SAFER FOR CYCLING: EVALUATING SAFETY AND OPERATIONAL EFFECTS OF PROTECTED INTERSECTION GEOMETRIC DESIGN THROUGH MICROSIMULATION

by

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ABSTRACT

ABIGAIL PRESTON. Safer for Cycling: Evaluating Safety and Operational Effects of Protected Intersection Geometric Design through Microsimulation. (Under the direction of DR. SRINIVAS S. PULUGURTHA)

On-street bike lanes have been increasingly visible in the City of Charlotte but rarely utilized. The Charlotte Bikes bicycle program, adopted by City Council May, 2017, proposed that bicycle facilities implemented on arterials should be separated from traffic by a concrete barrier or grass buffer. However, providing on-street bike lanes and separating from traffic alone may not attract residents to use cycle as a mode of transportation. This could be attributed to roughly 30% of all bike-related crashes that generally occur at urban intersections. Therefore, this research seeks to improve safety at intersections. The focus is primarily to evaluate the safety and operational effects of Protected Intersection design on cyclists' safety at intersections.

The Protected Intersection design was modeled and evaluated at the intersection of Tyvola Rd and South Blvd in south Charlotte. Traffic was modeled on the existing and proposed intersections using PTV VISSIM microscopic simulation software under conditions of zero percent bikes to fifteen percent bikes. Safety was then analyzed using Surrogate Safety Assessment Model (SSAM), and conflicts were defined as a 1.5 second intersection of two or more trajectories. The results indicate as much as an 80% reduction in bicycle-related crossing-type conflicts. It was also found that atmospheric emissions can be reduced by as much as 40% by offering separate right of way for bicycles, versus placing bicycles on a shared lane with motorists. The results support the hypothesis that

the Protected Intersection significantly reduces conflicts at intersections, and therefore improves safety.

ACKNOWLEDGMENTS

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Scott Curry and Will Washam from the City of Charlotte were kind enough to meet with me to brain-storm ideas and aided in selecting the study location. They were the first to suggest researching Protected Intersections. Scott additionally provided data on traffic counts and signal design for the three intersections. At UNC Charlotte, Sarvani Duvvuri and Ajinkya Mane offered their time and assistance with learning VISSIM and debugging and calibrating the model.

I would also like to acknowledge my family and friends who have offered support throughout the journey. Finally, I would like to thank my mom and fiancé, Scottie, for listening to my excitement during good times and encouraging me through the harder times. I could not have done it without you.

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LIST OF ABBREVIATIONS

ADT	Average daily traffic
EOT	Edge of travel
GHG	Greenhouse gas(es)
LOS	Level of service
mph	Miles per hour
ROW	Right of way
RTOR	Right turn on red
SSAM	Surrogate Safety Assessment Module

CHAPTER 1: INTRODUCTION

In the spring of 2017, the City of Charlotte adopted a ninety-three-page plan for fostering a more bicycle-friendly city. Over the preceding seventeen years, the city has added ninety miles of bicycle lanes, fifty-five miles of signed routes, and forty miles of greenways and off-street paths (Charlotte Bikes, 2017). Many city planners have claimed that greater bicyclist prevalence is an indication of a healthy and happy city (Gilpin, 2015; Charