volumes

Parameter	Estimate (β)	Std. Error	P-Value
Control Site Model			
Intercept	-3.972	1.159	0.001
Bike Through Volume	0.068	0.043	0.112
Turning Veh Volume	0.021	0.012	0.081
Parallel Pedestrian Volume	0.068	0.027	0.011
Bike Box Model			
Intercept	-1.195	0.437	0.006
Bike Through Volume	0.034	0.018	0.067
Turning Veh Volume	0.013	0.009	0.147
Parallel Pedestrian Volume	0.017	0.019	0.359
Mixing Zone Model			
Intercept	-2.770	1.055	0.009
Bike Through Volume	0.044	0.049	0.361
Turning Veh Volume	0.031	0.010	0.002
Parallel Pedestrian Volume	0.008	0.028	0.776

As shown in Table 3.6, hourly right-side parallel pedestrian volumes are associated with statistically significant increase in predicted conflict frequency at control sites. This is an intuitive finding, since vehicles turning right must yield when right side parallel pedestrians are present, and drivers may slow or stop their vehicle in the path of through bicyclists as they're yielding. However, pedestrian volumes were not significant predictors of conflict frequency at bike box or mixing zone locations. Pedestrian volumes were least associated with conflict frequency at mixing zones; an expected result given the conflict area at approaches with this treatment is upstream of the actual intersection and pedestrian presence would not be expected to significantly impact conflicts. At bike box locations, bicyclists are generally positioned ahead of the motorist (if traffic is stopped), and in these cases, the presence of pedestrians would not be expected to significantly impact conflicts.

3.2.2 Analysis of Bicycle-Vehicle Conflict Severities

While the analyses presented in section 3.2.1 focused on factors affecting conflict frequencies (with a focus on conflicts with PET ≤ 1.5 sec), the section will analyze factors potentially associated with conflict severity including PET values, vehicle speeds, and order of unit arrival at the conflict area (i.e. bike first or vehicle first).

3.2.2.1 Analysis of Conflict Severity based on PET by Site Type

As shown in Table 3.3 and mentioned previously, the severity of each observed conflict (with PET ≤ 5 sec) was categorized into one of three discrete categories:

- High severity conflict: PET ≤ 1.5 sec
- Medium severity conflict: PET > 1.5 to 3.5 sec
- Low severity conflict: PET > 3.5 to 5 sec

As discussed previously, the thresholds for these severity categories are based on previous research (Russo, Kothuri, et al., 2020; Zangenehpour et al., 2016), and high severity conflicts are considered potentially dangerous interactions while low severity conflicts are considered mild interactions. As such, it is important to assess whether certain treatments may be associated with a higher percentage of high severity conflicts. Table 3.7 shows a summary of both mean observed conflict PET and a summary of frequency and percent of different conflict severities by site type.

Table 3.7: Summary of Bicycle-Vehicle Conflicts by Severity and Site Type

Site Type	Mean Conflict PET (s)	High Severity Conflicts (PET ≤ 1.5 sec)		Medium Severity Conflicts (PET >1.5-3.5 sec)		Low Severity Conflicts (PET >3.5-5 sec)		Total Conflicts (PET ≤ 5 sec)	
		Freq.	Percent	Freq.	Percent	Freq.	Percent	Freq.	Percent
Control	1.97	16	40.0%	19	47.5%	5	12.5%	40	100.0%
Bike Box	1.87	40	47.1%	36	42.4%	9	10.6%	85	100.0%
Mixing zone	2.22	15	50.0%	10	33.3%	5	16.7%	30	100.0%
Total Combined	1.96	71	45.8%	65	41.9%	19	12.3%	155	100.0%

As shown in Table 3.7, the mean PET across all three site types varies only by +/- 0.35 sec, which likely does not represent an operationally significant difference given that the mean PET for each site type is more than 0.35 sec above the threshold which defines a high severity conflict. The percentage of high severity conflicts is generally also similar for all three site types (ranging from 40-50%), with mixing zone sites exhibiting the highest percentage of high severity conflicts.

To statistically explore whether treatment type is significantly associated with conflict severity, an ordered logit model was estimated. This modeling framework is appropriate given the discrete ordered nature the conflict severity data (low severity, medium severity, high severity). In estimating an ordered logit model, a latent variable *z* is specified for modeling the ordered ranking of the conflict severity data such that (Washington et al., 2010):

$$\boldsymbol{Z} = \boldsymbol{\beta X} + \boldsymbol{\varepsilon}$$

(3-3)

where:

> *X*: vector of variables determining the discrete ordering for each conflict severity observation
>
> β: vector of estimable parameters (e.g., treatment type)
>
> ε: disturbance term

The observed ordered data, *y*, for each conflict observation is then defined as:

$$y = 1 \text{ (PET > 3.5-5 sec)} \quad \text{if } z \leq \mu_1,$$

(3-4)

$$y = 2 \text{ (PET > 1.5-3.5 sec)} \quad \text{if } \mu_1 < z \leq \mu_2,$$

(3-5)

$$y = 3 \text{ (PET} \leq \text{1.5 sec)} \quad \text{if } z > \mu_2,$$

(3-6)

where:

> μ_i: estimable threshold parameters that define *y*, which corresponds to the ordered conflict severity categories.

The μ thresholds are parameters that are estimated jointly with the model parameters β. Ultimately, of most interest are the signs of the β parameters for each independent variable; a positive β indicates that variable tends to increase the probability of a severe conflict, while the opposite is true for a negative β estimate. Table 3.8 shows the results of the ordered logit model with parameter estimates for both bike box and mixing zone indicator variables (control sites are excluded as the reference category).

Table 3.8: Results of the Ordered Logit Severity Model Considering Site Type

Parameter	Estimate (β)	Std. Error	P-Value
Bike Box Indicator	0.256	0.364	0.481
Mixing Zone Indicator	0.234	0.459	0.611
Threshold 1	-1.788	0.349	<0.001
Threshold 2	0.353	0.305	0.247

Based on the results presented in Table 3.8, bike box and mixing zone indicators are not significantly associated with increased conflict severity based on PET (as compared with control sites) based on the high p-values (0.418 and 0.611, respectively). This is not unexpected given the relative similarity between mean PET values and percent of high severity conflicts across all site types presented in Table 3.7.

While the ordered logit model considers all three conflict severity levels, binary logistic regression modeling can also be considered to assess conflict severity with two severity categories: severe vs. non-severe. In binary logit regression, the probability of a conflict being severe is estimated as (Washington et al., 2010):

$$\boldsymbol{P_i = \frac{EXP[\beta_o + \beta_1 X_{1,i} + \beta_2 X_{2,i} + \cdots + \beta_K X_{K,i}]}{1 + EXP[\beta_o + \beta_1 X_{1,i} + \beta_2 X_{2,i} + \cdots + \beta_K X_{K,i}]}}$$

(3-7)

where:

P_i is the probability of conflict *i* being severe,

β_0 is the model constant, and

$\beta_1, .. \beta_K$ are estimable parameters corresponding with explanatory variables X_K (i.e. site type).

Table 3.9 shows the results of the binary logistic model where a binary indicator for severe conflict is the dependent variable modeled as a function of indicators for bike box and mixing zone site types (with control sites left out as the reference category. As with the previously presented ordered logit model, bike box and mixing zone indicators are not significantly associated with increased probability of a severe conflict based on their large p-values (0.460 and 0.405, respectively).

Table 3.9: Results of the Binary Logit Severity Model Considering Site Type

Parameter	Estimate (β)	Std. Error	P-Value
Constant	-0.405	0.323	0.209
Bike Box Indicator	0.288	0.389	0.460
Mixing Zone Indicator	0.405	0.487	0.405

The results of the ordered and binary logistic models presented in Table 3.8 and Table 3.9 indicate that treatment type (i.e., bike box or mixing zone) are not statistically significantly associated with conflict severity (defined by PET) as compared with control sites, all else being equal for a particular conflict occurrence.

3.2.2.2 Analysis of Conflict Severity Considering Vehicle Speed and Unit Type Arrival

The analyses presented in section 3.2.2.1 assessed conflict severity defined only by PET (i.e. PET ≤ 1.5 sec = severe conflict). However, other factors may contribute to the 'severity' of a conflict if the severity definition considers how severe a crash might be if that conflict were to have resulted in a crash, namely:

- Vehicle speed: The faster a vehicle is traveling during a conflict with a bicycle, the more severe a crash is likely to be (if it were to occur) given the increased impact forces associated with higher speeds.

- Unit type arrival: In each observed bicycle conflict, either the vehicle or the bicycle arrives to the conflict point first. If the bicycle arrives first, it is more likely a vehicle driver has seen the bicyclist and is yielding to them, while when the vehicle arrives first, they likely have turned in front of the bicyclist's path, potentially leading to the bicyclist (who legally has the right of way) striking the vehicle.

Table 3.10 shows a summary of average vehicle speeds during a conflict and the percent of conflicts with either the vehicle or bicycle arriving first to the conflict point. Conflicts occurring at bike boxes exhibited the lowest average vehicle speeds (6.9 mph) followed by conflicts occurring at control sites (8.5 mph). Conflicts occurring at mixing zones exhibited the highest average vehicle speeds (15.1 mph), which is not unexpected since the conflict area at mixing zones is upstream of the intersection and vehicles are traveling with a relatively straighter trajectory at the conflict area while vehicles involved in conflicts at bike box and control sites are generally turning (hence their lower average speeds). Additionally, in conflicts occurring at mixing zones, the bike arrived first 53.3% of the time compared with 72.5% and 77.6% at control sites and bike box sites, respectively.

Table 3.10: Summary of Average Conflict Speed and Unit Arrival by Site Type

Treatment	Average Conflict Vehicle Speed (mph)	Percent of Conflicts with Bike Arriving First	Percent of Conflicts with Vehicle Arriving First
Control	8.5	72.5%	27.5%
Bike Box	6.9	77.6%	22.4%
Mixing zone	15.1	53.3%	46.7%

To investigate whether vehicle speed or unit type arrival are correlated with PET severity, both ordered logistic and binary logistic models (similar to those presented in section 3.2.2.1) with conflict speed and unit type arrival (i.e. indicator for vehicle arriving first) as independent variables. Table 3.11 presents the results of these models, and these results indicate that neither vehicle speed nor vehicle arriving first are significantly associated with PET severity (p-values range from 0.508 to 0.926 for these variables in both models).

Table 3.11: Results of Ordered and Binary Logit Models Assessing Vehicle Speed and Unit Type Arrival

Parameter	Estimate (β)	Std. Error	P-Value
Ordered Logistic Model			
Vehicle speed (mph)	0.008	0.028	0.768
Vehicle arriving first indicator	-0.225	0.34	0.508
Threshold 1	-1.957	0.352	<0.001
Threshold 2	0.184	0.301	0.540
Binary Logistic Model			
Constant	-0.176	0.312	0.573
Vehicle speed (mph)	-0.003	0.029	0.926
Vehicle arriving first indicator	0.111	0.359	0.757

It is also possible to assess the severity of a conflict considering both PET and vehicle speed. In this context, a conflict with both a low PET (≤ 1.5 sec) and a high vehicle speed would be considered most severe, while a conflict with a higher PET (> 3.5-5 sec) and a low vehicle speed would be considered least severe. To make this determination, the distribution of vehicle speeds in all observed conflicts (across all site types) was analyzed and the median of this distribution was found to be 8.0 mph. Based on this information, any conflict in which the vehicle speed was less than 8.0 mph was coded as 'low vehicle speed' while any conflict in which the vehicle speed was 8.0 mph or greater was coded as 'high vehicle speed'. These speed categories were then combined with the previously described severity categories based on PET. The result is six discrete severity categories, and to the authors' knowledge, this type of conflict severity assessment is novel and has not been described in existing literature. Table 3.12 shows a summary of both the frequency and percent of conflicts in each of the six PET-vehicle speed severity categories by site type, and Figure 3.6 shows a graphical representation of these percentages.

Table 3.12: Summary of Conflict Observations by PET-Vehicle Speed Severity

Treatment Type	PET-Veh Speed Severity Category (1=most severe)					
	1	2	3	4	5	6
	PET ≤ 1.5 sec, High Vehicle Speed	PET ≤ 1.5 sec, Low Vehicle Speed	PET > 1.5-3.5 sec, High Vehicle Speed	PET > 1.5-3.5 sec, Low Vehicle Speed	PET > 3.5-5 sec, High Vehicle Speed	PET > 3.5-5 sec, Low Vehicle Speed
Control	11 (27.5%)	5 (12.5%)	15 (37.5%)	4 (10.8%)	4 (10.0%)	1 (2.5%)
Bike Box	13 (15.3%)	27 (31.8%)	10 (11.8%)	26 (30.6%)	2 (2.4%)	7 (8.2%)
Mixing Zone	12 (40.0%)	3 (10.0%)	9 (30.0%)	1 (3.3%)	3 (10.0%)	2 (6.7%)

Note: values in table represent frequency (percentage) in each category

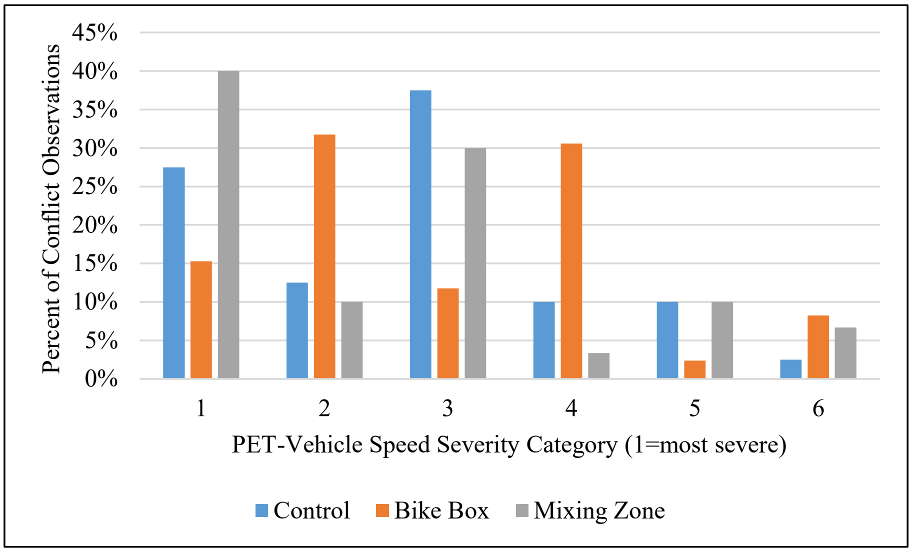


Figure 3.6: Percent of conflicts categorized by PET-vehicle speed severity by site type

As shown in Table 3.12 and Figure 3.6, 40.0% of conflicts occurring at mixing zones fall into the most severe PET-vehicle speed category, followed by conflicts occurring at control sites (27.5%) and bike boxes (15.3%). These are results are likely due to the conflict area design of mixing zones sites where vehicles are not slowing to turn at the upstream conflict area. To examine whether treatment type is statistically associated with PET-vehicle speed severity, both ordered logistic (considering all six severity categories) and binary logistic (with category 1 as the dependent variable) were estimated using similar statistical frameworks to those described previously in section 3.2.1.1.

The results of these models are shown in Table 3.13. Based on these results, the bike box and mixing zone indicators are not statistically significantly associated with severe PET-vehicle speed conflicts in either model. However, in the binary logistic model, the bike box indicator was close to statistical significance at 90% confidence (p-value = 0.110), with a negative parameter estimate meaning that all else equal, a conflict occurring at a bike box is less likely to fall in the most severe PET-vehicle speed category. An odds ratio for this parameter can be determined by taking exp(-.702) = 0.496, meaning that a conflict occurring at a bike box site is 50.4% less likely to fall in the most severe category as compared with control sites (left out as the reference category).

In this same model, the mixing zone indicator has a positive parameter estimate, meaning conflicts occurring at these locations are more likely to fall in the most severe category, though this result is not as close to statistical significance (p-value = 0.273). Although it does appear from summary statistics and the statistical models that conflicts occurring at bike boxes are least likely to fall in the most severe PET-vehicle speed category, it should be noted that a large proportion of conflicts at bike boxes fall in the second most severe category (low PET, low vehicle speed). That being said, it does appear that even when low PET conflicts occur at bike box locations, they are generally less likely to involve high speed vehicles.

Table 3.13: Results of the PET-Vehicle Speed Severity Models

Parameter	Estimate (β)	Std. Error	P-Value
Ordered Logistic Model			
Bike Box Indicator	-0.322	0.34	0.344
Mixing Zone Indicator	0.358	0.431	0.406
Threshold 1	-2.811	0.411	<0.001
Threshold 2	-2.108	0.349	<0.001
Threshold 3	-0.868	0.299	0.004
Threshold 4	0.052	0.29	0.857
Threshold 5	1.088	0.305	<0.001
Binary Logistic Model			
Constant	-0.969	0.354	0.006
Bike Box Indicator	-0.742	0.465	0.110
Mixing Zone Indicator	0.564	0.514	0.273

3.2.2.3 Consideration of Signal Indication on Arrival and Bicyclist Stopping Position at Bike Box Locations

Bike box locations are unique in terms of the stopping position for bicyclists when they arrive on a red signal indication. At these locations, bicyclists can stop in the bike box which is located in front of the stop bar for vehicles, positioning bicyclists more in view of the driver (this is one of the primary benefits of bike boxes), as opposed to control site locations, mixing zone sites, and even bicycle signal sites where both bicyclists and vehicles generally stop at the same stop bar. To assess potential impacts of different stopping locations on conflicts, additional information was collected for conflicts occurring at bike box sites including:

- The signal indication (red or green) as the bicyclist approached the intersection
- If the bicyclist stopped (arrival on red), their location within the bike was recorded as one of three areas (A, B, or C) as defined in Figure 3.7.

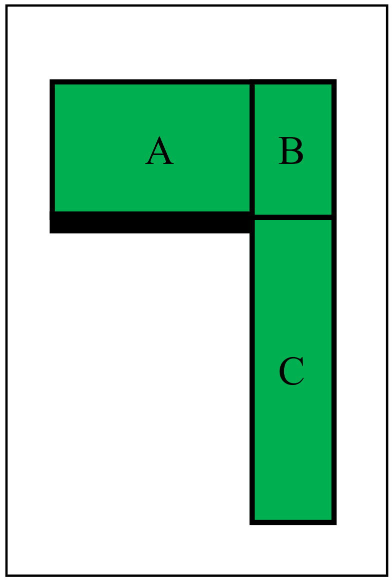


Figure 3.7: Stopping locations for bicyclists in bike boxes

Table 3.14 shows a summary of the frequency and percent of conflicts where bicyclists arrived on red or green signal indications and summary of stopping position for those that arrived on red. As shown in Table 3.14, most bicyclists involved in conflicts at bike boxes (71.8%) arrived on green signal indication, and the average PET for conflicts involving bicyclists arriving on green or red were almost identical (1.88 sec and 1.86 sec, respectively). For those conflict-involved bicyclists that stopped (after arriving on red), none stopped in the 'A' area of the bike box, 16.7% stopped in the 'C' area, while the majority (83.3%) stopped in the 'B' area. It should be noted that these statistics do not include the stopping positions of bicyclists who were not involved in observed conflicts, so it is possible that stopping in the 'A' area (in front of the lead vehicle) may help prevent conflicts, though that inference cannot be verified with this data set. It should be noted that these percentages of different bicyclist stopping positions are generally in line with previous research observing all stopped bicyclists at bike boxes which found 64% of bicyclists stopped in the 'B' area and a much lower percentage (9%) stopped in the 'A' area (Dill et al., 2012).

Table 3.14: Summary of Signal Indication at Arrival and Bicyclist Stopping Position at Bike Box Sites

Signal Indication on Bicyclist Arrival and Stopping Position (if applicable)	Frequency	Percent	Average PET (s)
Arrived on Green	61	71.8	1.88
Arrived on Red	24	28.2	1.86
Stopped in Position A	0	0	N/A
Stopped in Position B	20	83.3	1.97
Stopped in Position C	4	16.7	1.27

*Note: values in this table represent only conflict-involved bicyclists

3.3 SUMMARY AND DISCUSSION

This chapter described the collection and analysis of conflict data reduced from field-collected videos at 12 study intersection approaches (3 with bike boxes, 3 with mixing zones, 3 with bicycle signals, and 3 control sites with no specific bicycle-focused treatment aside from bike lanes). Videos of each study approach were recorded for 12 hours (7am-7pm) between August 6, 2020 and September 1, 2020, and road user volumes (vehicles, bicycles, and pedestrians) by movement were reduced in 15-minute bins and then summarized by hour. Conflicts (defined by PET) between bicycles and vehicles were then reduced from the field-collected videos and also summarized by hour for each site.

At bicycle signal locations, there were zero conflicts observed between bicyclists and vehicles who properly used bicycle signals given the time-separated movement of bicyclists and vehicles at these locations. For bike box, mixing zone, and control site locations, the hourly volumes of through bicyclists and right turning vehicles were used to estimate a series of Poisson regression models to assess the association between volumes and conflict frequency (with PET $\leq$ 1.5 sec), and how this association varied across site types. Using the Poisson models, hourly conflict frequency was predicted across a range of hourly turning vehicle and through bicycle volumes, and the following observations were made:

- Under conditions with 75 or less turning vehicles per hour and 25 or less bikes per hour, the predicted conflict frequency was similar for all three site types (bike boxes, mixing zones, and control sites).
- Under conditions with more than 25 through bikes per hour, the predicted conflict frequency at control sites were higher than those at bike boxes or mixing zones, with the notable exception being that predicted conflicts were higher at mixing zones when turning vehicle volumes were greater than 100 vehicles per hour. This finding indicated that both bike boxes and mixing zones provide a benefit compared to control sites when through bike volumes are greater than 25 per hour, but the bike box may be a better option if turning vehicle volumes are greater than 100 per hour.

The potential impact of right-side parallel crossing pedestrian volume on conflict frequency was also assessed, and it was found that increased pedestrian volumes were significantly associated with increased conflict frequency at control sites, but not at bike box or mixing zone sites. This indicates pedestrian volume should be considered in determining whether to apply a specific treatment.

In addition to conflict frequency, conflict severity was also analyzed in several different ways. First, conflicts were categorized into three severity categories based on PET, with the most severe category being PET $\leq$ 1.5 sec. While summary statistics showed mixing zones exhibited the highest percentage of high severity conflicts, estimation of ordered and binary logistic models found no statistically significant association between treatment type and this severity measure.

Vehicle speeds during conflicts and unit arrival order (i.e., bike first or vehicle first) were also analyzed by site type. While no statistically significant association was found, conflicts occurring at mixing zones had a much higher vehicle speed and were more likely have the bicyclist arrive first to the conflict point. Additionally, with respect to bike box locations specifically, of bicyclists who arrived on red and had to stop in the bike box none stopped in the ‘box’ area immediately in front of the lead vehicle. Only data for bicyclists involved in conflicts were collected for this study, so it is unknown how many non-conflict-involved bicyclists stopped in this area, but it’s possible that this positioning may help prevent bicycle-vehicle conflicts.

Finally, a novel method to categorize conflict severity was developed considering both PET and vehicle speed. Six severity categories were defined with the most severe being ‘low PET-high vehicle speed’ and least severe being ‘high PET-low vehicle speed’. It was found that bike box locations exhibited the lowest percentage of conflicts in the most severe category, though there were not statistically significant associations between this severity measurement and treatment type. Ultimately, the results from this chapter are used to help develop recommendations to practitioners presented in Chapter 6.0.

4.0 MICROSIMULATION MODELING

This chapter discusses the development of microsimulation models and the extraction of bicycle-vehicle conflict data from these models using the Surrogate Safety Assessment Model (SSAM). The primary objective of this analysis was to conduct a sensitivity analysis (i.e., assessing changes in conflicts under different ranges of road user volumes for sites with different treatment types).

4.1 DEVELOPMENT OF MICROSIMULATION MODELS

For this analysis, PTV Vissim software was used to conduct microsimulation modeling. The process used to create the Vissim models followed the guidance of the ODOT Analysis Procedures Manual (APM) (ODOT, 2020). This process included recreating the geometry, field-observed road user volumes, and signal timing for each of the 12 study intersections presented in Chapter 3.0 within Vissim. The geometries were drawn directly onto satellite images of the intersections using the Vissim Bing Maps function.

Once the geometry for each location was completed, the field-observed road user volumes (as discussed in section 3.1.1) were used to enter hourly volumes and turning ratios for each study approach. The turning ratios were added using the static routing function, and vehicle compositions were adjusted to match the percentages of heavy vehicles observed in the field at each site. The field observed hourly volumes of bicyclists and pedestrians were also added to each of the 12 models. It should be noted that bicycle speed distributions in all models were set to 10-15 mph to represent typical bicyclist speeds (ODOT, 2011). 12 one-hour time intervals (representing 7am-7pm) were created in Vissim to match the volumes in the 12 hours of video footage collected, plus a 15-minute startup period to populate the models.

Signal timing information for each intersection was provided by the city of Portland, and this information was then used to replicate signal operations in the models that matched the real-world operation of the intersection. The road user travel paths, conflict areas, and priority rules were setup to match as closely as possible the behaviors observed in the field-collected videos at each of the 12 study sites. These 12 models with field observed vehicle, bicycle and pedestrian volumes represent the ‘baseline’ models and volumes are then adjusted from these ‘baseline’ models for completing sensitivity analyses. Figure 4.1 shows a screen shot of the Vissim model from Broadway and Hoyt (bike box), Figure 4.2 shows a screen shot of the Vissim model from Multnomah and 9th (mixing zone), Figure 4.3 shows a screen shot of the Vissim model from Rosa Parks and Greeley (bicycle signal), and Figure 4.4 shows a screen shot of the Vissim model from Burnside and 8th (control site). In these figures, the blue lines represent ‘links’, the pink lines represent ‘connectors’ (turning paths connecting different links), and the thicker lines represent stop lines with a green color indicating that road users approaching that stop line currently have the right of way in the simulation model.

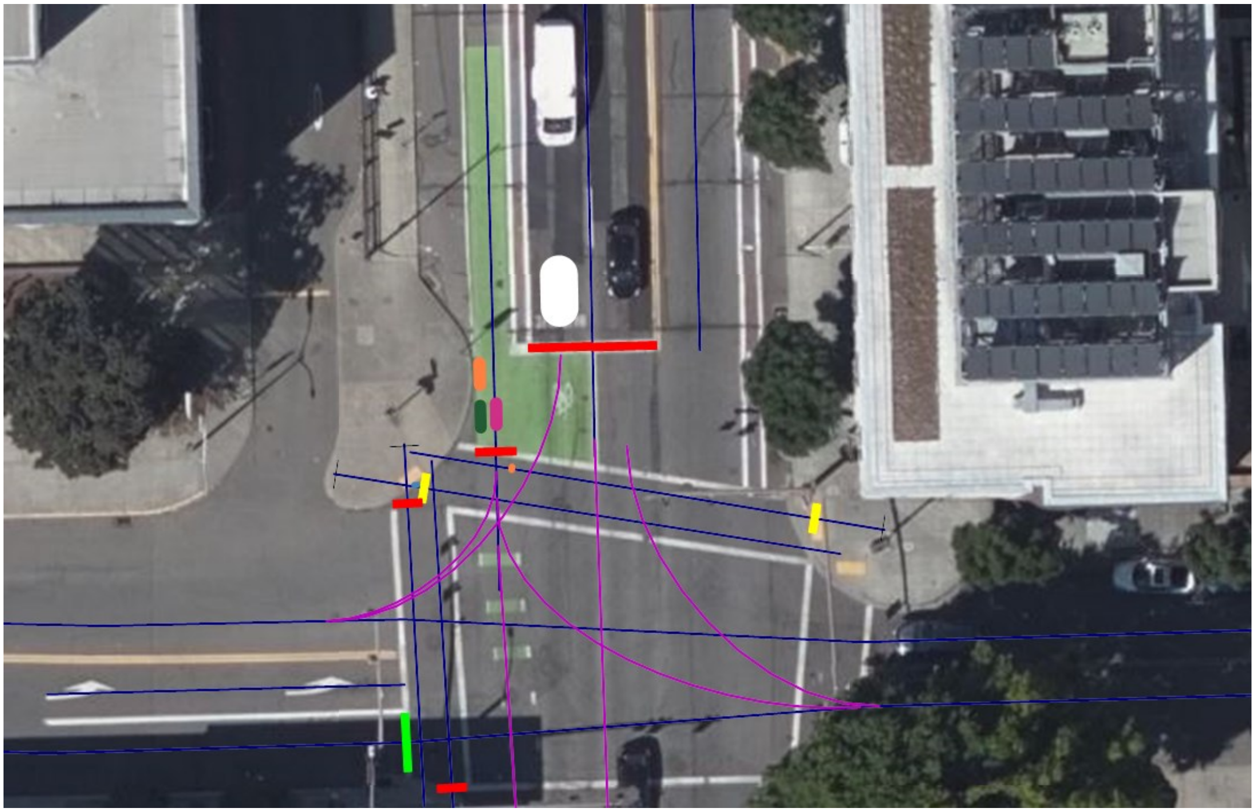


Figure 4.1: Screen shot of Vissim model for Broadway and Hoyt (bike box)

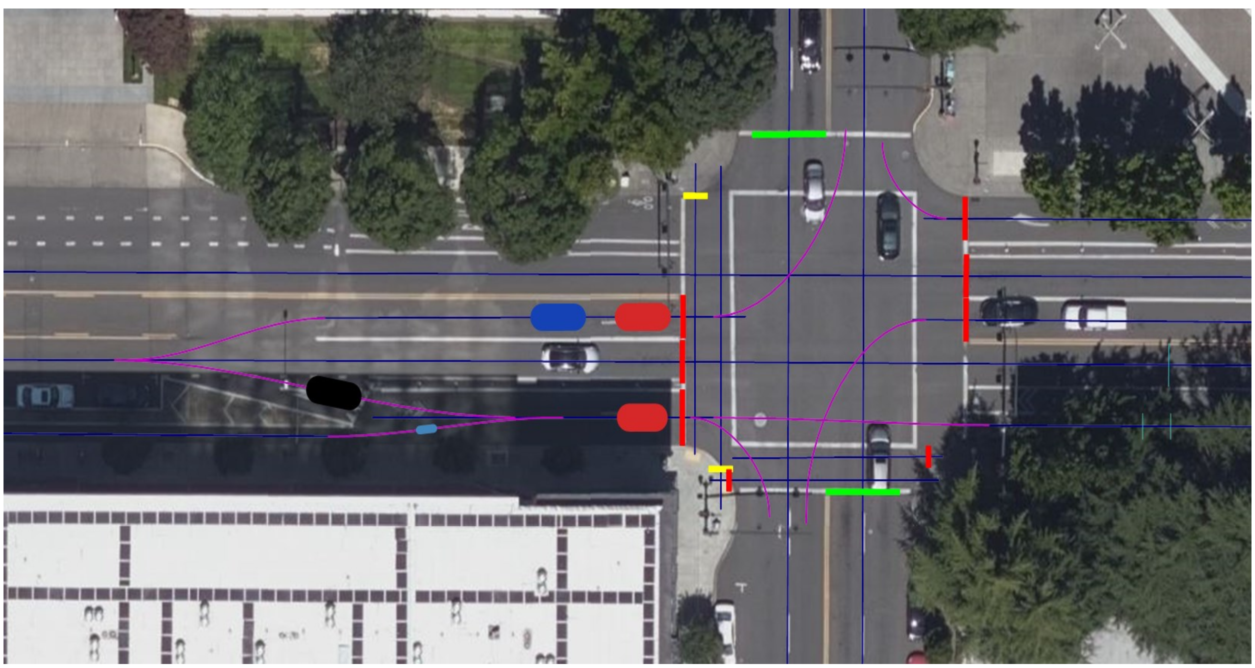


Figure 4.2: Screen shot of Vissim model from Multnomah and 9th (mixing zone)

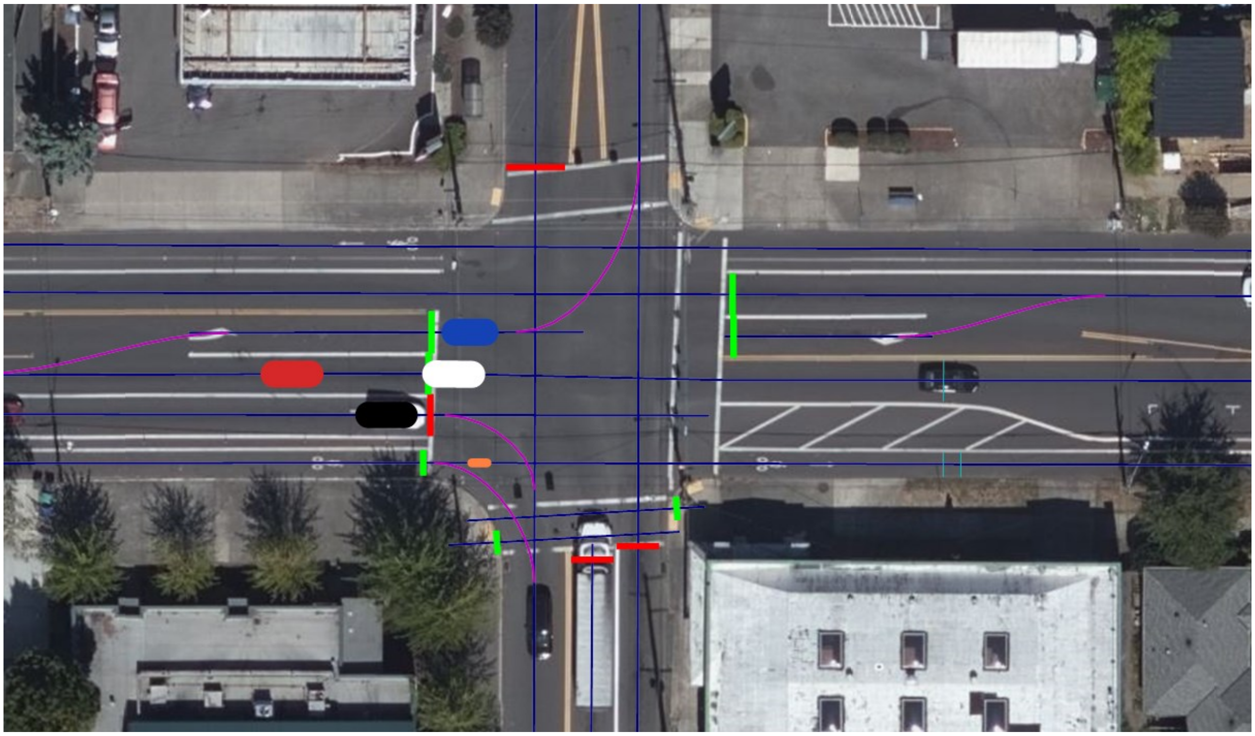


Figure 4.3: Screen shot of Vissim model from Rosa Parks and Greeley (bicycle signal)

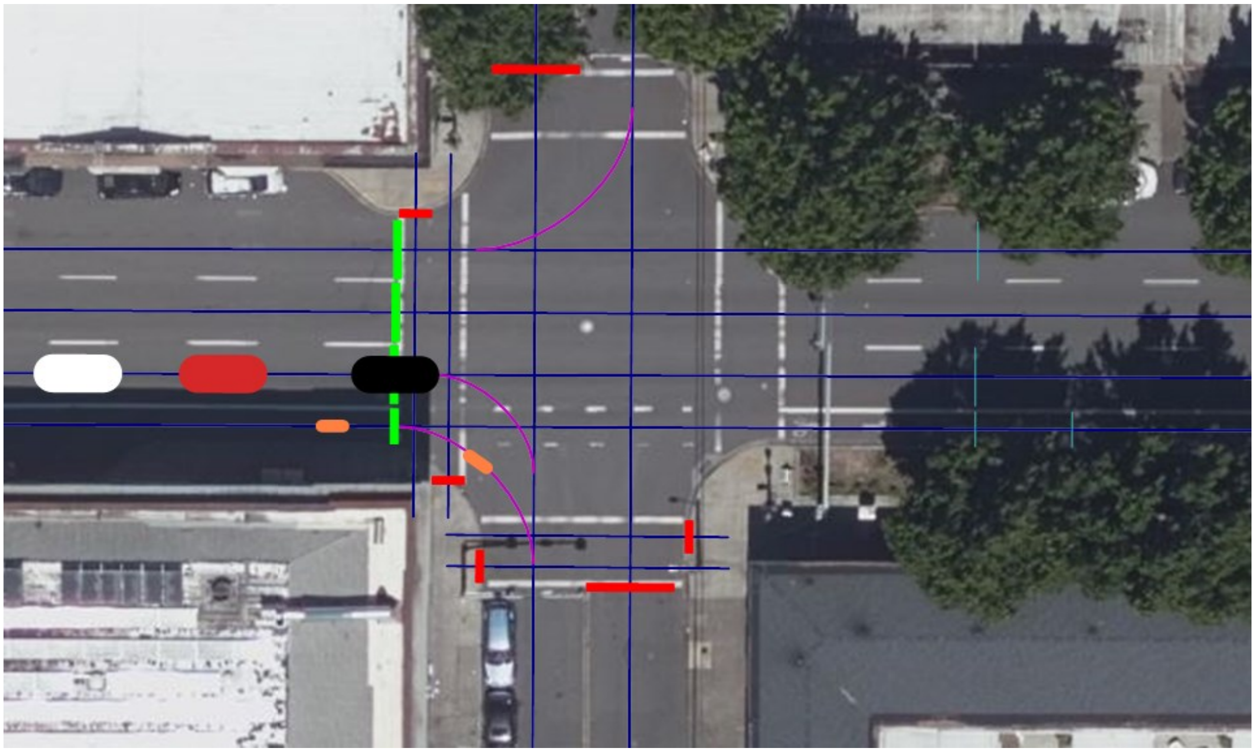


Figure 4.4: Screen shot of Vissim model from Burnside and 8th (control site)

4.1.1 Calibration of Microsimulation Models

Calibration of the Vissim models was performed in accordance with the ODOT APM (ODOT, 2020). Calibration focused on replicating queue lengths and ensuring the simulation output volumes matched the observed field volumes. Average queue lengths were manually observed and recorded from one hour of video for each model, and the study period for the queue length observations was 9-10 AM in order to avoid having the queue lengths extend past the view of the cameras (note that Site 4 used a study period of 3-4 PM due to low volumes of vehicles observed from 9-10 AM). The field observed queue lengths were then compared to the simulated queue lengths in order to identify any inconsistencies in the models. Each model also had a general visual inspection to verify no excessive or scant queuing behaviors occurred. As shown in Table 4.1, the average queues obtained from Vissim are all within one or two passenger vehicle lengths of those queues observed from the field-collected videos, assuming an average passenger vehicle length of 19 ft (AASHTO, 2011).

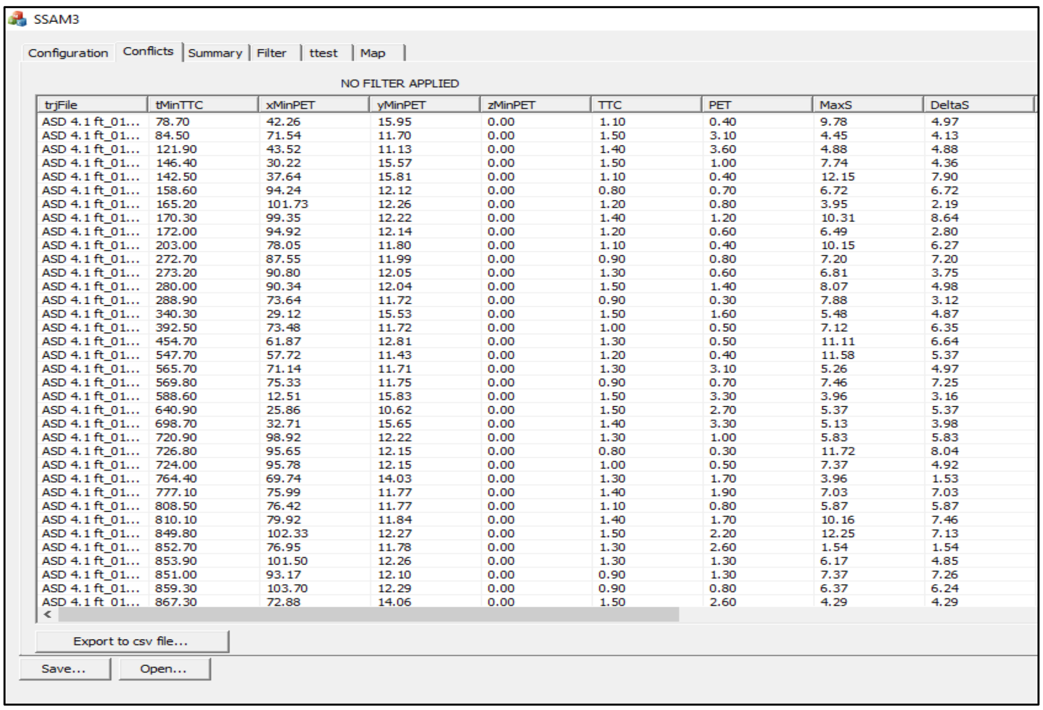
Vissim notifies after each simulation run if any vehicles failed to be generated. All models were run through simulation to verify that all volumes programed in the models were served, and this ensured that the vehicles exited in the simulation matched what was observed in the field. Overall, based on the queue lengths and vehicles exited, the baseline Vissim models developed "provide a reasonable representation of existing conditions measured in the field" (ODOT, 2020).

Table 4.1: Comparison of Field-Observed and VISSIM-Simulated Average Queue Lengths

Site	Site Name	Manually Measured Queue from video (ft)	Simulated Queue from VISSIM (ft)	Absolute Value of Queue Difference (ft)	Approx. Number of Passenger Vehicle Difference between field observed and VISSIM queue
1	Broadway (SB) and Hoyt	50.6	12.1	38.5	2
2	7th Ave (SB) and Madison St.	43.3	6.9	36.4	2
3	Gladstone (WB) and Cesar E. Chavez	12.2	2.4	9.9	1
4	Multnomah (EB) and 9th Ave	15.4	4.0	11.4	1
5	Multnomah (EB) and 16th Ave	16.2	0.9	15.3	1
6	Multnomah (WB) and Grand Ave	10.7	2.7	8.0	1
7	N Broadway (WB) and N Williams	30.7	35.7	5.0	1
8	Rosa Parks (EB) and Greeley Ave	17.5	4.6	12.9	1
9	Halsey (EB) and 102nd Ave	27.9	5.8	22.1	1
10	SE 7th Ave (NB) and SE Clay Ave	21.8	7.4	14.4	1
11	Weidler (EB) and 9th Ave	12.1	7.5	4.6	1
12	Burnside (EB) and 8th Ave	25.7	5.7	20.0	1

4.2 EXTRACTING CONFLICTS FROM MICROSIMULATION MODELS

Once all microsimulation models were developed, SSAM was used to extract conflict data from the model results. Each Vissim model was configured so that trajectory files were generated for each simulation run. The trajectory files describe the course of vehicle and bicycle positions through the network, and these trajectories are used as the basis to identify conflicts (PTV Group, 2018). These trajectory files were uploaded into SSAM and analyzed to identify all conflicts in the models. Figure 4.5 shows an example output from SSAM, where each row represents a conflict identified in the microsimulation run, and PET values can be observed in the seventh column titled PET. Note that the default output from SSAM includes conflicts between all road users (including vehicle-vehicle conflicts), and bike-vehicle conflicts were identified using the vehicle length columns in the SSAM results. The conflict data were filtered such that only those involving a bicycle and a vehicle in the conflict zone being studied remained.



trjFile	tMinTTC	xMinPET	yMinPET	zMinPET	TTC	PET	MaxS	DeltaS
ASD 4.1 ft_01...	78.70	42.26	15.95	0.00	1.10	0.40	9.78	4.97
ASD 4.1 ft_01...	84.50	71.54	11.70	0.00	1.50	3.10	4.45	4.13
ASD 4.1 ft_01...	121.90	43.52	11.13	0.00	1.40	3.60	4.88	4.88
ASD 4.1 ft_01...	146.40	30.22	15.57	0.00	1.50	1.00	7.74	4.36
ASD 4.1 ft_01...	142.50	37.64	15.81	0.00	1.10	0.40	12.15	7.90
ASD 4.1 ft_01...	158.60	94.24	12.12	0.00	0.80	0.70	6.72	6.72
ASD 4.1 ft_01...	165.20	101.73	12.26	0.00	1.20	0.80	3.95	2.19
ASD 4.1 ft_01...	170.30	99.35	12.22	0.00	1.40	1.20	10.31	8.64
ASD 4.1 ft_01...	172.00	94.92	12.14	0.00	1.20	0.60	6.49	2.80
ASD 4.1 ft_01...	203.00	78.05	11.80	0.00	1.10	0.40	10.15	6.27
ASD 4.1 ft_01...	272.70	87.55	11.99	0.00	0.90	0.80	7.20	7.20
ASD 4.1 ft_01...	273.20	90.80	12.05	0.00	1.30	0.60	6.81	3.75
ASD 4.1 ft_01...	280.00	90.34	12.04	0.00	1.50	1.40	8.07	4.98
ASD 4.1 ft_01...	288.90	73.64	11.72	0.00	0.90	0.30	7.88	3.12
ASD 4.1 ft_01...	340.30	29.12	15.53	0.00	1.50	1.60	5.48	4.87
ASD 4.1 ft_01...	392.50	73.48	11.72	0.00	1.00	0.50	7.12	6.35
ASD 4.1 ft_01...	454.70	61.87	12.81	0.00	1.30	0.50	11.11	6.64
ASD 4.1 ft_01...	547.70	57.72	11.43	0.00	1.20	0.40	11.58	5.37
ASD 4.1 ft_01...	565.70	71.14	11.71	0.00	1.30	3.10	5.26	4.97
ASD 4.1 ft_01...	569.80	75.33	11.75	0.00	0.90	0.70	7.46	7.25
ASD 4.1 ft_01...	588.60	12.51	15.83	0.00	1.50	3.30	3.96	3.16
ASD 4.1 ft_01...	640.90	25.86	10.62	0.00	1.50	2.70	5.37	5.37
ASD 4.1 ft_01...	698.70	32.71	15.65	0.00	1.40	3.30	5.13	3.98
ASD 4.1 ft_01...	720.90	98.92	12.22	0.00	1.30	1.00	5.83	5.83
ASD 4.1 ft_01...	726.80	95.65	12.15	0.00	0.80	0.30	11.72	8.04
ASD 4.1 ft_01...	724.00	95.78	12.15	0.00	1.00	0.50	7.37	4.92
ASD 4.1 ft_01...	764.40	69.74	14.03	0.00	1.30	1.70	3.96	1.53
ASD 4.1 ft_01...	777.10	75.99	11.77	0.00	1.40	1.90	7.03	7.03
ASD 4.1 ft_01...	808.50	76.42	11.77	0.00	1.10	0.80	5.87	5.87
ASD 4.1 ft_01...	810.10	79.92	11.84	0.00	1.40	1.70	10.16	7.46
ASD 4.1 ft_01...	849.80	102.33	12.27	0.00	1.50	2.20	12.25	7.13
ASD 4.1 ft_01...	852.70	76.95	11.78	0.00	1.30	2.60	1.54	1.54
ASD 4.1 ft_01...	853.90	101.50	12.26	0.00	1.30	1.30	6.17	4.85
ASD 4.1 ft_01...	851.00	93.17	12.10	0.00	0.90	1.30	7.37	7.26
ASD 4.1 ft_01...	859.30	103.70	12.29	0.00	0.90	0.80	6.37	6.24
ASD 4.1 ft_01...	867.30	72.88	14.06	0.00	1.50	2.60	4.29	4.29

Figure 4.5: Example output from SSAM

4.3 CONFLICT DATA COLLECTION FROM MICROSIMULATION MODELS

To collect conflict data from microsimulation, all 12 'baseline' models (representing each field study site) were run for all 12 hours (representing 7am-7pm) ten times with ten different random seed values (the 10 different random seed values were the same for each site). Ultimately, the average number of conflicts across the ten simulation runs with different random seeds at each site are used in this study. The use of average values from simulation runs with ten random seeds is in accordance with the ODOT APM (ODOT, 2020), and for each site, the random seed value started at 42 (default value) and increased in increments of one for each additional simulation run. For each of the 12 baseline models, a total of 7,350 minutes of simulation time was completed (12 hours x 60 minutes/hour x 10 random seeds plus 15 minutes startup time x 10 random seeds).

After the average number of conflicts across the simulation runs were obtained using SSAM, the conflicts obtained from the microsimulation models were compared to the conflicts observed from the field-collected video. It was found that for the most part, a far lower number of conflicts were obtained from the microsimulation models compared with conflicts observed in the field. Past research has shown that conflicts do tend to be undercounted in microsimulation modeling compared with field-observed values, and that behavioral and other parameters can be adjusted in Vissim to better match these values (Lemcke et al., 2021; Russo, Lemcke, et al., 2020). It should be noted that at bicycle signal locations, the models produced zero bicycle-vehicle conflicts as expected given these users are time-separated at these locations.

In an attempt to better match conflicts obtained from the baseline models to those observed in the field, several behavioral parameters in the microsimulation were adjusted based on judgement from the research team and past research in this area (Lemcke et al., 2021; Russo, Lemcke, et al., 2020) including:

- Additive Part of Safety Distance (Wiedemann 74): "Value used for the computation of the desired safety distance *d*. Allows to adjust the time requirement values." (PTV Group, 2018)

- Average Standstill Distance (Wiedemann 74): "Defines the average desired distance between two cars" (PTV Group, 2018). The same definition would apply to bicycles.

- Safety Distance Reduction Factor (Signals): "Defining the behavior of vehicles close to a stop line. If a vehicle is located in an area between Start upstream of stop line and end downstream of stop line, the factor is multiplied by the safety distance of the vehicle. The safety distance used is based on the car following model. For lane changes in front of a stop line, the two values calculated are compared. VISSIM will use the shorter of the two distances." (PTV Group, 2018)

- Safety Distance Factor (Conflict Areas): "Only for the type merging conflicts; This factor is multiplied with the normal desired safety distance of a vehicle in the main traffic stream in order to determine the minimum distance a vehicle of the yielding traffic stream must keep when it is completely in the conflict area." (PTV Group, 2018)

Exhaustive efforts were undertaken to adjust the above-mentioned behavioral parameters and conflict area designs in an attempt to better match conflicts collected from the microsimulation models to those in the field. After each adjustment, the models were run for 12 hours (with ten random seeds as mentioned previously) to obtain conflict outputs to compare with field-observed conflicts. Ultimately, it was determined that for the bike box sites and control locations, a reasonable number of conflicts could not be obtained from the microsimulation model to make meaningful conclusions based on the model results.

While a previous study based on a location with a bike lane and exclusive right turn lane concluded microsimulation could be used to reasonably match field-observed conflicts (Lemcke et al., 2021), the efforts conducted as part of this project (SPR833) indicate that microsimulation modeling with conflicts extracted by SSAM may not be particularly useful to assess bicycle-vehicle conflicts on some approaches with other characteristics. A qualitative manual inspection of the microsimulation models developed for this project while they were running showed that vehicle and bicycle behavior in the models at the study approaches matched the behavior observed in the field-collected videos quite well. In fact, during this manual inspection of running models, what appeared to be conflicts between bicycles and vehicles were observed, however, for reasons that are unclear, they were not identified in the outputs from SSAM. That being said, based on the calibration measures and model observations, microsimulation may be useful in assessing the operational impacts (e.g., delay) of bicycle-specific treatments, however this project was focused solely on potential safety impacts.

4.4 CONFLICT DATA ANALYSIS FROM MICROSIMULATION MODELS

As described in section 4.3, the baseline microsimulation models developed based on the bicycle signal locations yielded zero conflicts (as expected), and the models developed based on bike box and control locations yielded an excessively low number of conflicts (either zero or just one or two over the 12 hours of simulation for certain random seeds). As such, strong conclusions could not be made on the potential impacts of increased or decreased volumes on conflict frequency at these sites using microsimulation.

The average total number of conflicts over 12 hours obtained from the microsimulation models at mixing zone sites actually matched field observed conflicts at these sites reasonably well:

- Site 4 (Multnomah and 9th): 8 field observed conflicts, average of 7.1 conflicts extracted from microsimulation model.
- Site 5 (Multnomah and 16th): 2 field observed conflicts, average of 0.4 conflicts extracted from microsimulation model.
- Site 6 (Multnomah and Grand): 20 field observed conflicts, average of 18.9 conflicts extracted from microsimulation model.

The difference of both fields observed, and microsimulation generated conflicts between these three sites make intuitive sense; while all three sites had average hourly through bike volumes ranging from 7.3-12.0 bikes per hour, site 6 had a much higher average hourly turning vehicle volume (58.7 vph) and thus more observed and simulated conflicts, compared with site 5 which had a much lower average hourly turning vehicle volume (3.4 vph), and thus less observed and simulated conflicts.

To investigate the potential impacts of both increased and decreased volumes on conflicts at the mixing zone sites, the volumes of all users (vehicles, bikes, pedestrians) were both increased and decreased by 5%, 10%, and 15%, resulting seven models for each site:

- Baseline model (with field-observed volumes)
- 5% increase in volumes
- 10% increase in volumes
- 15% increase in volumes
- 5% decrease in volumes
- 10% decrease in volumes
- 15% decrease in volumes

For each of the six additional models (with adjusted volumes) at each mixing zone site, ten 12-hour simulation runs with different random seeds were completed as previously described in section 4.3. Table 4.2 shows the results (in terms of conflict frequency) of the both the baseline model and adjusted volume models for each of the 3 mixing zone sites.

Table 4.2: Summary of Conflict Frequencies for Baseline and Adjusted Volumes at Mixing Zone Sites

Mixing Zone Site	Random Seed	Baseline Model Bike-Vehicle Conflicts	Conflicts with Volumes Increased			Conflicts with Volumes Decreased		
			5%	10%	15%	-5%	-10%	-15%
Multnomah & 9th	42	5	7	1	3	4	5	5
Multnomah & 9th	43	10	10	9	10	5	4	6
Multnomah & 9th	44	6	11	4	10	6	3	9
Multnomah & 9th	45	6	3	12	2	11	6	6
Multnomah & 9th	46	7	9	8	6	5	2	6
Multnomah & 9th	47	6	10	8	2	2	4	4
Multnomah & 9th	48	6	6	10	6	4	6	6
Multnomah & 9th	48	9	10	8	10	9	6	4
Multnomah & 9th	50	9	5	10	5	5	5	5
Multnomah & 9th	51	7	12	7	15	7	7	5
Multnomah & 9th	**Average:**	**7.1**	**8.3**	**7.7**	**6.9**	**5.8**	**4.8**	**5.6**
Conflict Change vs. Baseline:		**N/A**	**1.2**	**0.6**	**-0.2**	**-1.3**	**-2.3**	**-1.5**
Percent Change vs. Baseline:		**N/A**	**16.9%**	**8.5%**	**-2.8%**	**-18.3%**	**-32.4%**	**-21.1%**
Multnomah & 16th	42	0	1	1	0	0	1	2
Multnomah & 16th	43	1	2	3	1	0	1	2
Multnomah & 16th	44	0	0	1	4	0	1	1
Multnomah & 16th	45	1	0	0	0	1	0	1
Multnomah & 16th	46	0	2	1	1	3	0	2
Multnomah & 16th	47	1	1	0	4	2	0	0
Multnomah & 16th	48	1	1	1	0	1	1	2
Multnomah & 16th	48	0	2	1	4	1	2	2
Multnomah & 16th	50	0	1	2	3	2	1	1
Multnomah & 16th	51	0	1	0	1	1	1	1
Multnomah & 16th	**Average:**	**0.4**	**1.1**	**1.0**	**1.8**	**1.1**	**0.8**	**1.4**
Conflict Change vs. Baseline:		**N/A**	**0.7**	**0.6**	**1.4**	**0.7**	**0.4**	**1.0**
Percent Change vs. Baseline:		**N/A**	**175.0%**	**150.0%**	**350.0%**	**175.0%**	**100.0%**	**250.0%**
Multnomah & Grand	42	25	24	20	24	19	14	13
Multnomah & Grand	43	16	25	21	22	20	16	6

Multnomah & Grand	44	21	18	17	26	26	21	16
Multnomah & Grand	45	12	21	33	26	24	17	12
Multnomah & Grand	46	19	14	22	14	19	24	22
Multnomah & Grand	47	18	21	24	30	22	20	19
Multnomah & Grand	48	22	20	26	20	22	15	20
Multnomah & Grand	48	18	18	27	25	18	10	16
Multnomah & Grand	50	20	24	25	35	19	26	19
Multnomah & Grand	51	18	15	27	21	16	14	12
Multnomah & Grand	**Average:**	**18.9**	**20.0**	**24.2**	**24.3**	**20.5**	**17.7**	**15.5**
Conflict Change vs. Baseline:		**N/A**	**1.1**	**5.3**	**5.4**	**1.6**	**-1.2**	**-3.4**
Percent Change vs. Baseline:		**N/A**	**5.8%**	**28.0%**	**28.6%**	**8.5%**	**-6.3%**	**-18.0%**

In examining the results presented in Table 4.2, some observations can be made for each site:

- Multnomah and 9th: The sensitivity analysis performed at this location yielded somewhat counterintuitive results for different ranges of increased volumes. When volumes were increased by 5% and 10%, average conflict frequency increased marginally (16.9% and 8.5%, respectively); this increase in conflicts was expected, however one would expect the 10% increase in volume to yield a larger increase in conflicts than the 5% increase in volume. The most counterintuitive result was obtained when volumes were increased by 15% and conflict frequency was reduced by 2.8%. A closer inspection of the results for all ten random seeds in this simulation revealed this result is driven by several random seeds yielding only 2 or 3 conflicts. While it's not clear exactly why this occurred, previous research indicated that different random seed can have a large effect on conflict frequencies obtained from microsimulation (Lemcke et al., 2021). When volumes were reduced by 5%, 10%, and 15%, average conflict frequencies were reduced by 18.3%, 32.4%, and 21.1%, respectively. While these reductions are not proportional, they are generally in agreement with the analysis of field observed conflicts in Chapter 3.0 which show that lower vehicle and bike volumes are associated with fewer conflicts.

- Multnomah and 16th: At this location, the average conflict frequency across all volume ranges (baseline, increased volumes, and decreased volumes) fell between 0.4 and 1.8 conflicts, with the highest average conflict frequency (1.8) being for the model with 15% increased volumes, as one would expect. However, since these conflict frequencies are such small numbers, the percent increases and decreases in conflicts presented in Table 4.2 for this site are not particularly meaningful.

- Multnomah and Grand: At this site, when volumes were increased by 5%, 10%, and 15%, average conflict frequencies were increased by 5.8%, 28.0%, and 24.2%, respectively; generally intuitive results. When volumes were decreased by 5%, average conflicts were increased by 8.5% (a counterintuitive result), and when volumes were decreased by 10% and 15%, average conflict frequencies were reduced by 6.3% and 18.0%, respectively.

It should be noted that this same sensitivity analysis (running models with increased and decreased volumes) was also performed for the other nine study sites (bike boxes, bicycle signals, and control sites). With all volume adjustments (increasing and decreasing), simulation models of bicycle signal sites continued to yield zero conflicts (as expected), and bike box and control sites continued to yield unreasonably low conflicts with results that were not useful to make meaningful conclusions.

4.5 SUMMARY AND DISCUSSION

This chapter described the development of calibrated microsimulation models matching each of the 12 field study sites and use of these models to collect conflict data from SSAM with the goal to perform sensitivity analyses by both increasing and decreasing road user volumes. The results of the microsimulation modeling efforts in general did not yield results that were sufficient to make conclusions regarding the impacts of different volume ranges on conflicts at different site types, especially for bike box and control sites.

While the bicycle signal locations yielded zero conflicts as expected, the models for bike box and control site locations yielded excessively low numbers of conflicts across all volume ranges. The baseline models for mixing zone sites did yield conflict frequencies that were relatively close to those observed in the field. With this observation, it is speculated that the use of microsimulation modeling/SSAM to identify conflicts may be sensitive to the angle of conflict, with conflicts occurring close to 90 degrees (such as those between turning vehicles and bikes at bike box and control sites) under identified compared with field-observed conflicts. Conflicts occurring at mixing zone sites and at sites assessed in previous research (Lemcke et al., 2021) generally occur at closer to a 45 degree angle, and conflict frequencies obtained from microsimulation were found to much more closely match those observed in the field at these locations.

The sensitivity analyses performed for mixing zone sites yielded generally expected and intuitive results with some exceptions. For the models at Multnomah and 16th, the average conflict frequencies were very low, and the sensitivity analysis (running models with increased and decreased volumes) generally did not provide noteworthy results. At the other two sites (Multnomah and 9th and Multnomah and Grand), the sensitivity analyses showed that generally increased volumes led to increased conflicts and decreased volumes led to decreased conflicts with varying proportions. There were two exceptions; one where increased volume led to decreased conflicts (+15% volume at Multnomah and 9th) and one where decreased volumes led to increased conflicts (-5% volume at Multnomah and Grand).

The primary conclusions of the microsimulation modeling effort are:

- For the mixing zone sites, it was generally found (with a couple exceptions) that conflict frequencies are correlated with vehicle and bike volumes, strengthening the results of the analysis of field-observed conflict frequencies presented in Chapter 3.0.

- Microsimulation may not be a suitable option for conflict analysis at all site types. While exhaustive efforts were undertaken to develop models that produced similar conflict frequencies to those observed in the field, the models for bike box and control site locations consistently produced unreasonably low conflict frequencies. While numerous behavioral parameters and characteristics of conflict areas and priority rules were adjusted, further research may be warranted if these modeling efforts are to be used for future analyses of bicycle-vehicle conflicts.

- A qualitative inspection of the microsimulation models, along with a comparison of simulated vs. field-observed queue lengths and confirmation of vehicles served indicated the models for all site types performed reasonably well operationally. While beyond the scope of this study, it appears microsimulation modeling could be used to investigate the operational (i.e., delay) impacts of the treatment types assessed in this study. In fact, past research (Kothuri et al., 2018) has used microsimulation modeling to assess the operational impacts of split leading bike interval operation at bicycle signal locations.

5.0 BICYCLING SIMULATOR EXPERIMENT

5.1 SIMULATOR EQUIPMENT

This section provides detailed information about the OSU Bicycling Simulator and the Applied Science Laboratory (ASL) eye-tracking equipment, the primary pieces of equipment used to gather data in the simulated environment.

5.1.1 Bicycling Simulator

The OSU Bicycling Simulator features a Novara bicycle mounted on a stationary platform that faces a 3.20 m x 2.54 m (10.5 ft x 8.3 ft) projected screen displaying a resolution of 1,024 x 768 pixels. The simulator room features a surround sound system with speakers on all sides of the bike to emulate and project sounds from approaching vehicles and ambient noise. Figure 5.1 provides a view of the bicycle simulator from a participant's perspective while seated on the bike.

Visuals and sound effects are received from the connection to the host computer in the adjacent room running Realtime Technologies SimCreator Software Version 3.2 at a 60 Hz refresh rate. Researchers operate the host computer and observe participants from this room during the experiment without introducing unnecessary distractions for participants.

Figure 5.1: Participant view while situated in OSU bicycling simulator

Virtual environments were developed using programs that include Internet Scene Assembler (ISA) Version 2.0, Blender Version 2.71, and SimCreator Version 3.2. JavaScript text files were used to code dynamic elements such as signal changes and vehicular movements within the ISA program. The Blender platform allowed researchers to model 3-D elements that have not been previously used in the simulated environment. Figure 5.2 shows the setup of the OSU Development Simulator, the system that allowed researchers to design and test environments before transitioning to the full-scale OSU Bicycling Simulator.

Figure 5.2: OSU development simulator in design (left) and testing (right) phase

5.1.1.1 Simulator Data Output

Data acquisition began when an environment was loaded into the simulator. At this start-up, precise measurements such as the bicycle's position, speed, acceleration, and braking patterns were recorded using the SimObserver platform throughout the entirety of the ride. All measurements output from this system were instantaneous and measured at 60 Hz.

The SimObserver platform records tabulated data, as well as accompanying video footage from the simulator room. Researchers used the recorded videos to compare and assess the accuracy of the data output to ensure consistency across both datasets. Figure 5.3 gives an example of how recorded video appears on the SimObserver platform.

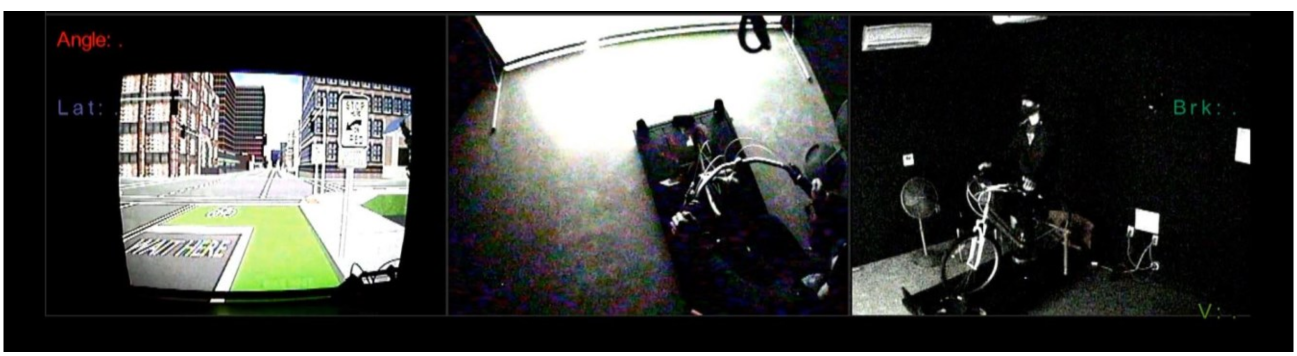


Figure 5.3: Sim observer video data acquisition

5.1.2 Eye Tracker

The ASL Mobile Eye-XG eye tracking equipment was used to collect data on the visual attention of participants. After a calibration procedure was conducted for each participant, the system uses a head mounted camera to track the users eye movements throughout the duration of the study at a rate of 30 Hz. The ASL data collection platform consists of the eye-tracking glasses connected with a data transmit unit (DTU) to measure fixation data and calculate saccade data. The output of this system is a file comprised of both a video feed showing the user's field of view, with an overlay of where the participant gaze was at certain points of time.

5.2 EXPERIMENTAL DESIGN

To better understand bicyclist's safety at intersections and the influence of conflicting right and left turning vehicles, an experiment was designed using the OSU Bicycling Simulator and eye-tracking equipment. The intersection treatments selected for the experiment necessitated the development of novel pavement markings and bicycle signal heads using Blender version 2.71. All other design aspects were coded using Internet Scene Assembler (ISA) version 2.0 to resemble scenarios participants may experience in the real-world as authentically as possible.

5.2.1 Roadway Geometry

Intersection approaches varied slightly due to the treatment applied, although a 1.83 m (six ft) bicycle lane, adjacent 3.05 m (10 ft) vehicular lane, and a 1.52 m (five ft) pedestrian sidewalk were constant cross-sectional elements on the approach to the intersection. Figure 5.4 provide the participant's view on approach to the various intersection treatments.

A solid double yellow line separated the opposing direction of traffic, with a single 3.05 m (10 ft) vehicular lane in the opposing direction. Pavement markings, geometric configurations, and signage were designed in accordance with standards from the 2021 Oregon Department of Transportation Traffic Line Manual (ODOT, 2021) and the 2009 Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009). Light ambient traffic was included in the study, as well as a posted speed limit of 25 mph. Adjacent land use was designed to resemble an urban environment and was consistent throughout the study duration.

Figure 5.4: Cross-sectional geometry for (a) Bike box, (b) Mixing zone, and (c) Bicycle signal, treatments on approach to intersection

5.2.2 Experimental Variables

5.2.2.1 Independent Variables

Three independent variables were included in the experiment and are described in Table 5.1: type of conflict, treatment, and stopping requirement. The type of conflict indicates the arrival time of the conflicting vehicle in relation to a right or left-hook crash. The treatment variable includes three types of intersection treatments: bike box, mixing zone, or bicycle signals. These treatments are shown in Figure 5.5. The stopping requirement variable describes whether the cyclist is permitted to proceed, or if they are required to stop at the intersection upon arrival. This movement is dictated by a red or green signal display on either the vehicular or bicycle signal head, dependent on which treatment they are approaching.

Table 5.1: Independent Variable Levels and Description

VARIABLE	CATEGORY	LEVEL	LEVEL DESCRIPTION
Type of Conflict	Nominal (categorical)	1	Right turning vehicle is arriving at intersection
		2	Right turning vehicle is waiting at intersection
		3	Left turning vehicle
		4	No conflicting vehicle
Intersection Treatment	Nominal (categorical)	1	Bike Box
		2	Bicycle Signal
		3	Mixing Zone
Stopping Requirement	Discrete	1	Red indication upon arrival
		2	Green indication upon arrival

Figure 5.5: Bike box, mixing zone, bicycle signal treatments (from left to right)

5.2.2.2 Dependent Variables

The dependent measurements recorded in this study were used to assess participant's response to the scenarios and include:

- Lateral position- The horizontal offset between the cyclist's center of gravity and the center of lane.

- Average velocity- The average forward velocity of the cyclist while approaching and traversing the intersections.

- Eye-tracking fixations- The time spent viewing areas of interests (AOI) to define the allocation of visual attention.

The instantaneous positioning and velocity data were recorded using the SimObserver platform throughout the study duration, this data was then segmented to assess each scenario individually.

Participant's eye fixations were collected and analyzed using the ASL Mobile Eye XG and accompanying software, ET Analysis. Researchers were able to assess what AOIs participants tend to focus their visual attention on most frequently when traversing the experimental scenarios.

Table 5.2: Grid and Scenario Design

Int #	Signal Indication	Treatment	Type of Conflict
Grid 1			
1	Green	Bike Box	Waiting
2	Red	Mixing Zone	Waiting
3	Red	Bicycle Signal	Left
4	Green	Mixing Zone	Waiting
5	Green	Bike Box	Left
6	Green	Bicycle Signal	Arriving
Grid 2			
1	Red	Bicycle Signal	Waiting
2	Red	Mixing Zone	Arriving
3	Green	Bike Box	None
4	Green	Mixing Zone	Arriving
5	Green	Bicycle Signal	None
6	Red	Bike Box	Left
Grid 3			
1	Green	Mixing Zone	Left
2	Red	Bike Box	Arriving
3	Red	Bicycle Signal	None
4	Green	Bicycle Signal	Waiting
5	Green	Bike Box	Arriving
6	Red	Mixing Zone	None
Grid 4			
1	Red	Bike Box	None
2	Red	Bicycle Signal	Arriving
3	Green	Mixing Zone	None
4	Red	Bike Box	Waiting
5	Red	Mixing Zone	Left
6	Green	Bicycle Signal	Left

5.2.3 Factorial Design

Due to the 4x3x2 factorial design of independent variables, 24 scenarios were presented to each participant. The scenarios were separated into four different grids, each with six intersections of interest. An additional intersection without any of the experimental variables was placed at the beginning of two of the grids to help mitigate the chance of participants anticipating study motivation (Jashami et al., 2019). All scenarios were counterbalanced to reduce the chance of order effects, e.g., practice or learning, from occurring, and the grids were presented to participants in a randomized order. Participants were given limited instructions to ride as they normally would. Information regarding the factorial, grid, or scenario design was not revealed so as not to influence participants responses. Table 5.2 describes the scenario lists within each grid, while Figure 5.6 provides a visual representation of grid three as an example.

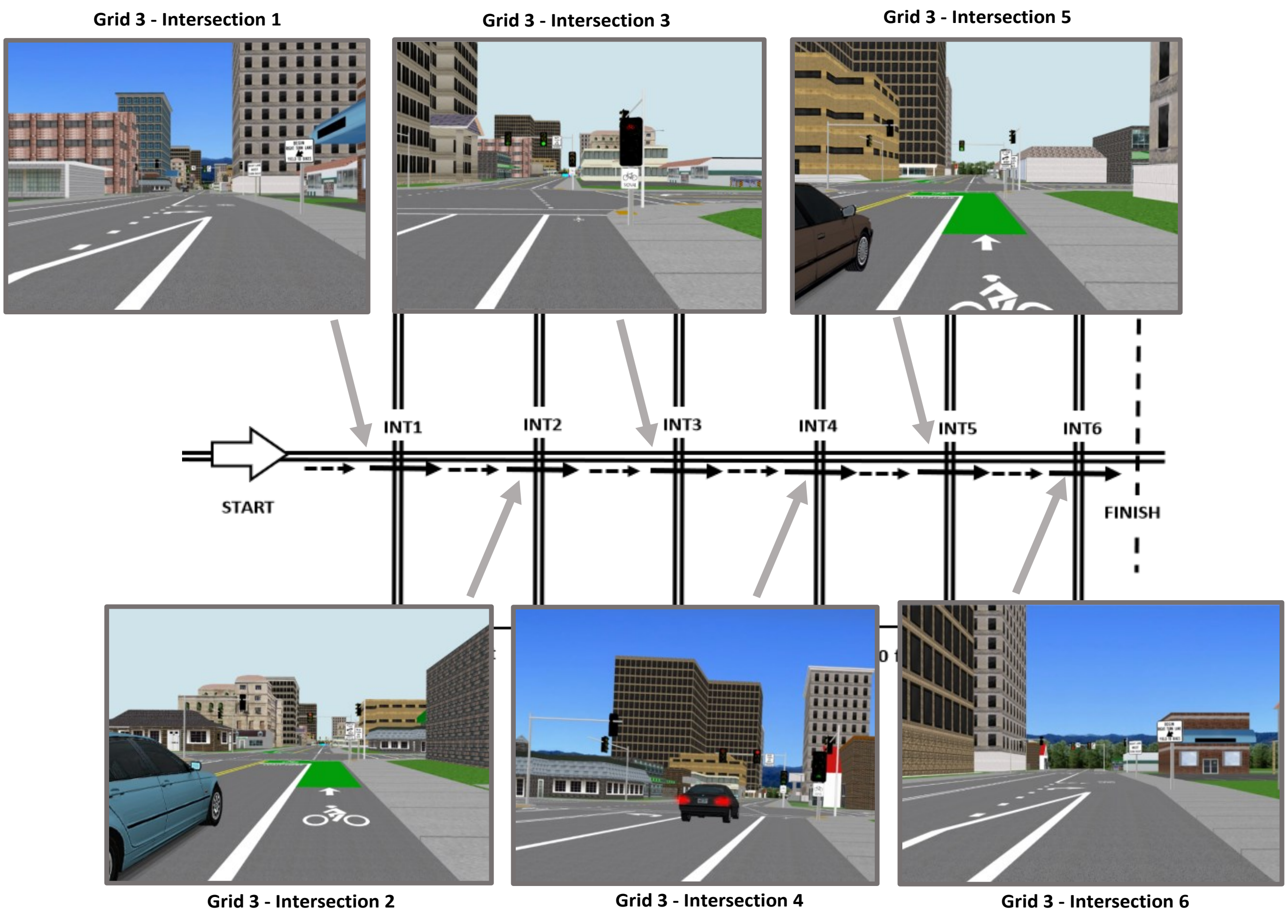


Figure 5.6: Grid three track layout

5.3 EXPERIMENTAL PROTOCOL

The simulator study was designed to mitigate the chances that participants experienced fatigue or simulator sickness while riding the OSU Bicycling Simulator. Short breaks between grids and limited turning maneuvers helped to accomplish this. The following section provides an outline of the steps taken to recruit, collect, and perform testing procedures in the simulator.

5.3.1 Recruitment

A total of 40 individuals were recruited for participation in this study from the area surrounding Corvallis, Oregon. Recruitment of participants was conducted through flyers posted in bike shops and common areas around town, through social media, and from various email listservs. An effort was made to incorporate participants between the ages of 18 to 75 years, with one additional exclusionary criterion being that participants must not require the use of glasses while riding a bicycle. Throughout the entirety of the study, participants were assigned a number to remove identifiable information, and all information was kept under double-lock security in accordance with the OSU Institutional Review Board (IRB) approval (Study Number IRB-2020-0531).

5.3.2 Informed Consent

Interested participants arriving at the laboratory first had to read and acknowledge the IRB-approved consent form. This document outlines the purpose of the study, potential risks and benefits, and the compensation of $20 for participation. To avoid any potential bias effects on participant's responses, they were not provided with the research hypothesis or specific details regarding the experimental design in advance of their participation. COVID-19 related safety protocols were followed during bicycling simulator experiment as outlined in further detail in Section 3.3.

5.3.3 COVID-19 Protocols

The research process required implementation of COVID-19 protocols throughout the study duration in compliance with the OSU Driving and Bicycling Simulator Laboratory's approved Research Resumption Plan. These protocols were implemented to ensure the safety of researchers as well as those participating in the experiment. The precautions taken to minimize the potential spread of COVID-19 included:

- Maintain six feet of physical distance at all times between researcher and participant;
- Adherence to cleaning protocols as described by Environment Health and Safety (EHS);
- Limit the number of persons in the lab to two - one researcher and one participant;
- Researchers were properly trained in the protocols for on-site resumption;
- Two HEPA grade air filtration units operating during data collection;
- Researcher wearing a KN-95 mask and participant wearing at least a surgical face mask;

- No outside travel required.

These protocols were closely followed to ensure participants and researchers felt comfortable being in the simulator laboratory during the study.

5.3.4 Pre-Ride Survey

Participants were asked to answer survey questions in two phases: before conducting the simulated riding portion of the study (pre-ride questionnaire), and after completing the riding portion (post-ride questionnaire). The pre-ride questionnaire gathered demographic information about the participants, such as their riding frequency and previous experience as a cyclist.

5.3.5 Eye-Tracking Calibration

The eye-tracking equipment was adjusted and calibrated prior to any of the riding tasks. While using the ASL software, participants were instructed to look at certain points on the projected scene while researchers calibrated their eye movements. This process is unique to all individuals, and if errors occurred the glasses had to be re-calibrated before proceeding. Participants were asked not to adjust the glasses after this phase as it could affect the calibration. There were no participants in this study who had initial calibration issues. Figure 5.7 shows a photo of an OSU researcher demonstrating the eye-tracking unit.

Figure 5.7: OSU researcher demonstrating the eye-tracking unit

5.3.6 Calibration Ride

Participants were asked to complete a calibration ride before the data collection phase. The calibration ride allowed participants to get acclimated to the simulated environment and riding the bicycle while wearing the eye-tracking equipment. This ride also allows the chance for the researcher to assess if the participant is at risk of experiencing simulator sickness. The calibration grid did not include any treatments or conflicting vehicle movements that were being studied as independent variables in the collection phase to avoid inference of the study motivations. An example of one of the intersections in the calibration ride is shown in Figure 5.8. This example allowed participants to experience traversing an intersection without a stopping requirement.

Figure 5.8: Example intersection from calibration ride

5.3.7 Experimental Ride

The experimental ride followed the calibration grid and is when researchers began collecting eye-tracking and SimObserver data. Participants were instructed to ride as they normally would and were not provided any information about how to maneuver the scenarios of interest. The four grids were presented in a randomized order, between each grid was a brief break to prevent fatigue and assess for simulator sickness. The experimental ride was designed to take approximately 20 minutes to complete, but majority of participants required less time.

5.3.8 Post-Ride Survey

Following their ride, participants were asked to respond to questions related to their experience with the various scenarios presented. These questions were designed to better understand participants perceived level of comfort and understanding about the intersection treatments being studied.

5.4 DATA REDUCTION

The scenarios of interest were coded with markers prior to data collection to make extraction of the eye-tracking and simulator data more accurate and efficient. The following sections describe the process researchers used to reduce this data.

5.4.1 Eye Tracking

The eye movements of participants can be defined by a combination of fixations and saccades, where fixations are the length of time a participant is focused on a single location and saccades are the eye-movements between fixations (Fisher et al., 2011; Greene, 2002). To reduce the data that was collected, researchers used the *ETAnalysis* software to define fixations on AOIs for each participant. AOIs are defined zones where participants may frequently focus their visual attention while traversing the experimental scenarios. An example of some of the experimental AOIs used in this study are shown in Figure 5.9.

Each scenario began 40 meters before the treatment and lasted until the participant cleared the intersection, resulting in approximately 30-60 seconds of clip length per scenario depending on the participants riding speed and whether the stopping requirement variable was present. Researchers manually coded polygons around the AOIs, these polygons were adjusted incrementally to fit the shape of the object and were anchored to the video approximately every 10 frames. Four AOIs were defined for this study:

- Treatment- Pavement markings or bicycle signal heads dependent on type of treatment;
- Vehicular signal- Traffic signal mounted on mast arm for the direction of travel;
- Conflict- Right or left turning vehicle that poses a potential conflict for cyclist and
- Signage- Standard signage for each treatment following MUTCD guidelines.

Figure 5.9 shows a screen-capture depicting the AOI zones during the reduction process for a participant traversing grid four, intersection four. In this scenario, the participant is approaching a bike box treatment with a conflicting vehicle waiting at the intersection prior to their arrival, and a red signal indication was displayed indicating a stopping requirement.

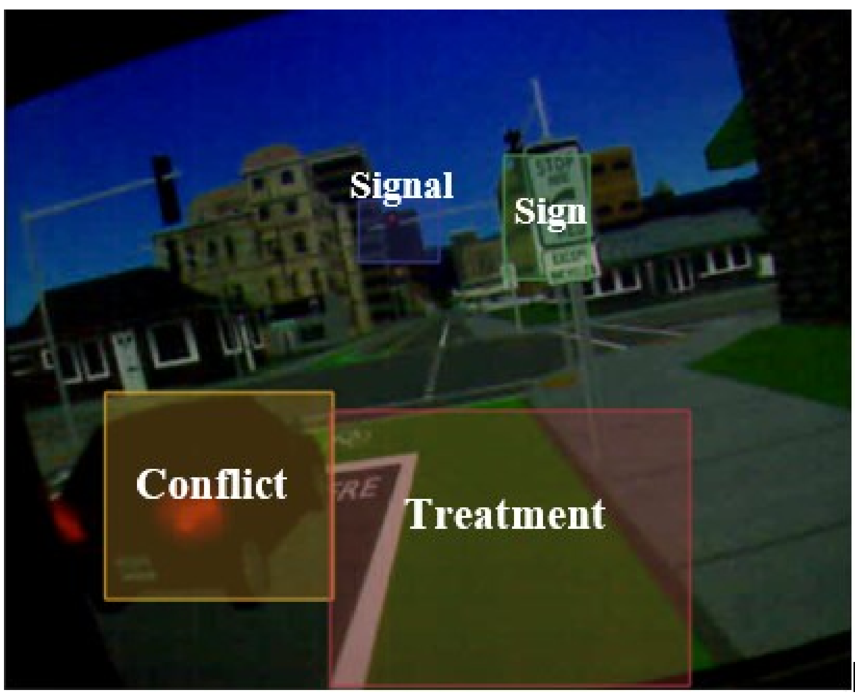


Figure 5.9: AOI example from grid four intersection four

5.4.1.1 Total Fixation Duration (TFD)

The total fixation duration (TFD) of each participant was used to measure the total amount of visual attention (in seconds) allocated within a defined AOI. For each scenario, the TFD was found by summation of fixations across the various AOI's for each participant. After the manual coding of polygon adjustments, the TFD for each AOI was output by the *ETAnalysis* program.

5.4.1.2 Average Fixation Duration (AFD)

The average fixation duration (AFD) is the average dwell time for each AOI. This metric is commonly used to assess unsafe glances off the road, previous research has shown that glances away from the roadway of greater than two seconds doubles the risk of a crash or near crash scenario (Klauer et al., 2006).

5.4.2 Simulator Data

The simulator data was extracted from the SimObserver platform and analyzed using Excel, SPSS, and RStudio version 1.2. The output of this data uses a coordinate system and time-stamps relative to each grid allowing for the reduction of the scenarios of interest within certain coordinates. Researchers were able to extract the instantaneous speed and position across a time-period of interest.

5.5 DATA RESULTS AND ANALYSIS

The experimental design exposed each participant to all combinations of independent variables; Thus, a repeated measures analysis of variance (ANOVA) test was used to assess differences in the dependent measurements. The repeated measures ANOVA is a common test for designs where each participant generates multiple measurements (Fleskes & Hurwitz, 2019). The results for each of the variables of interest are presented in the following section.

5.5.1 Participants

The study consisted of 40 participants from the area surrounding Corvallis, OR. Of these 40 participants, there was 23 women (57.5%) and 17 men (42.5%), none self-identified as non-binary or prefer not to answer. Their age ranged from 19-74 years with an average and standard deviation of 37 and 15.2 years, respectively. There were no participants who experienced simulator sickness, therefore the final sample size for SimObserver data is 40 participants. There was one participant that had technical issues with the eye-tracking acquisition, therefore the final sample size for eye-tracking data is 39 participants.

5.5.2 Survey Results

5.5.2.1 Pre-Ride Survey Results

The pre-ride questions gathered demographic information about the participants. It was found that the sample was well distributed in biking experience and frequency. This is shown in the results of the pre-ride survey questions in Table 5.3.

Table 5.3: Pre-Ride Questionnaire Response

Question	Response Options	# of Participants	% of Participants
How often do you ride a bike per week?	0 times	7	17.5
	1 time	10	25
	2-4 times	9	22.5
	5-10 times	11	27.5
	More than 10	3	7.5
How long do you ride a bike per week?	0-1 hour	18	45
	1-2 hours	7	17.5
	2-3 hours	6	15
	3-4 hours	2	5
	More than 4 hours	7	17.5
What type of riding do you do?	Urban	8	20
	Rural	3	7.5
	Local	22	55
	None	7	17.5

5.5.2.2 Post-Ride Survey Results

The post-ride questions were used to better understand the participants experience with the treatments presented, these questions and the response breakdown are presented in Table 5.4.

An additional free-response question was presented at the end of the survey, which asked participants if any treatment (bike box, mixing zone, or bicycle signal) made them feel uncomfortable while approaching the intersection. The responses show that participants felt the most uncomfortable approaching the mixing zone treatment. Participants were allowed to state if multiple treatments made them feel discomfort, Figure 5.10 provides a graphical representation of the response breakdown that said which treatment they felt uncomfortable approaching.

Table 5.4: Post-Ride Questionnaire Response

Question	Response Options	# of Participants	% of Participants
Were there any roadway treatments you have not seen before? If yes, how many?	0	4	10
	1	16	40
	2	10	25
	3	10	25
How Comfortable did you feel while approaching an intersection with a treatment you have not seen before?	Very Comfortable	4	11.1
	Comfortable	4	11.1
	Neutral	3	8.3
	Uncomfortable	22	61.1
	Very Uncomfortable	3	8.3
	No Response*	4	--
During the experiment, was your bicycle involved in any collisions?	Yes	23	57.5
	No	17	42.5
Whose fault was the collision?	Myself	7	30.4
	Vehicle	15	65.2
	Other	1	4.3
	No Response*	17	--

*Note that certain questions only appeared if participants answered the previous question in a way that allows for further assessment

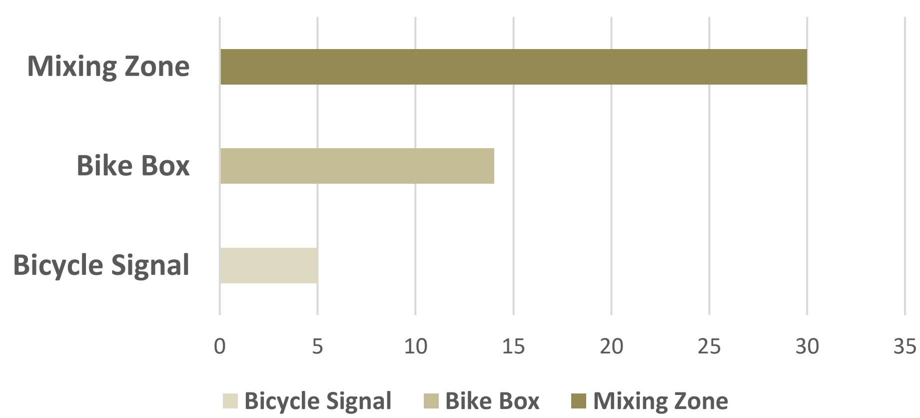


Figure 5.10: Participant count that indicated discomfort by treatment type

5.5.3 Lateral Positioning

The lateral positioning of participants was assessed in accordance with the Society of Automotive Engineers (SAE) standards on driver performance measures. The lateral offset was measured as the distance between the participant's center of gravity and the center of lane in meters. It is common to use this method to assess lateral positioning in a simulator setting (SAE J2944, 2015).

The average lateral offset was calculated for each participant separated across the type of treatment. The mean and standard deviation for each treatment is described in Table 5.5. This data shows that participants tended to deviate furthest from center of lane when traversing the mixing zone treatment when compared to the bike box and bicycle signals. In accordance with SAE standards, a right-handed coordinate system was used and therefore a negative position indicates a center of gravity on the left side of the lane center. On average, participants rode 0.24, 1.02, and 0.17 m (0.8, 3.3, and 0.6 ft) to the left of the center of lane when traversing the bike box, mixing zone, and bicycle signal treatments, respectively.

Table 5.5: Descriptive Statistics for Lateral Offset

Descriptive Statistics	Bike Box	Mixing Zone	Bicycle Signal
µ	-0.24 m	-1.02 m	-0.17 m
(Std. Dev.)	1.02 m	0.20 m	0.13 m

Figure 5.11 through Figure 5.13 show the positioning of participants measured at one-meter intervals across one scenario for each intersection treatment. In this scenario, there was a potential conflicting vehicle waiting at the treatment prior to the participant's arrival, and the signal display was green.

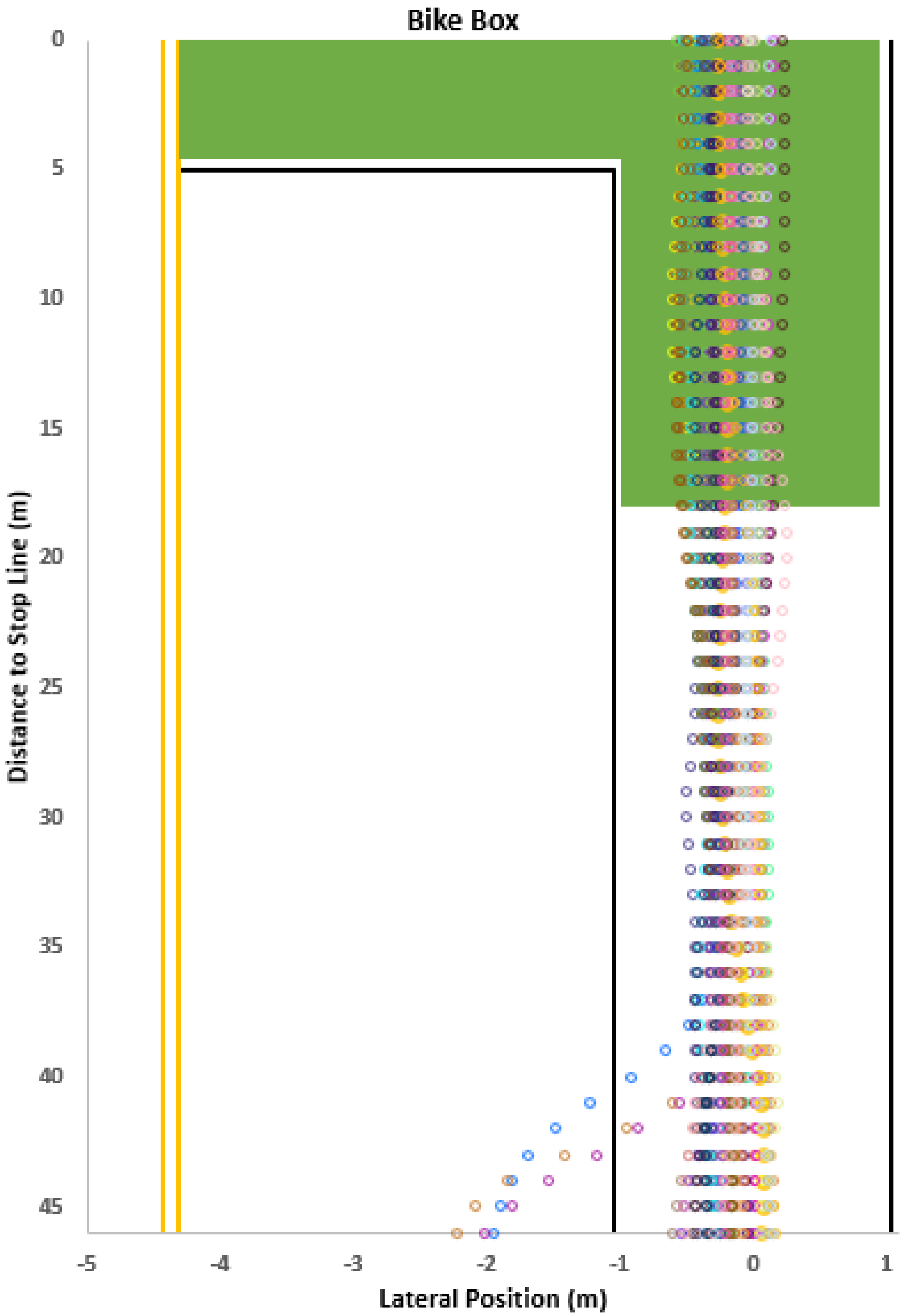


Figure 5.11: Lateral position for bike box treatment

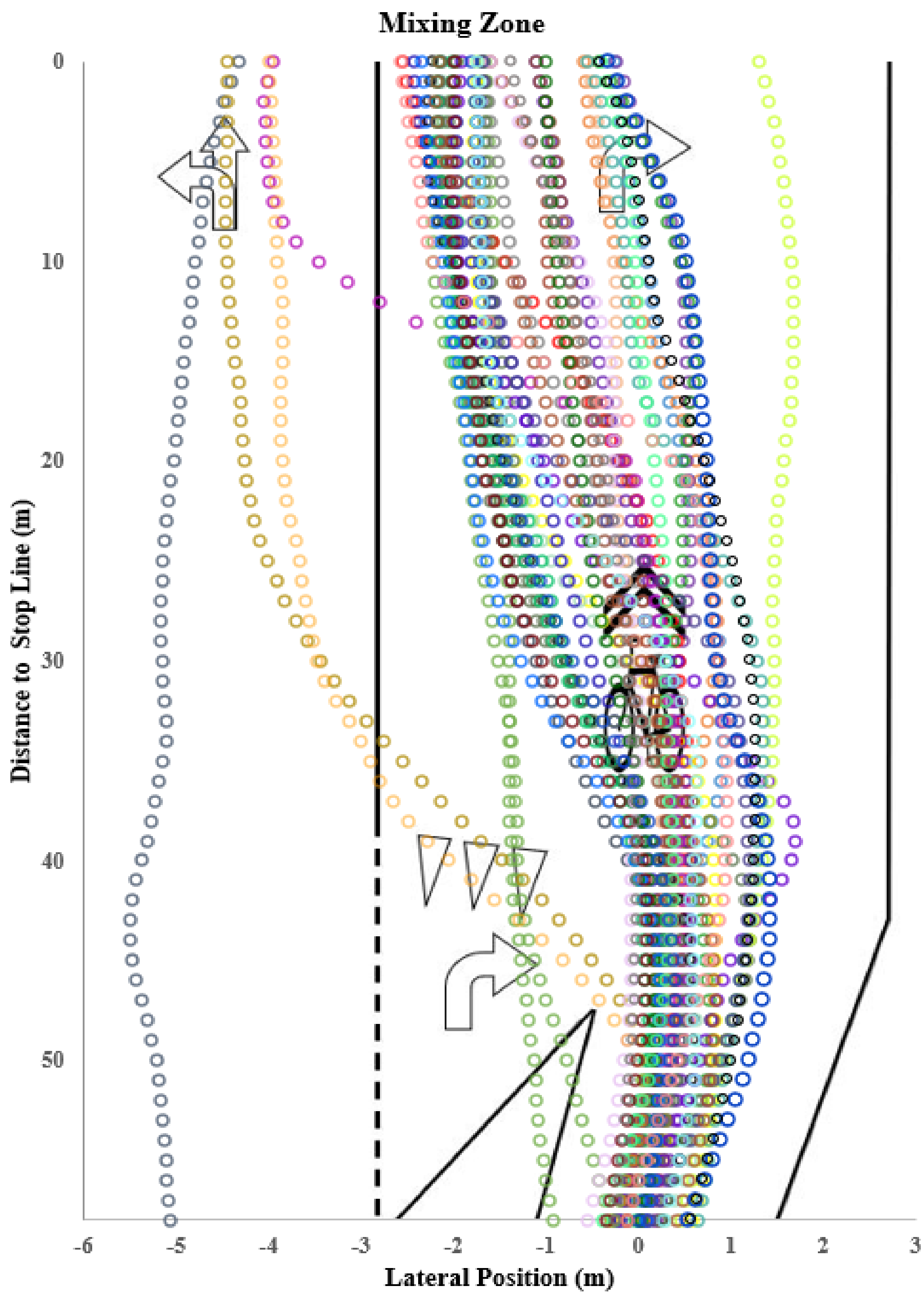


Figure 5.12: Lateral position for mixing zone treatment

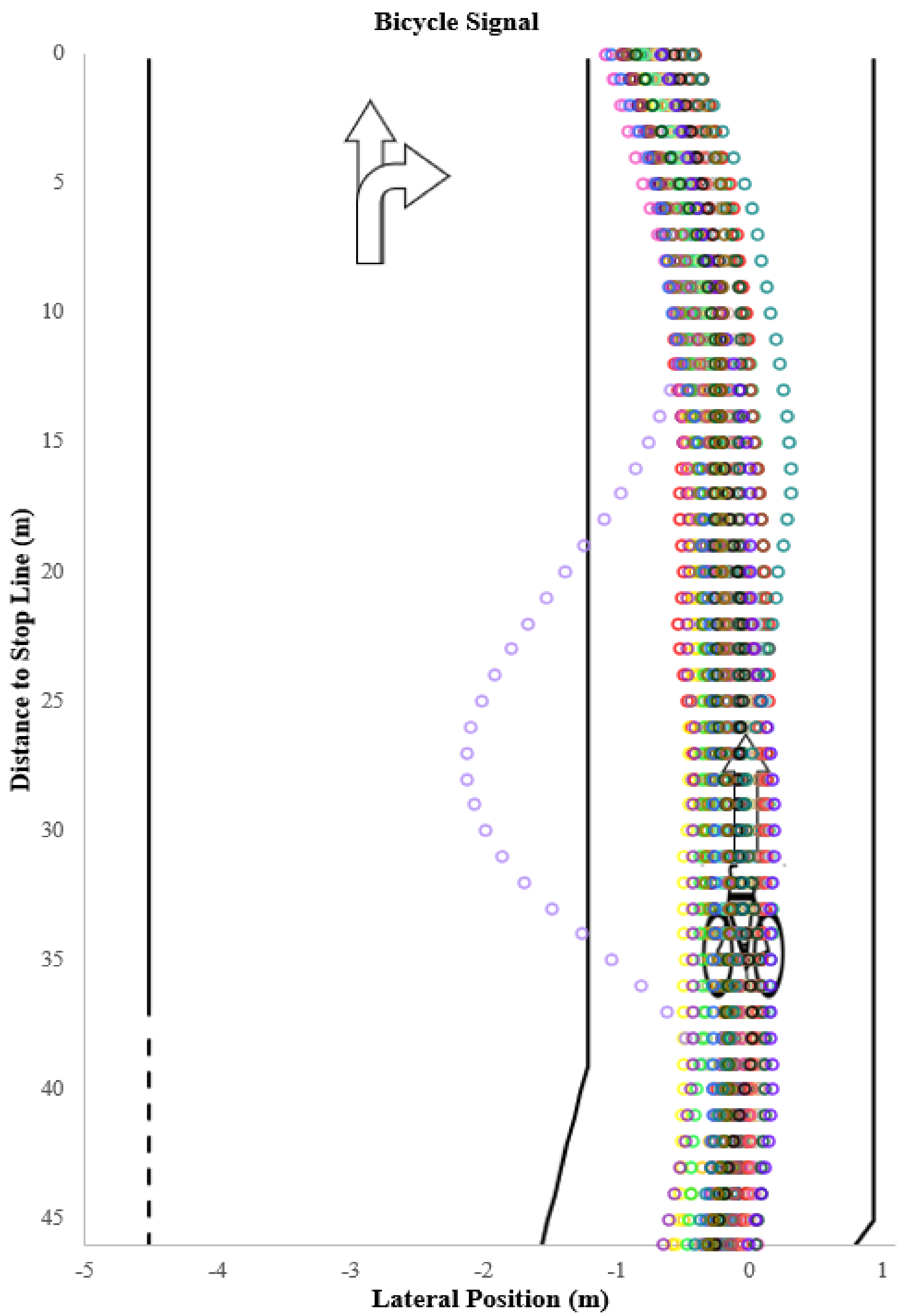


Figure 5.13: Lateral position for bicycle signal treatment

5.5.3.1 Statistical Modeling for Lateral Position

A repeated measures ANOVA was used to analyze the lateral offset data for participants compared across the treatment variable. The lateral offset from center of lane was recorded for each participant starting at 40 m before the intersection stop line, the average of this value was then taken to find the average offset for each participant when traversing the bike box, mixing zone, and bicycle signal treatments. Mauchly's test of sphericity was found to be significant (p-value<0.05) indicating the equal variance assumption may be violated, therefore the Huynh-Feldt adjusted p-value has been reported as it has been found to be more powerful than the other alternatives (Abdi, 2010).

The difference in lateral offset from center of lane was found to be statistically significant across the treatment variable (F-stat=26.825, p-value<0.01). A Bonferroni pairwise comparison test was conducted on the positioning dataset to assess which treatments varied. The results of the Bonferroni test are shown in Table 5.6.

Table 5.6: Pairwise Comparison for Treatment Variable on Lateral Offset

Treatment (i)	Treatment (j)	Estimate	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Bike Box	Mixing Zone	0.782	0.153	<0.01*	0.399	1.166
	Bicycle Signal	-0.067	0.024	0.029*	-0.128	-0.005
Mixing Zone	Bike Box	-0.782	0.153	<0.01*	-1.166	-0.399
	Bicycle Signal	-0.849	0.160	<0.01*	-1.250	-0.448
Bicycle Signal	Bike Box	0.067	0.024	0.029*	0.005	0.128
	Mixing Zone	0.849	0.160	<0.01*	0.448	1.250

*Significant at the 95% Confidence Level

The Bonferroni pairwise comparison test proved the offset from center of lane to be statistically significant between all treatment types. Participants tended to deviate furthest from center of lane when traversing the mixing zone treatment, riding approximately 0.80 m (2.6 ft) further to the left of lane center than when participants traversed the bike box and bicycle signal treatments. When approaching the bike box treatment, participants tended to ride approximately 0.07 m (0.2 ft) further to the left when compared to the bicycle signal approach.

5.5.4 Average Velocity

The average velocity of participants was analyzed to find how the variables affect the average velocity through the scenarios. The descriptive statistics are included in Table 5.7, along with a visual representation of this data in Figure 5.14 and Figure 5.15. This data shows that participants tended to have a higher velocity when traversing a mixing zone treatment and they are not required to stop. When required to stop at the intersection, participant's average velocity tended to vary when looking at the treatment variable in the different scenarios. Table 5.7 also shows that when a left turning conflict is present, the average velocity was lower for each treatment relative to the other conflicting vehicle locations.

Table 5.7: Descriptive Statistics for Average Velocity at Variable Levels

Treatment	Stats	Green Indication				Red Indication			
		Waiting	**Arriving**	**Left**	**None**	**Waiting**	**Arriving**	**Left**	**None**
Bike Box	μ	5.04	5.22	4.66	5.56	2.90	3.04	2.25	2.82
	(SD)	(0.59)	(0.75)	(0.94)	(0.77)	(1.15)	(0.93)	(1.46)	(0.83)
Mixing Zone	μ	5.38	5.48	5.05	5.61	2.77	2.59	1.71	3.37
	(SD)	(0.75)	(0.68)	(1.07)	(0.67)	(0.21)	(0.87)	(0.87)	(1.29)
Bicycle Signal	μ	5.25	4.57	3.86	5.26	3.09	2.58	3.60	3.61
	(SD)	(0.87)	(1.05)	(0.84)	(1.25)	(0.56)	(0.65)	(1.35) (0.61)	

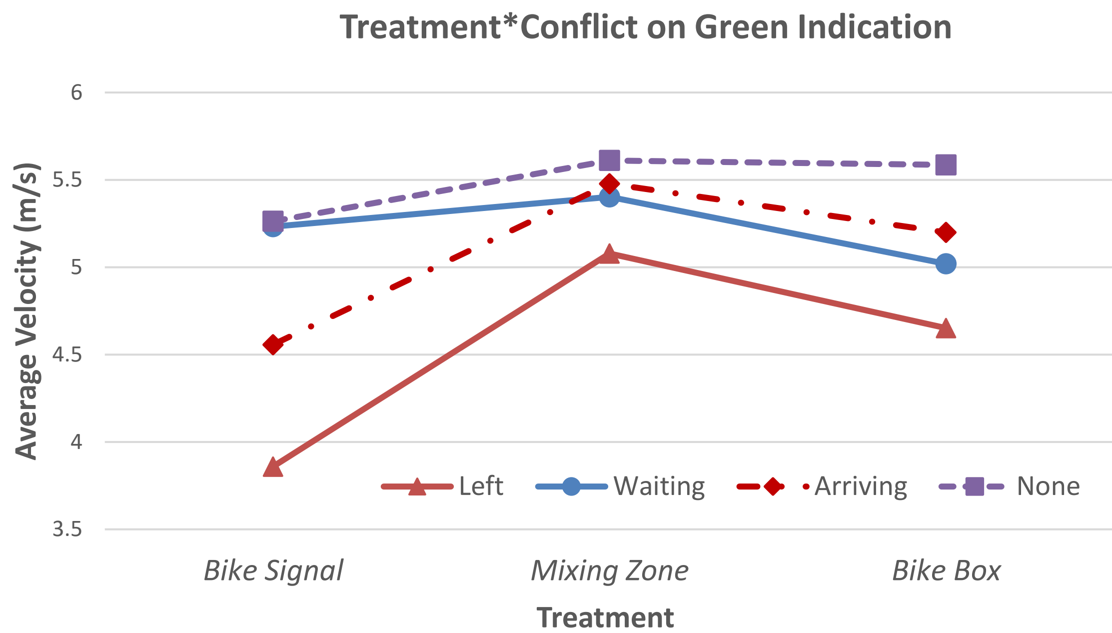


Figure 5.14: Average velocity on green indication

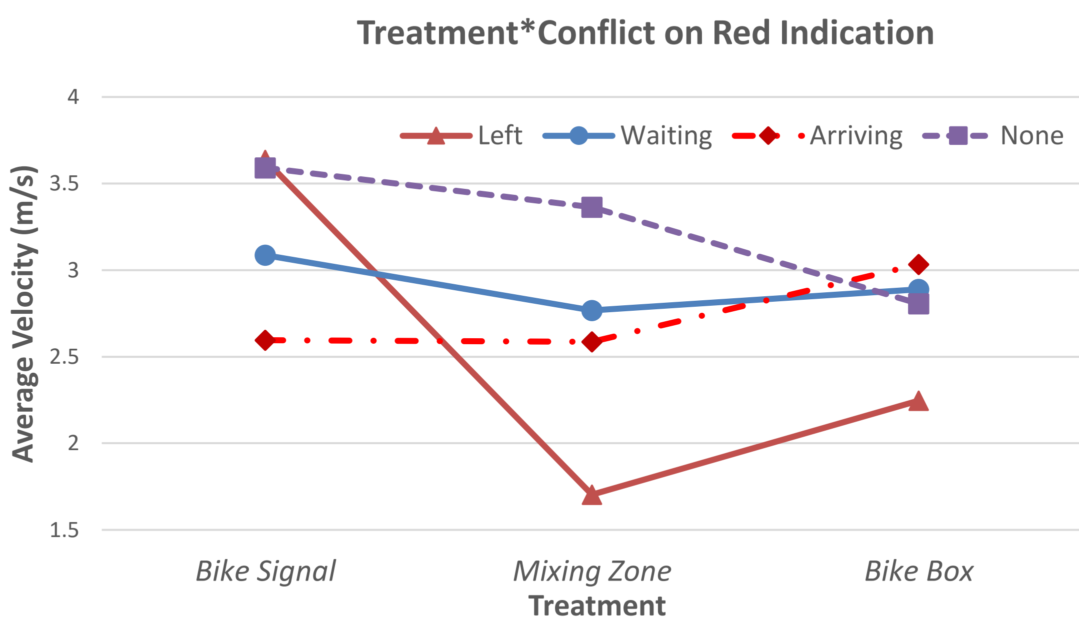


Figure 5.15: Average velocity on red indication

Figure 5.16 shows a boxplot of the average velocity grouped by treatment type applied. In scenarios where there was no stopping requirement, the mixing zone scenarios had the largest average velocity with a median of approximately 5.50 m/s (12.3 mph) while the bicycle signals had a median of approximately 4.75 m/s (10.6 mph). When participants were required to stop at the intersection, the average velocity through the bicycle signal treatment was found to be larger than the other treatments with a median velocity of approximately 3.10 m/s (6.7 mph). Data from the boxplots for bicyclists arriving on a green indication in the field was used to calibrate approach speeds in the micro-simulation model.

The velocity data collected in the simulated environment was compared with the field data to validate the simulator results by assessing for differences in means. This comparison was conducted on each treatment type individually to validate that the speeds in the simulator are representative of what is seen in the built-environment. Boxplots visualizing the comparison of the two datasets are shown in Figure 5.17. Assessments were made just upstream of the stop line and on observations where participants were presented a green indication and there was no conflicting vehicle present. The field data included 30, 73, and 59 observations from the bike box, mixing zone, and bicycle signal sites, respectively. The location of these sites and the treatment that is present at each location include:

- Broadway and Hoyt (Bike Box)
- Multnomah and 16th (Mixing Zone)
- Broadway and Williams (Bicycle Signal)

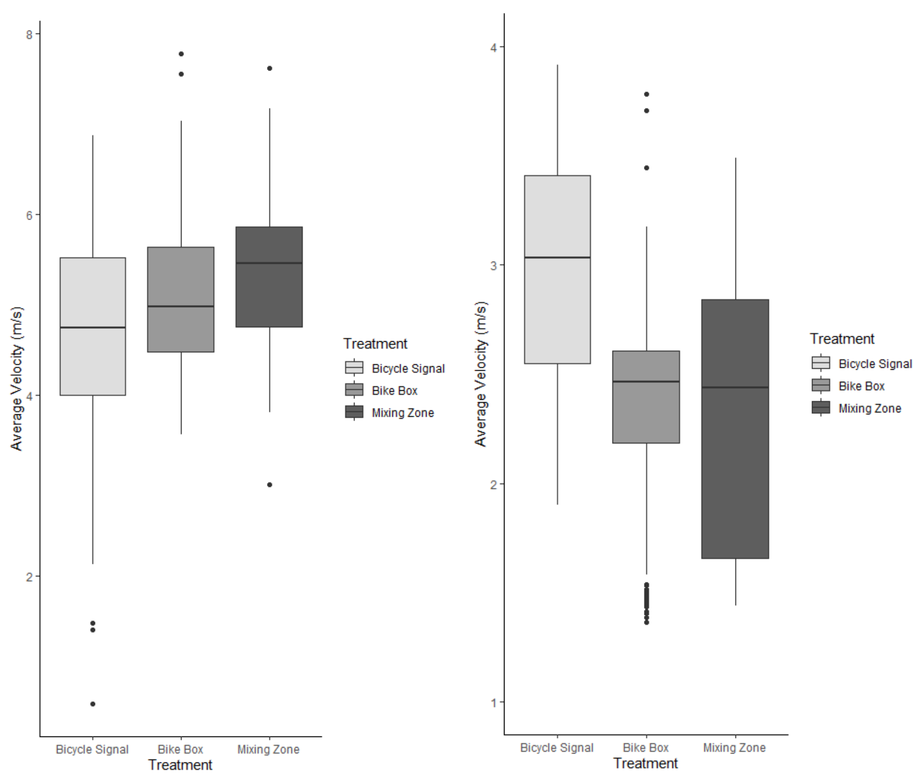


Figure 5.16: Average velocity boxplot in response to a green (left) and red (right) indication

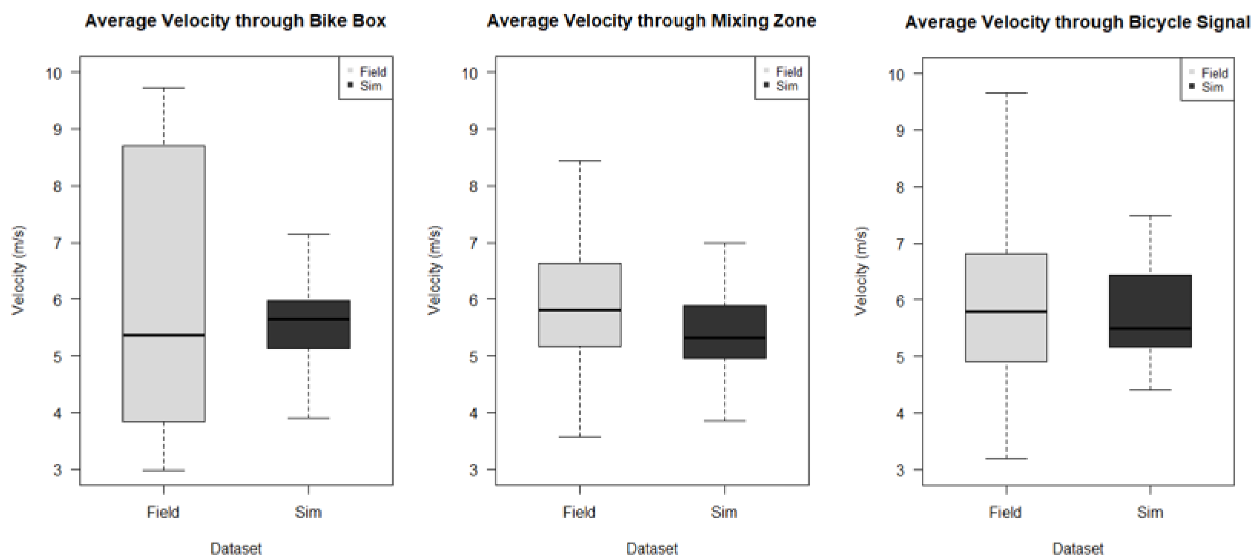


Figure 5.17: Velocity boxplots in field vs. simulator

5.5.4.1 Statistical Modeling for Average Velocity

A repeated measures ANOVA test was conducted on the average velocity through the various scenarios. Because the requirement to stop variable influenced participants velocity responding to a red indication, two separate models were run to account for this forced difference in velocity. The two models assessed how average speed varied when participants approached a green indication, and when participant approached a red indication. The analysis of both models has been separated in the following sections.

Comparison of the velocity measurements from the simulator with the field data was assessed using an independent two-sample t-test and a Wilcoxon Rank Sum test. These tests were performed to better understand if speeds in the simulator are representative of those observed in the built-environment by testing for statistically significant differences in means. Table 5.8 shows that the independent two-sample t-test found no statistically significant difference in means when assessing scenarios with a bicycle signal (p-value=0.774), indicating that the average speed in the simulator is representative of what was gathered from the field for this treatment. As seen in Figure 5.17, the variances were not equal across the bike box datasets, while visual inspection of the mixing zone data revealed a non-normal distribution. Meeting these two assumptions are required to proceed with the two-sample t-test, and therefore a Wilcoxon Rank Sum test was used to analyze the bike box and mixing zone treatments. The results are described in Table 5.8. A statistically insignificant result was discovered for the bike box (p-value=0.685), while a statistically significant result was found to be associated with the mixing zone (p-value=0.049).

These findings indicate that what was gathered in the simulator is representative of what was seen in the built-environment. Although the mixing zone showed statistical significance, the confidence interval described in Table 5.8 indicates that the actual difference in means is between 0.00 and 0.78 m/s, a difference with little practical significance in this context.

Table 5.8: Results for Simulator Validation

Treatment Type	t-stat	*W*	*P*	95% Confidence Interval	
				Lower Bound	Upper Bound
Bike Box	--	551	0.685	-1.15	1.22
Mixing Zone	--	1724	0.049*	0.00	0.78
Bicycle Signal	-0.288	--	0.774	-0.58	0.43

*Significant at the 95% Confidence Level

Arriving on Green Indication

Mauchly's test of sphericity was found to be statistically significant in the model where participants were not required to stop. Therefore, the Huynh-Feldt corrected p-values are shown in Table 5.9 for the different independent variables. A Bonferroni pairwise comparison test was conducted to assess which variables were found to differ.

Table 5.9: ANOVA Results for Average Velocity in Response to a Green Indication

Within-Subjects Factors	$F\ (v_1, v_2)$	*P*	η_{p2}
Treatment Type	27.075 (2, 38)	<0.01*	0.416
Conflict Arrival Position	80.710 (3, 38)	<0.01*	0.680
Treatment x Conflict	7.867 (6, 33)	<0.01*	0.172

*Significant at the 95% Confidence Level

The Bonferroni pairwise comparison test revealed that there was a statistically significant effect from treatment type on the average velocity through the scenarios (Table 5.10). It was shown that when traversing the mixing zone treatment, participants tended to have an average velocity of 0.25 and 0.65 m/s (0.6 and 1.4 mph) faster than the bike box and bicycle signal treatments, respectively. The bicycle signal scenario had the lowest average velocity when compared to the other treatments by about 0.50 m/s (1.1 mph) on average.

The position of the conflicting vehicle was found to have a statistically significant difference across all levels except for one comparison (Table 5.11). No statistically significant difference was found in average velocity when the conflicting vehicle was waiting at the intersection compared to when a conflicting vehicle was arriving at the intersection (p-value=0.182). When a left-turning conflict was present, the average velocity was found to greatly reduce when compared to all other types of conflicts.

Table 5.10: Average Velocity Comparison by Treatment in Response to a Green Indication

Treatment (i)	Treatment (j)	Estimate	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Bike Box	Mixing Zone	-0.253	0.053	<0.01*	-0.384	-0.121
	Bicycle Signal	0.392	0.096	<0.01*	0.152	0.633
Mixing Zone	Bike Box	0.253	0.053	<0.01*	0.121	0.384
	Bicycle Signal	0.645	0.107	<0.01*	0.377	0.913
Bicycle Signal	Bike Box	-0.392	0.096	<0.01*	-0.633	-0.152
	Mixing Zone	-0.645	0.107	<0.01*	-0.913	-0.377

*Significant at the 95% Confidence Level

Table 5.11: Average Velocity Comparison by Conflict Type in Response to a Green Indication

Conflict (i)	Conflict (j)	Estimate	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Waiting	Arriving	0.133	0.059	0.182	-0.031	0.297
	Left	0.700	0.074	<0.01*	0.495	0.906
	None	-0.264	0.063	<0.01*	-0.439	-0.088
Arriving	Waiting	-0.133	0.059	0.182	-0.297	0.031
	Left	0.568	0.060	<0.01*	0.400	0.735
	None	-0.396	0.065	<0.01*	-0.576	-0.216
Left	Waiting	-0.7800	0.074	<0.01*	-0.906	-0.495
	Arriving	-0.568	0.060	<0.01*	-0.735	-0.400
	None	-0.964	0.063	<0.01*	-1.138	-0.790
None	Waiting	0.264	0.063	<0.01*	0.088	0.439
	Arriving	0.396	0.065	<0.01*	0.216	0.576
	Left	0.964	0.063	<0.01*	0.790	1.138

*Significant at the 95% Confidence Level

5.5.4.2 Arriving on Red Indication

The second model for average velocity was constructed for scenarios when participants were required to stop at the intersection. This stopping was influenced by a red signal indication upon arrival and was found to cause the average velocity to decrease, as shown in Table 5.7. Mauchly's test of sphericity was found to be statistically significant in this model, and a Huynh-Feldt corrected p-value was therefore used to account for this. The corresponding F-statistic and p-values are shown in Table 5.12.

Table 5.12: ANOVA Results for Average Velocity in Response to a Red Indication

Within-Subjects Factors	$F\ (v_1, v_2)$	P	η_{p2}
Treatment Type	17.809 (2, 38)	<0.01*	0.319
Conflict Arrival Position	22.886 (3, 38)	<0.01*	0.376
Treatment x Conflict	17.158 (6, 33)	<0.01*	0.311

*Significant at the 95% Confidence Level

A Bonferroni pairwise comparison test was conducted on the red signal indication model to assess which variables differed in average velocity. The results for the treatment and conflicting vehicle variables are shown in Table 5.13 and Table 5.14. When the red signal indication was displayed, no statistically significant difference in velocity between the bike box and mixing zone treatments was found (p-value=0.760). The average velocity through the bicycle signal treatment was found to be higher, with statistical significance, when compared with the other two treatments (p-value<0.01). Participants that traversed the bicycle signal treatment were found to ride 0.47 and 0.61 m/s (1.1 and 1.4 mph) faster on average than when traversing the bike box and mixing zone treatments, respectively.

The position of the conflicting vehicle was found to have a statistically significant effect on the average velocity. Similar to the model conducted on a green indication, there was no statistically significant difference in average velocity when the conflicting vehicle was waiting compared to a vehicle arriving at the intersection (Table 5.14). In this model, there was also no statistically significant difference when comparing an arriving vehicle and a left turning vehicle. Participants were found to ride with a higher velocity when traversing the scenarios where no conflicting vehicle was present, riding approximately 0.5 m/s (1.1 mph) faster on average.

Table 5.13: Average Velocity Comparison by Treatment in Response to a Red Indication

Treatment (i)	Treatment (j)	Estimate	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Bike Box	Mixing Zone	0.142	0.122	0.760	-0.164	0.448
	Bicycle Signal	-0.468	0.123	<0.01*	-0.777	-0.159
Mixing Zone	Bike Box	-0.142	0.122	0.760	-0.448	0.164
	Bicycle Signal	-0.610	0.064	<0.01*	-0.771	-0.449
Bicycle Signal	Bike Box	0.468	0.123	<0.01*	0.159	0.777
	Mixing Zone	0.610	0.064	<0.01*	0.449	0.771

*Significant at the 95% Confidence Level

Table 5.14: Average Velocity Comparison by Conflict Type in Response to a Red Indication

Conflict (i)	Conflict (j)	Estimate	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Waiting	Arriving	0.183	0.079	0.152	-0.036	0.402
	Left	0.400	0.106	<0.01*	0.104	0.696
	None	-0.348	0.074	<0.01*	-0.553	-0.144
Arriving	Waiting	-0.183	0.079	0.152	-0.402	0.036
	Left	0.217	0.099	0.211	-0.060	0.494
	None	-0.531	0.083	<0.01*	-0.762	-0.301
Left	Waiting	-0.400	0.106	<0.01*	-0.696	-0.104
	Arriving	-0.217	0.099	0.211	-0.494	0.060
	None	-0.748	0.114	<0.01*	-1.065	-0.431
None	Waiting	0.348	0.074	<0.01*	0.144	0.553
	Arriving	0.531	0.083	<0.01*	0.301	0.762
	Left	0.748	0.114	<0.01*	0.431	1.065

*Significant at the 95% Confidence Level

5.5.5 Visual Attention

ASL Mobile Eye XG was used to collect and reduce the visual attention data of the 40 participants. Due to technical issues data from one participant was unusable. Therefore, 39 is the sample size for usable eye-tracking data. This section describes where participants focused their visual attention when traversing the different intersection scenarios.

5.5.5.1 Conflict AOI

The TFD on the conflicting vehicle AOI was assessed to better understand if the independent variables influence the time allocated to viewing the conflict. Previous research has shown that one potential cause of right/left-hook crashes is that the cyclist was not able to recognize the danger until it was too late (Rasanen & Summala, 1998). Visual attention data was studied to assess if the independent variables had an impact on the participants ability to recognize the conflict.

The descriptive statistics shown in Table 5.15 describe the TFD in seconds viewing the conflict AOI. From this table, participants tended to focus more visual attention on the conflicting vehicle when traversing the mixing zone treatment as compared to the bike box and bicycle signals. It is also shown that when a vehicle was arriving at the intersection (as opposed to waiting or turning left) participants had a lower fixation time on the conflicting vehicle than the other scenarios.

Table 5.15: Total Fixation Duration on Conflict AOI

Treatment	Stats	Green Indication			Red Indication		
		Waiting	Arriving	Left	Waiting	Arriving	Left
Bike Box	μ	1.34	0.37	1.52	2.10	0.75	5.49
	(SD)	(1.07)	(0.36)	(1.48)	(2.35)	(0.82)	(5.48)
Mixing Zone	μ	1.84	1.05	2.41	5.14	4.57	7.99
	(SD)	(1.27)	(0.78)	(1.70)	(3.15)	(3.14)	(4.36)
Bicycle Signal	μ	0.94	0.48	1.70	1.26	0.83	0.52
	(SD)	(1.12)	(0.70)	(2.10)	(2.44)	(0.62) (0.88)	

5.5.5.2 Statistical Model for Conflict AOI

A repeated measures ANOVA was conducted to test for differences in the TFD on the conflicting vehicle across the variables of interest. Mauchly's test of sphericity was found to be statistically insignificant, and the sphericity assumed p-values are therefore reported in Table 5.16. This table shows that all variables were found to be statistically significant, and a Bonferroni pairwise comparison test was conducted to assess which variables differed.

The Bonferroni comparison test revealed that all treatments varied in TFD on the conflicting vehicle, and that the bicycle signal resulted in the least amount of visual allocation on the conflict. When traversing the bicycle signal treatment participants viewed the conflict approximately one second less than the bike box scenario (p-value<0.01), and nearly three seconds less when compared to the mixing zone scenario. The mixing zone resulted in the largest amount of visual attention on the vehicle, resulting in nearly two seconds more than the bike box scenario. This data can be found in Table 5.17.

Table 5.16: Repeated Measures ANOVA for TFD on Conflict AOI

Within-Subjects Factors	*F* (v_1, v_2)	*P*	η_{p2}
Treatment Type	59.603	<0.01*	0.739
Conflict Arrival Position	23.460	<0.01*	0.528
Signal Indication	42.461	<0.01*	0.669
Treatment x Conflict	5.807	<0.01*	0.217
Treatment x Indication	40.296	<0.01*	0.657
Conflict x Indication	5.719	<0.011	0.214
Treatment x Conflict x Indication	4.857	<0.01*	0.188

*Significant at the 95% Confidence Level

Table 5.17: TFD on Conflict AOI by Treatment Variable

Treatment (i)	Treatment (j)	Estimate	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Bike Box	Mixing Zone	-1.906	0.300	<0.01*	-2.686	-1.126
	Bicycle Signal	0.976	0.210	<0.01*	0.430	1.522
Mixing Zone	Bike Box	1.906	0.300	<0.01*	1.126	2.686
	Bicycle Signal	2.882	0.287	<0.01*	2.135	3.628
Bicycle Signal	Bike Box	-0.976	0.210	<0.01*	-1.522	-0.430
	Mixing Zone	-2.882	0.287	<0.01*	-3.628	-2.135

*Significant at the 95% Confidence Level

5.5.5.3 AFD on Roadside Objects

A repeated measures ANOVA test was conducted on the AOIs that were located on the side of the road. This test was conducted on the signage AOI in the bike box and mixing zone scenarios and was compared with the bicycle signal AOIs. Because these were located on the side of the road, AFD was used to assess if one treatment caused longer glance durations away from the roadway.

Log-transformed values were used in the repeated measures ANOVA test as they better fit the required assumptions of normality and homogeneity of variances necessary for this testing method. The difference in AFD on roadside objects was found to be statistically significant (p-value<0.01), and a Bonferroni pairwise comparison test was conducted to assess which treatment contributed to longer glances away from the road. These results are shown in Table 5.18.

Table 5.18: AFD for Roadside Glances by Treatment Variable

Treatment (i)	Treatment (j)	Estimate	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Bike Box	Mixing Zone	0.044	0.019	0.063	-0.002	0.090
	Bicycle Signal	-0.012	0.018	1.00	-0.056	0.032
Mixing Zone	Bike Box	-0.044	0.019	0.063	-0.090	0.002
	Bicycle Signal	-0.056	0.018	<0.01*	-0.100	-0.012
Bicycle Signal	Bike Box	0.012	0.018	1.00	-0.032	0.056
	Mixing Zone	0.056	0.018	<0.01*	0.012	0.100

*Significant at the 95% Confidence Level

Table 5.18 shows that there was only one statistically significant difference in the AFD on roadside objects across all treatments. The bicycle signal scenarios caused roadside glances of approximately 1.1 times the median of the mixing zone scenario glances. Aside from this comparison, models that compared other treatments did not prove to be statistically significantly in AFD glances away from the roadway for the other treatments.

5.6 SUMMARY AND DISCUSSION

The simulator portion of this study was conducted using the OSU Bicycling Simulator to assess participant responses to the scenarios presented. Researchers evaluated the effect of three independent variables: treatment applied, position of conflicting vehicle, and stopping requirement on the dependent measurements of lateral positioning, velocity, and visual attention. The dependent measurements are discussed throughout this section to justify the three objectives of the simulator study, these objectives are:

- Assessment of which treatment promoted the safest riding habits from the participants;
- Understanding the positive and negative effects on riding behavior for each treatment;
- Recommendations for the most effective treatment type.

Throughout this section, the average velocity is assessed for each treatment type. Past research has revealed that large speed differentials between bicyclists and vehicles are what create the most dangerous crash scenarios (Klop & Khattak, 1999). Due to the limitation that conflicting vehicles were coded by researchers (and therefore maintained constant speeds), we cannot make accurate observations about velocity differentials between the surrounding vehicles and participants. For this reason, average velocity has been assessed in relation to the response we would expect from real-world vehicles.

5.6.1 Bicycle Signal

As indicated in Figure 5.10, participants felt most comfortable when traversing the intersections with a bicycle signal as compared to those without. It is assumed that this is because participants were provided their own protected phase and thus, were not required to yield the right-of-way. Although participants preferred this treatment over the others, it is important to note the expectations that drivers will yield as required by Oregon statute is one common cause of right/left hook crashes (Jannat et al., 2018; Rasanen & Summala, 1998). This idea is further emphasized in the visual attention results presented in section 5.5.5. It was found that participants traversing intersections with bicycle signal treatments tended to allocate less visual attention towards the conflicting vehicle, as well as longer glances away from the roadway; both of which might increase crash risk with errant conflicting vehicles.

The average velocities through the bicycle signal scenarios were found to be faster when compared to the bike box and mixing zone treatments when the traffic indication required the bicyclist to stop. With this higher velocity, we expect a smaller speed differential between the vehicle and participant, resulting in a safer situation for the bicyclist. As mentioned initially in section 5.5.4, this is an assumption that would require additional experimentation to further understand authentic driver responses to these scenarios.

5.6.2 Mixing Zone

Participants indicated the mixing zone treatment to cause the most discomfort. Despite this aspect, safe riding behaviors were observed when assessing the eye-tracking results. The visual attention data of participants indicated that they spent more time looking at the conflict vehicle as documented in section 5.5.5.1. The eye-tracking results also revealed that participants had shorter glances away from the roadway in comparison to the other treatments. We suspect this is because participants felt the most discomfort in these scenarios and were more focused on potential conflicts.

As described in section 5.5.4, the average velocity of participants through the mixing zone treatment was the slowest when the indication displayed required the participant to stop. Because of this reduced velocity, we recommend that this treatment be implemented on slower speed approaches to maximize bicyclist safety. This will help to reduce the speed differential between vehicles and bicyclists traversing this treatment type. This recommendation is consistent with research conducted in Australia in 2019, which found that vehicle speeds should be restricted to less than 30 km/h (18.6 mph) if bicyclists are required to claim the lane (Meuleners et al., 2019). In situations where this speed reduction is not possible, other treatments may prove to be more suitable.

The lateral position of participants is where the mixing zone was found to differ most significantly from the other two treatments. As Figure 5.11 through Figure 5.13 show, the movement of the participants was more unpredictable when traversing the mixing zone scenarios. This was expected as the participants were not provided any information about how to ride, and the lack of bike lane forced them to maneuver into a different lane. These unpredictable movements can lead to higher potential crash risk, as past research found that uncertainty regarding the presence of the other party elicits more dangerous situations (Houtenbos, 2008).

5.6.3 Bike Box

The dependent measurements with the bike box treatment were consistently found to be a common middle-ground between the mixing zone and bicycle signal scenarios. The survey responses, positioning, speed, and eye-tracking data found the bike box to lie between the other treatment types in the statistical analysis. The TFD spent viewing the conflict vehicle AOI in the bike box scenarios was found to be almost exactly halfway between the difference between the mixing zone and bicycle signal.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 SYNTHESIS OF RESULTS

This study assessed the safety impact and performance of 3 different bicycle-specific intersection treatments (bike boxes, mixing zones, and bicycle signals) using surrogate safety measures (i.e., bicycle-vehicle conflicts and other measures). To date, limited research had been conducted to analyze how these treatments along with traffic characteristics (e.g., bicycle, pedestrian, and vehicle volumes) impact the frequency and severity bicycle-vehicle conflicts, and research was needed to provide practitioners guidance on when and where to install these treatments. As such, the primary objectives of this study were:

- Determine which factors affect the frequency or severity of bicycle vehicle-conflicts at intersection approaches with different bicycle-related treatments: bike boxes, mixing zones, and bike signals.

- Provide data-driven guidance as to the efficacy of certain intersection treatments in mitigating vehicle-bicycle conflicts (thereby improving bicyclist safety by this surrogate measure), including consideration of how traffic and site characteristics impact these conflicts.

- Develop guidance to practitioners to assist in countermeasure selection which describes the performance of bicycle-specific intersection treatments (bike boxes, mixing zones, and bike signals) under different conditions. This includes providing advantages/disadvantages of different treatments, and descriptions of conditions under which each treatment should/could be considered, as well as relative time frames and cost for implementation for each treatment.

To achieve these objectives, data were collected from 3 different sources and separate analyses were conducted on each. The sources of data for this study are:

- Video was recorded for 12 hours (7am-7pm) for one day at 12 intersection approaches in Oregon (3 with bike boxes, 3 with mixing zones, 3 with bicycle signals, and 3 control sites with no specific bicycle-focused treatment aside from bike lanes). From these videos, road user volumes, bicycle-vehicle conflicts (identified and measured using PET), and conflict-involved road user speeds were extracted.

- Microsimulation models were created and calibrated based on each of the 12 study intersection approaches, and using SSAM, bicycle-vehicle conflict frequencies were extracted with the goal to perform sensitivity analyses across different volume ranges.

- A bicycling simulator experiment was conducted with 40 participants wherein the participants rode through all 3 study treatments under varying scenarios.

The following subsections provide a summary of the primary findings and conclusions for the analyses of data from all 3 sources.

6.1.1 Summary of Field Data Analysis Findings and Conclusions

At the 12 study intersection approaches, road user volume and conflict data were summarized by hour and speeds of conflict-involved road users were also collected. These data were used to analyze bicycle-vehicle conflict frequency in several ways. It should be noted that at bicycle signal locations, there were zero conflicts observed between bicyclists and vehicles who properly used bicycle signals given the time-separated movement of bicyclists and vehicles at these locations.

For bike box, mixing zone, and control site locations, the hourly volumes of through bicyclists and right turning vehicles were used to estimate a series of Poisson regression models to assess the association between volumes and conflict frequency (with PET ≤ 1.5 sec), and how this association varied across site types. Through estimation of a series of Poisson regression models, hourly conflict frequency was predicted across a range of hourly turning vehicle and through bicycle volumes, and the following conclusions were made:

- Under conditions with 75 or less turning vph and 25 or less bikes per hour, the predicted conflict frequency was similar for all three site types (bike boxes, mixing zones, and control sites). This indicates bike boxes and mixing zones may not provide a significant benefit (in terms of conflict frequency reduction) compared with control sites under these conditions.

- Under conditions with more than 25 through bikes per hour, the predicted conflict frequency at control sites were higher than those at bike boxes or mixing zones, with the notable exception being that predicted conflicts were higher at mixing zones when turning vehicle volumes were greater than 100 vehicles per hour. This finding indicated that both bike boxes and mixing zones provide a safety benefit compared to control sites when through bike volumes are greater than 25 per hour, but the bike box may be a better option if turning vehicle volumes are greater than 100 per hour (though a bicycle signal could be considered when turning volumes are greater than 150 vph).

The potential impact of right-side parallel crossing pedestrian volume on conflict frequency was also assessed through inclusion in the Poisson regression models, and it was found that increased pedestrian volumes were significantly associated with increased conflict frequency at control sites, but not at bike box or mixing zone sites. This indicates pedestrian volume should be considered in determining whether to apply a specific treatment.

In addition to conflict frequency, conflict severity was also analyzed in several different ways. First, conflicts were categorized into three severity categories based on PET, with the most severe category being PET ≤ 1.5 sec. While summary statistics showed mixing zones exhibited the highest percentage of high severity conflicts (50.0%), estimation of ordered and binary logistic models found no statistically significant association between treatment type and this severity measure.

Vehicle speeds during conflicts and unit arrival order (i.e., bike first or vehicle first) were also analyzed by site type. While no statistically significant association was found, conflicts occurring at mixing zones had a much higher vehicle speed (15.1 mph compared to 8.5 mph and 6.9 mph at control sites and bike box sites, respectively), and were more likely have the bicyclist arrive first to the conflict point. Additionally, with respect to bike box locations specifically, of bicyclists who arrived on red and had to stop in the bike box, none stopped in the 'box' area immediately in front of the lead vehicle. Only data for bicyclists involved in conflicts were collected for this study, so it is unknown how many non-conflict-involved bicyclists stopped in this area, but it's possible that this positioning may help prevent bicycle-vehicle conflicts.

Additionally, a novel method to categorize conflict severity was developed considering both PET and vehicle speed. Six severity categories were defined with the most severe being 'low PET-high vehicle speed' and least severe being 'high PET-low vehicle speed'. It was found that bike box locations exhibited the lowest percentage of conflicts in the most severe category (15.3% compared to 27.5% and 40.0% at control sites and mixing zone sites, respectively), though there were not statistically significant associations between this severity measurement and treatment type.

Overall, based on analysis of the field-collected data, it appears that both bike boxes and mixing zones have the potential to provide safety benefits compared to the control sites, but bike boxes generally seem to provide the largest safety benefit in terms of bicycle-vehicle conflict frequency and severity. While this study assessed safety impacts in terms of conflict frequency and severity, it should be noted that user comfort should also be considered when making treatment selection. The conclusions from this analysis of the field-collected data are used in part to provide recommendations for practice presented in section 6.2.

6.1.2 Summary of Microsimulation Modeling Findings and Conclusions

With the goal of performing sensitivity analyses on conflict frequency by both increasing and decreasing road user volumes (+/- 5%, 10% and 15% volumes), calibrated microsimulation models matching each of the 12 field study sites were developed using Vissim and conflicts were extracted from these models using SSAM. Extensive efforts were undertaken to adjust behavioral parameters and conflict area designs in the models to match conflict frequencies collected from the microsimulation models to those observed in the field.

While the bike signal locations yielded zero conflicts as expected, the models for bike box and control site locations yielded excessively low numbers of conflicts across all volume ranges and meaningful conclusions could not be made based on the model results. The baseline models for mixing zone sites did yield conflict frequencies that were relatively close to those observed in the field. With this observation, it is speculated that the use of microsimulation modeling/SSAM to identify conflicts may be sensitive to both the angle of conflict and also to the random seed value within the microsimulation model.

The sensitivity analyses performed for mixing zone sites yielded generally expected and intuitive results with just a couple exceptions. It was generally found that conflict frequencies are correlated with vehicle and bike volumes, strengthening the results of the analysis of field-observed conflict frequencies.

Overall, it appears microsimulation may not be a suitable option for bicycle-vehicle conflict analysis at all site types. While exhaustive efforts were undertaken to develop models that produced similar conflict frequencies to those observed in the field, the models for bike box and control site locations consistently produced unreasonably low conflict frequencies. While numerous behavioral parameters and characteristics of conflict areas and priority rules were adjusted, further research may be warranted if these modeling efforts are to be used for future analyses of bicycle-vehicle conflicts. That being said, a qualitative inspection of the microsimulation models, along with a comparison of simulated vs. field-observed queue lengths and confirmation of vehicles served indicated the models for all site types performed reasonably well operationally. While beyond the scope of this study, it appears microsimulation modeling could be used to investigate the operational (i.e., delay) impacts of the treatment types assessed in this study and potentially other treatment types.

6.1.3 Summary of Bicycling Simulator Experiment Findings and Conclusions

To further assess bicyclist safety and behavior at intersections and the influence of conflicting right and left turning vehicles, an experiment was designed using the OSU Bicycling Simulator and eye-tracking equipment. The treatments assessed in this experiment (bike boxes, mixing zones, and bicycle signals) necessitated the development of novel pavement markings and bicycle signal heads using Blender version 2.71. All other design aspects were coded using Internet Scene Assembler (ISA) version 2.0 to resemble scenarios participants may experience in the real-world as authentically as possible.

A total of 40 individuals were recruited for participation in the bicycling simulator experiment from the area surrounding Corvallis, Oregon. Of these 40 participants, there were 23 women (57.5%) and 17 men (42.5%) with none self-identifying as non-binary or preferring not to answer, and their age ranged from 19-74 years with an average and standard deviation of 37 and 15.2 years, respectively. The participants rode though all three study treatments under varying scenarios including arrival on red and green signal indications, and situations where a right turning vehicle was either arriving or waiting at the intersection, where a left-turning vehicle was present, and where no conflicting vehicles were present. Several measurements were collected as participants rode through the different scenarios including:

- Lateral position- The horizontal offset between the cyclist's center of gravity and the center of lane;
- Average velocity- The average forward velocity of the cyclist while approaching and traversing the intersections;
- Eye-tracking fixations- The time spent viewing areas of interests (AOI) to define the allocation of visual attention.

Additionally, both pre- and post-ride surveys were completed by the participants to gauge their general bicycling activity before the experiment and their relative familiarity and comfort while riding through each study treatment.

With respect to lateral positioning, participants tended to deviate furthest from center of lane when traversing the mixing zone treatment when compared to the bike box and bicycle signals. On average, participants rode 0.8, 3.3, and 0.6 ft to the left of the center of lane when traversing the bike box, mixing zone, and bicycle signal treatments, respectively, and these differences were statistically significant.

With respect to bicyclist velocity, in scenarios where there was no stopping requirement, the mixing zone scenarios had the highest average velocity with a median of approximately 12.3 mph while the bicycle signals had a median of approximately 10.6 mph. When participants were required to stop at the intersection, the average velocity through the bicycle signal treatment was found to be higher than the other treatments with a median velocity of approximately 6.7 mph. It should be noted velocities on green indication in the simulator experiment were compared to those observed in the field, and no statistical difference was found between the two data sources for bike boxes or bicycle signals, and only a small (0.0-1.7 mph) statistically but not operationally significant difference was found for mixing zones. This indicates bicyclist operational behavior in the simulator matches that observed in the real world reasonably well by this measure.

The analysis of visual attention revealed that participants tended to focus more visual attention on a conflicting vehicle when traversing the mixing zone treatment as compared to the bike box and bicycle signals. The results of the post-ride survey also showed that participants were most uncomfortable traversing mixing zones (76.9% of participants) compared with 46.7% and 12.8% of participants feeling discomfort at bike boxes and bicycling signals, respectively.

An overall conclusion of the bicycling simulator experiment was that all 3 treatment types were found to have positive and negative effects on the riding habits of participants and therefore implementation of the various treatments should be situational. It is possible using a treatment too frequently may influence bicyclists to adopt negative riding habits that reduce their safety and the safety of others on the roadway. As an example, this research found that bicycle signals provide a high level of comfort and perceived safety, potentially influencing bicyclists to stop searching for a potential conflict on an approach which may be a safety issue under some bicycle signal phasing schemes. The mixing zone treatment brought participants out of their comfort zone and required them to be alert of potential conflicts when claiming lane as evidenced by their increased visual attention on conflicting vehicles. Despite this effect, the sporadic and unpredictable riding habits associated with this treatment may expose bicyclists to higher risk scenarios. The bike box treatment seems to be a common middle ground between the bicycle signal and mixing zone. Ultimately, the conclusions from the bicycling simulator experiment are used in part to provide recommendations for practice presented in section 6.2.

6.2 RECOMMENDATIONS FOR PRACTICE

Based on the results of the analyses of all three data sources collected for this study (with a focus on analysis of the field-observed and bicycling simulator data), guidance for practitioners on when and where to consider the three different treatment sites studied (bike boxes, mixing zones, and bicycle signals) was developed. This guidance should not be considered a 'warrant' for when to install a specific treatment, but rather general guidance based on the results of this study. Note that all of the field-observed sites and those assessed in the bicycling simulator were signalized and had bike lanes, so the provided guidance assumes that a certain location is signalized and either has bike lanes or bike lanes could be added.

6.2.1 Relative Costs and Time Frames for Installation Considerations

It is important to recognize that the three treatments considered in this study have different installation costs, maintenance costs, and time frames for implementation. The bicycle signal treatment clearly has the highest installation cost, maintenance cost, and would likely have the longest time for implementation compared with bike boxes and mixing zones which require primarily only pavement markings and potentially signage. Additional considerations for bicycle signal installation include the need for signal retiming, utility locations, the ability to place the bicycle signal head in a viable location, and detection. Past research has shown that the average cost for a bicycle signal retrofit is $52,000 and the cost for bike box installation is $5000 (Weigand et al., 2013). These cost values are based on a 2013 report so they may not reflect current prices, and estimated costs for mixing zone installation could not be located in the literature, but these values reflect the relative expense of a bicycle signal vs. a bike box (or mixing zone) treatment. Table 6.1 provides a basic summary of relative costs and implementation times for the three study treatments. Note that bike boxes are expected to have slightly higher installation and maintenance costs compared with mixing zones due to the large area of green paint at these installations.

Table 6.1: Relative Costs and Installation Time Frames for Study Treatments

Treatment	Relative Cost of Installation	Relative Cost of Maintenance	Relative Time Frame for Application
Bike Box	Low-Med	Low-Med	Short
Mixing Zone	Low	Low	Short
Bicycle Signal	Low-High	Medium	Short-Long

6.2.2 Recommendations for Treatment Selection Based on Conflict Analyses and Bicycling Simulator Experiment

All three treatments assessed in this study have advantages and drawbacks, and the selection of a particular treatment should be based on several factors, including engineering judgement and user comfort. Additionally, as a general recommendation, agencies should try to be as homogeneous as possible in their design and application of each treatment type to improve driver and bicyclist expectation.

As one initial consideration, Figure 6.1 was created based on the results of the Poisson regression models developed with the field-collected data presented in Table 3.5 and the associated conflict predictions presented in Figure 3.4 and Figure 3.5. It should be noted that the volumes presented in Figure 6.1 are hourly, so the volume thresholds presented should be interpreted as hourly volumes that are typically met or exceeded regularly at a particular site, likely during weekday peak hours. Based on this guidance, sites with hourly through bike volumes 25 or less per hour and turning vehicle volumes of 75 or less per hour may not greatly benefit from a bicycle-specific treatment. In these cases, a bike box or mixing zone could be considered based on other factors (including engineering judgement), especially in cases where there is a relatively high volume of pedestrians using the right-side parallel crosswalk (based on the results of the models presented in Table 3.6).

Bike boxes or mixing zones could be considered at locations with greater than 25 through bikes per hour and 100 or less turning vehicles per hour, while only bike boxes should be considered at locations with greater than 100 turning vehicles per hour (conflicts were predicted to increase markedly at mixing zone locations when turning vehicle volumes were greater than 100 per hour). Finally, bicycle signals could be considered when turning vehicle volumes are greater than 150 per hour and/or through bike volumes are greater than 50 per hour. Expanding on this information, Figure 6.2 shows a flow chart which provides additional step by step treatment selection guidance (including the volume-related considerations presented in Figure 6.1). As stated previously, this guidance is not meant to be used as a warrant and should not be used to restrict options at any particular site, as the choice of treatment depends on numerous factors beyond bike and vehicle volumes. The following subsections provide additional guidance on the performance of specific treatments which may be useful in the treatment selection process.

<table>
<tr><th rowspan="2">Hourly Through Bicycle Volume</th><th colspan="7">Hourly Turning Vehicle Volume (vph)</th></tr>
<tr><th>25</th><th>50</th><th>75</th><th>100</th><th>125</th><th>150</th><th>>150</th></tr>
<tr><td><10</td><td colspan="3" rowspan="5">Low Conflict Reduction Potential for Bike Boxes[1] and Mixing Zones[1]</td><td rowspan="5"></td><td colspan="2" rowspan="10">High Conflict Reduction Potential for Bike Boxes[1]</td><td rowspan="11">High Conflict Reduction Potential for Bicycle Signals[1,2]</td></tr>
<tr><td>10</td></tr>
<tr><td>15</td></tr>
<tr><td>20</td></tr>
<tr><td>25</td></tr>
<tr><td>30</td><td colspan="4" rowspan="5">High Conflict Reduction Potential for Bike Boxes[1] or Mixing Zones[1]</td></tr>
<tr><td>35</td></tr>
<tr><td>40</td></tr>
<tr><td>45</td></tr>
<tr><td>50</td></tr>
<tr><td>>50</td><td colspan="6">High Conflict Reduction Potential for Bicycle Signals[1,2]</td></tr>
<tr><td colspan="8">[1]Note: Other factors such as presence of right turn lanes and speeds should be considered for treatment selection</td></tr>
<tr><td colspan="8">[2]Note: Bicycle signals have conflict reduction potential across all bicycle and vehicle volumes</td></tr>
</table>

Figure 6.1: Treatment consideration based on through bike and turning vehicle volumes

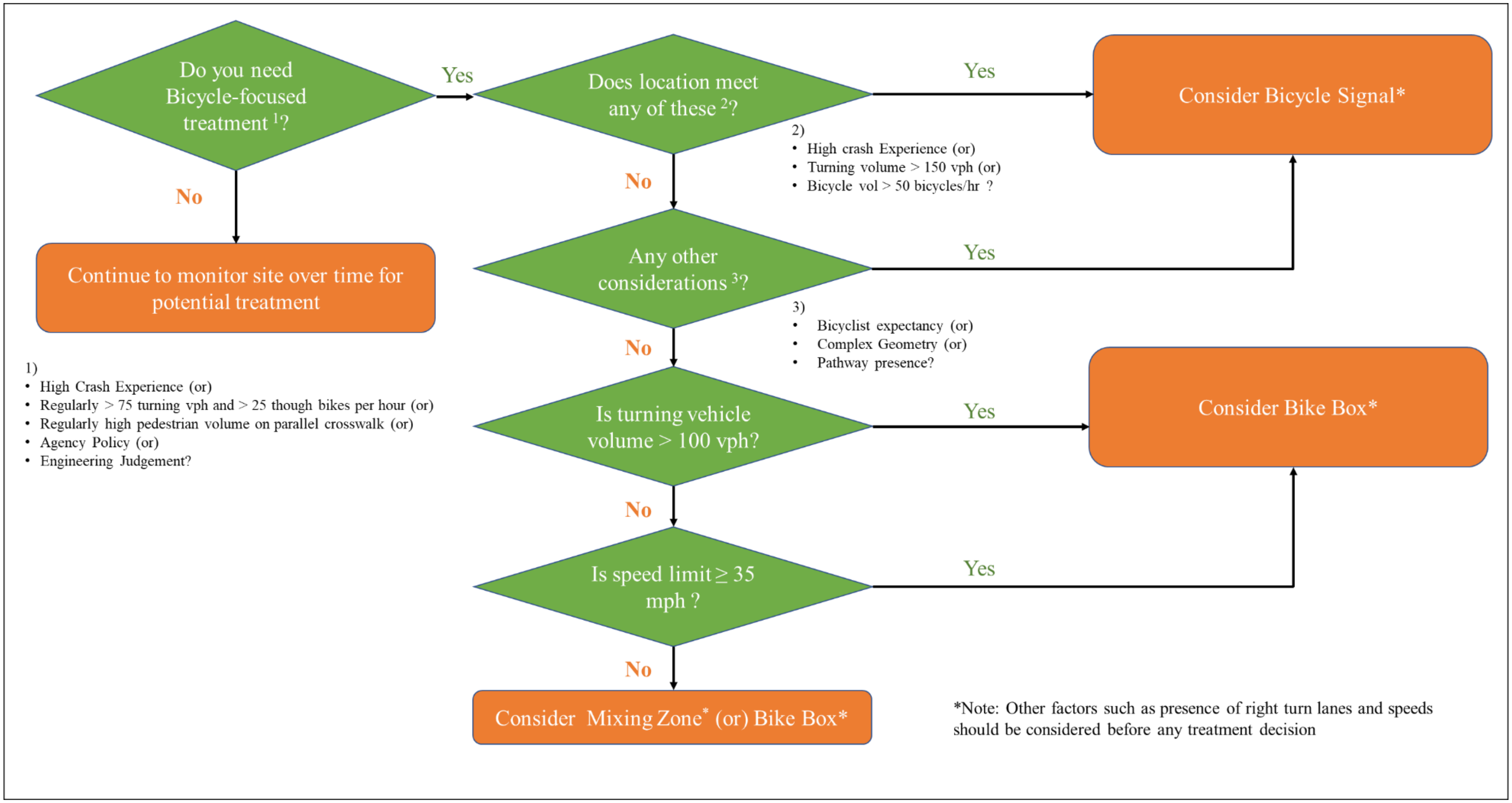


Figure 6.2: Flow chart showing treatment consideration guidance

6.2.2.1 Additional Guidance for Bicycle Signal Selection

As noted previously, bicycle signals would generally be the most expensive treatment option considered in this study (though costs could vary depending on scenario), so care should be taken to confirm they will provide reasonable benefit when installed. In terms of conflicts, bicycle signals (with time-separated bicycle and vehicle movements) yielded zero bicycle-vehicle conflicts in both the field-observed and microsimulation analyses, which indicates a significant safety benefit. Additionally, the results of the bicycling simulator experiment found only 12.8% of participants felt discomfort at bicycle signals (much lower than bike boxes and mixing zones), and bicyclists tended to travel closer to the center of the bicycle lane at these treatments. It's worth mentioning that one notable finding related to bicycle signals was that bicyclists tend to allocate less visual attention to conflicting vehicles compared with other treatment types, though this finding was not completely unexpected given the time-separated movements of bicycles and vehicles.

Given bicycle signals appear to provide a significant safety benefit but also come at a high cost, it is recommended they be considered in (but not limited to) the following scenarios:

- Crash data indicates a high frequency of bicycle-vehicle crashes at a location where time-separation between bikes and vehicles could prevent such crashes (reactive solution). Note that it is beyond the scope of this study to recommend crash frequency thresholds, but several methods for network screening can be found in the Highway Safety Manual (AASHTO, 2010) and other sources.

- Hourly turning vehicle volumes during weekday peak hours regularly exceed 150 vph and/or hourly through bike volumes regularly exceed 50 per hour (proactive solution). This guidance is based on the results of the field-observed conflict analysis and is in line with existing guidance on when to provide time-separation between bicycles and vehicles (MassDOT, 2015), and existing guidance also mentions consideration of pedestrian volumes when considering time-separation at bicycle signals (MassDOT, 2015).

- Any other scenario where engineering judgement would indicate a bicycle signal would provide a worthwhile benefit (e.g., corridor with other bicycle signals, intersections with complex geometry, pathway presence, etc.).

6.2.2.2 Additional Guidance for Bike Box or Mixing Zone Selection

If it is deemed a bicycle signal is not appropriate for a particular location, consideration could be given to either installation of a bike box or mixing zone. Given the relative cost and time frames for installation are similar for these two treatments, the choice between these two treatments could consider numerous factors. Table 6.2 provides a list of additional considerations along with guidance comparing bike boxes and mixing zones for each of these considerations. It is found that for most of the considerations listed in Table 6.2, the bike box appears to be the better option between the two, with the one exception being that bike boxes may not be practical to install on wide one-way roads, in which case the mixing zone could be considered. Overall based on the results of this study, if all else is equal, bike boxes should be selected over mixing zones when each treatment has equal feasibility of installation.

Table 6.2: Additional Guidance Comparing Bike Boxes and Mixing Zones

Consideration	Bike Box	Mixing Zone	Source of Guidance
Hourly Turning Vehicle Volumes and Through Bike Volumes	Generally similar predicted conflict frequency to mixing zones when turning vph < 100, but less predicted conflicts than mixing zones when turning vph > 100	Generally similar predicted conflict frequency to bike boxes when turning vph < 100, but more predicted conflicts than bike boxes when turning vph > 100	SPR833 Data Analysis
Right Side Parallel Pedestrian Volumes	Pedestrian volumes not significantly associated with conflict frequency	Pedestrian volumes not significantly associated with conflict frequency	SPR833 Data Analysis
Conflict Severity	Conflicts consistently less severe than mixing zones based on several severity measures	Conflicts consistently more severe than bike boxes based on several severity measures	SPR833 Data Analysis
Average Vehicle Speeds During Conflict	6.9 mph	15.1 mph	SPR833 Data Analysis
Bicyclist Comfort	46.7% of bicycling simulator participants felt discomfort	76.9% of bicycling simulator participants felt discomfort	SPR833 Data Analysis
Lateral Position of Bicyclists in Treatment	Rode near center of bike lane (average of 0.8 ft to the left of center of lane)	Rode more near the left edge of bike lane (average of 3.3 ft to the left of center of lane)	SPR833 Data Analysis
Bicyclist Visual Attention to Vehicle	Bicyclists give less visual attention to vehicle	Bicyclists give more visual attention to vehicle (nearly 2s more than at bike boxes)	SPR833 Data Analysis
Speed Limit	No specific guidance (apply engineering judgement)	Vehicle speeds should be 20mph or less at merge point. If speed limit is 35mph or greater, may need to provide deceleration lane	(MassDOT, 2015)
Bicycle Left Turn Volumes	May help facilitate left turns for bicyclists	Does not facilitate left turns for bicyclists	(NACTO, 2014)

6.3 LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

This research provides data-driven guidance related to the safety performance of 3 bicycle-specific intersection treatments: bike boxes, mixing zones, and bicycle signals. The results provide valuable guidance to practitioners regarding the safety impacts and conditions under which each of these 3 treatments should/could be considered. However, there were some limitations to the data and research methods, most of which could be considered possible directions for future research. First, there are other bicycle-specific intersection treatments (e.g., protected intersections, two-stage turn queue boxes, etc.) that were not considered in this research, and future studies could investigate the safety impacts and appropriate conditions for installation of these other treatments. Specifically related to bicycle signals, the safety impacts of alternative phasing schemes (e.g., LBI, split LBI, bike scramble, etc.) along with compliance to bicycle signals could also be investigated.

There were some limitations related specifically to the data reduced from field collected videos at the 12 study sites in this research. First, data were collected during the Covid-19 pandemic, and while both vehicle and bicycle volumes were approaching pre-pandemic levels when the videos were recorded, it's unknown whether the pandemic had any impact on motorist or bicyclist behaviors. Second, the volume, conflict, and speed data reduction from the field-collected videos was completed in an office setting by members of the research team. While training was provided and data reduction from test videos showed consistency among the data collectors, there is likely inherently some small level of counting or measurement error associated with this type of data collection in almost any context.

With respect to the microsimulation modeling analysis, exhaustive efforts were undertaken to match the frequency of conflicts obtained from microsimulation models and SSAM to those observed in the field. However, at the control and bike box sites, the conflict frequency outputs were excessively low and conclusions could not be made from these data. At the mixing zone sites, conflicts obtained from microsimulation matched reasonably to those observed in the field, however the sensitivity analyses performed at these sites yielded a few unexpected results. It appears that the frequency of bicycle-vehicle conflicts obtained from microsimulation and SSAM may be very sensitive to both angle of conflict and to random seed numbers within the microsimulation model, and further research is needed address this issue in future applications. However, it does appear that microsimulation modeling could be useful to investigate the operational (i.e., delay) impacts of the treatments assessed in this study and other treatments.

Regarding the bicycling simulator experiment, although the within-subject design of the bicycling simulator provides the potential for increased statistical power, a potential limitation is fatigue effects, which can cause a participant's performance to degrade over the course of the experiment as they become tired or bored. The order of the scenarios was partially randomized, ride times were minimized, and breaks were introduced between rides to limit the influence of fatigue effects. Future bicycling simulator work could focus on how participant behavior changes over time to assess if the responses change as they traverse the study treatments more frequently. This would allow researchers to better understand if negative riding habits are formed and could help guide the frequency of implementation. Additional research could also be expanded to include driver and pedestrian users in the simulator experiment. This would allow analysis of velocity differential between vehicles and bicyclists through the treatment types in a simulator setting, and how pedestrians may influence a bicyclist's response.

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APPENDIX A: ROAD USER VOLUME DATA REDUCTION INSTRUCTIONS

ODOT 833 Volume Counting Instructions

The counting at each location should be done from 7 AM - 7 PM. The excel template for volume counts has two sheets. The first sheet labeled videos is where the information for the videos that have been watched should be listed. This sheet contains the following columns.

Angle – Please list the angle or the corner of the intersection for the video that you are watching if applicable.

Video Name – List the video name, which should be a combination of letters and numbers.

Media Created Time – List the media created time. This information can be found by right - clicking on the video name, selecting properties and then selecting details.

Video Duration – List the exact video duration (typically around 17 mins or so) from the video that you are watching.

End Time – This will be the media created time + video duration.

Actual Start Time – It is the media created time + 7 hrs

Actual End Time – This will be the End time + 7 hrs.

The second sheet labeled counts is where the actual counts will be recorded. Each row on this sheet should correspond to a 15 min period. For example, the first row should contain counts from 7:00 – 7:15 am. It has the following columns.

File Name 1 - Please list the file name of the file that you are currently watching.

File Name 2 – If the 15 min period that you are watching spans across two files, enter the second file name for the rows that have information from the second file.

File 1 Video Start Time - The time stamp within video 1 where the 15-minute bin that you're collecting begins.

File 1 Video Start Time – The time stamp within video 1 where the 15-minute bin that you're collecting ends. If the 15-minute bin you're collecting will run in to video 2, this time stamp would just be the stamp at the end of video 1.

File 2 Video Start Time – If applicable, the time stamp within video 2 where the 15-minute bin that you're collecting begins. This would generally be 0:00 when you're continuing the 15-minute count from video 1.

File 2 Video End Time - If applicable, the time stamp within video 2 where the 15-minute bin that you're collecting ends.

Actual Start Time - This will be actual start time (.e.g pacific daylight time) for the 15 min block.

Actual End Time - Actual end time (e.g. pacific daylight time) of the 15 min block.

Bike Counts – For each 15 min period, count the bikes turning left, going thru and turning right. Count the bikes as they cross the stop bar.

Passenger Vehicle counts – For each 15 min period, count the cars, SUV's, van's, pickup's as they cross the stop bar. These counts should be placed in the appropriate lane that the vehicles are in - right turn only, thru lane 1, thru lane 2, left turn only lane.

Heavy Vehicle Counts – For each 15 min period, count the trucks, busses, RV's etc. as they cross the stop bar and place the counts in their appropriate lane - right turn only, thru lane 1, thru lane 2, left turn only lane.

Ped Counts – For each 15 min period, count the pedestrians (not in wheelchair/motorized wheelchair) on the crosswalks, both perpendicular (e.g. directly in front of the study approach) and parallel (e.g. to the right of the intersections where right turning vehicles would cross the parallel crosswalk) to the approach. Place these in the appropriate columns. If bicyclists are riding across the crosswalks, do not count them but just make a note in the notes column. But if the bicyclists dismount and walk their bikes across the crosswalk, include them in the count.

ADA Ped Counts – For each 15 min period, if there are any pedestrians using wheelchairs, count them and place the counts in the appropriate column (perpendicular or parallel).

In Street Scooter counts – For each 15 min period, count the number of scooters in the street (bike lane etc.)

Off-Street Scooter Counts – For each 15 min period, count the number of scooters off the street (i.e. sidewalk/crosswalk).

Notes – Include any unusual observations or clarifying comments here.

APPENDIX B: SAMPLE ROAD USER VOLUME DATA REDUCTION SPREADSHEET

Actual Time (PDT)		BIKE COUNTS			PASSENGER VEHICLE COUNTS (cars, SUVs, vans, pickups,					HEAVY VEHICLE COUNTS (Trucks, busses, RVs, etc..)					PED COUNTS		ADA PED COUNTS		SCOOTER COUNTS		Notes
Start Time	End Time	Left Turn	Thru	Right Turn	RT Lane 1	Thru Lane 1	Thru Lane 2	Thru Lane 3	LT Lane 3	RT Lane 1	Thru Lane 1	Thru Lane 2	Thru Lane 3	LT Lane 3	Perpendicular	Parallel (right side	Perpendicular	Parallel (right side	In Street	Off-Street	
7:00	7:15	0	0	0	6	17	17	6	1	0	1	3	0	1	1	1	0	0	0	0	
7:15	7:30	0	0	0	8	22	25	15	0	1	1	5	1	0	5	1	0	0	0	0	
7:30	7:45	0	1	0	9	23	36	11	2	0	0	3	1	0	2	0	0	0	0	0	
7:45	8:00	0	2	1	9	26	35	17	6	1	3	2	2	1	3	1	0	0	0	0	
8:00	8:15	0	2	0	13	35	42	12	5	1	2	0	1	0	0	1	0	0	0	0	
8:15	8:30	0	3	0	17	36	55	20	3	0	1	0	0	1	2	2	0	0	0	0	
8:30	8:45	0	2	0	11	36	52	28	5	1	1	2	1	0	2	6	0	0	0	0	
8:45	9:00	0	0	0	5	56	63	26	2	0	4	0	3	1	2	3	0	0	0	0	
9:00	9:15	0	1	0	12	38	65	35	2	1	2	3	0	0	2	1	0	0	0	0	
9:15	9:30	0	1	0	7	37	55	33	6	1	2	3	0	1	4	1	0	0	0	0	
9:30	9:45	0	6	0	4	46	64	33	4	1	3	2	0	0	7	3	0	0	0	0	
9:45	10:00	0	3	1	13	38	70	36	9	1	4	2	3	0	1	1	0	0	0	0	
10:00	10:15	0	1	0	13	38	63	30	6	0	2	4	0	1	4	4	0	0	0	0	
10:15	10:30	0	3	1	13	50	76	26	5	1	2	2	0	1	1	2	0	0	0	0	Cyclist cycling to
10:30	10:45	0	5	1	8	55	68	31	6	0	4	4	1	0	1	2	0	0	0	0	
10:45	11:00	0	1	0	20	68	74	39	7	0	1	1	3	0	1	5	0	0	2	0	
11:00	11:15	0	1	0	7	55	78	37	8	0	4	2	1	0	2	5	0	0	0	0	
11:15	11:30	0	4	0	14	60	70	35	6	0	1	2	2	0	2	2	0	0	0	0	2 cars turned left
11:30	11:45	0	4	0	13	67	86	49	6	0	4	1	2	0	7	2	0	0	0	0	
11:45	12:00	0	6	0	12	60	75	49	10	2	3	2	1	0	5	5	0	0	1	0	
12:00	12:15	0	2	0	25	84	96	58	14	0	4	2	3	1	5	7	0	0	0	0	
12:15	12:30	0	5	0	16	73	102	56	19	0	2	0	2	1	2	9	1	0	0	0	
12:30	12:45	0	8	0	13	73	87	49	12	0	4	1	3	0	8	5	0	0	0	0	
12:45	1:00	0	2	0	13	67	97	53	14	0	0	0	3	1	11	8	1	0	0	0	
1:00	1:15	0	9	3	12	82	103	43	19	0	3	2	1	0	7	5	1	1	0	0	
1:15	1:30	0	3	1	17	61	106	54	10	0	2	1	0	0	3	1	0	1	0	0	
1:30	1:45	1	3	0	16	64	97	52	8	1	2	2	1	0	14	3	0	0	0	0	
1:45	2:00	0	6	1	15	74	97	51	11	0	0	0	0	0	3	5	0	1	0	0	
2:00	2:15	0	4	0	25	65	92	49	5	0	1	1	1	0	2	11	0	0	1	0	
2:15	2:30	0	4	0	19	83	111	71	7	0	1	2	0	0	6	1	0	0	0	0	
2:30	2:45	0	5	1	19	91	113	56	10	0	2	2	1	3	5	9	0	0	0	0	
2:45	3:00	0	2	0	20	91	115	67	6	0	1	4	3	0	9	6	0	0	0	0	
3:00	3:15	1	5	0	22	87	108	59	12	0	4	5	1	0	11	8	0	0	0	0	
3:15	3:30	0	4	1	14	104	123	61	10	0	1	2	2	1	4	6	0	0	0	0	
3:30	3:45	0	6	0	12	110	123	90	14	0	2	4	1	1	6	4	0	0	0	0	
3:45	4:00	1	5	0	24	99	127	75	9	0	3	0	2	0	3	6	0	0	1	0	
4:00	4:15	0	11	1	21	84	130	61	10	1	1	2	0	0	6	6	0	0	0	0	
4:15	4:30	1	4	1	13	99	128	66	9	0	2	1	2	0	10	7	0	0	0	0	
4:30	4:45	0	8	0	18	91	134	66	6	0	5	2	0	0	4	3	0	0	1	0	
4:45	5:00	0	4	0	14	122	153	74	15	0	3	2	0	0	4	4	0	0	1	0	
5:00	5:15	0	7	0	18	109	129	93	10	0	3	0	2	0	6	10	0	0	0	0	
5:15	5:30	1	7	1	14	113	119	70	14	0	2	0	1	0	9	7	0	0	0	0	
5:30	5:45	0	8	0	12	93	122	63	25	0	1	0	0	0	10	6	0	0	0	0	
5:45	6:00	0	9	0	21	83	114	60	19	2	1	1	0	0	5	1	0	0	0	0	
6:00	6:15	0	14	1	16	80	110	63	10	0	1	0	0	0	1	4	0	0	0	0	
6:15	6:30	0	6	0	12	69	84	68	14	0	0	1	0	0	5	5	0	0	0	0	
6:30	6:45	0	7	0	6	74	95	46	11	0	1	1	0	0	10	5	0	0	0	0	
6:45	7:00	0	6	1	10	54	68	34	6	1	1	1	1	0	7	8	0	0	0	0	

APPENDIX C: CONFLICT DATA REDUCTION INSTRUCTIONS

SPR 833 Conflict Data Analysis Methods

Any video software with a resolution of one hundredth or thousandth of a second may be used.

Details regarding each column in the conflict data collection template are provided below:

Site Location (Column A)
Identify site location name (e.g., 8th Ave & Burnside)

Camera Placement (Column B)
Enter camera placement/label (i.e., NW, SW, NE, SE, Angle 1, etc…) of camera that is being viewed for data collection.

Time of Day (Column C)
Enter time of day of the incident. Incident should be within the study period between 7am-7pm and in the format: [hh:mm]

Video ID (Column D)
Enter video ID #/name that the event was recorded from.

Clip/Conflict No. (Column E)
Record a clip of the conflict event and save file 'Site - Clip No.'. The clip number should match that of the event recorded in the data collection sheet. Each conflict will utilize two rows, and information for the first arriving unit should always be entered in the upper row.

Event Units (Column F)
Enter code 1 for bicyclist (B), 2 for Motor Vehicle (MV), or 3 for Scooter for each unit involved in the conflict.

Time Stamp (Column G)
Record approximate time stamp of both units as the front wheel/bumper crosses the upstream landmark or conflict box.

Time Difference (Column H)
Calculated automatically in the template. It is the difference between the time stamp of a bicycle and the successive motor vehicle AND/OR a motor vehicle and the successive bicycle. The threshold when considering an event is ≤ 5 seconds. Note: *More than one bicycle(s) may be within ≤5s of more than one motor vehicle(s). Therefore, one motor vehicle or one bicycle may be included in multiple events*

Conflict Box Time Stamp Arrival (Column I)
Record the time when the unit enters the conflict zone. A section of the unit should be referenced (e.g., front bumper or tire) for consistency.

Conflict Box Time Stamp Departure (Column J)
Record the time when the unit exits the conflict block. A section of the unit should be referenced (e.g., rear bumper or tire) for consistency.

Incident? (Column K)
Determined automatically in the spreadsheet. This column determines whether the differences between the time stamps in column E for both units is ≤ 5 seconds. If Column G is less than the

threshold (i.e., ≤ 5 seconds), then the event is classified as an "incident". Events classified as such require data to be filled in columns K, L, M, N, O, P, and Q. Therefore, this column screens whether further data should be collected.

First Unit to Arrive (Column L)

Populated automatically in the spreadsheet. Code 1 for bike, 2 for MV, or 3 for scooter for the first unit when an event is being collected.

PET Value (Column M)

Calculated automatically in the spreadsheet. This column determines the difference between times stamps of the second unit's arrival at the conflict box and first unit's departure from the conflict box. If there are more than two units involved in an event, then succeeding unit's PET values should be determined in reference to the first unit's departure time.

Speed Time Stamp #1 (Column N)

Enter time when the unit's front wheel/bumper crosses over speed landmark 1.

Speed Time Stamp #2 (Column O)

Enter time when the unit's front wheel/bumper crosses over speed landmark 2.

Elapsed Time for Speed Measurements (Column P)

Identify two monuments and record the distances between them (Google Earth) and enter the distance in the appropriate cell in column T. The elapsed time between the arrival of a candidate at monument one and the arrival of the same candidate at monument two is calculated automatically in Column P.

This Column Converts P to a Number for Speed Calculation (Column Q)

Column M's cell format is 'Custom Time' and formulas do not work well with that format. To resolve this issue, this column converts cell's in column M to 'Number'. This helps formulas found in Column O and P that determine the speed of the unit based on measurements determined between two landmarks.

Speed (Column R & S)

These columns automatically calculate the speed of the unit based on the distance between two landmarks and elapsed time (column M). Column O determines speed in feet per second (fps), while Column P converts fps to miles per hour (mph)

Evasive Action (Column T)

Enter code 0 for no evasive action taken, 1 for hard braking, 2 for hard swerving, or 3 for other evasive action taken during the observed event (include comment in column U for 'other' evasive action).

Comments, Landmark Measurements, & Incident Set Threshold (Column U & V)

Leave any comments about the observed conflict that's rather unusual that may affect the data. For example, "large truck blocked entire view of conflict area. Time stamps for bike may be affected." In Column S-U enter the landmark measurements determined from the field or Google Maps. The set incident threshold is 5 seconds, but this column also contains that cell and may be changed accordingly.

APPENDIX D: TEMPLATE SPREADSHEET FOR CONFLICT DATA REDUCTION

Site Location	Camera Placement (NE, NW, SE, SW)	Time of Day	Video ID	Clip/Conflict No.	Event Unit [1=B, 2=MV, 3=Scooter]	Time Stamp [hh:mm:ss.00]	Time Difference [ss.00]	Conflict Box Time Stamp Arrival [hh:mm:ss.00]	Conflict Box Time Stamp Departure [hh:mm:ss.00]	Incident? [Calculated based on Threshold]	First Unit to Arrive (1=Bike, 2=MV, 3=Scooter)	PET Value [s]

Speed Time Stamp #1	Speed Time Stamp #2	Elapsed Time For Speed Measurement [s]	This Column Converts Column M to a Number for Speed Calc	Speed [fps]	Speed [mph]	Evasive Action [0=none, 1= hard braking, 2=hard swerving, 3=other (leave	Comments

Speed Calculation Measurements

Landmark Measurements		
Bike - 1	11.70	[ft]
Veh - 2	11.70	[ft]

NOTE: X-walk was used as landmark

Incident Set Threshold (s)

0:00:05.00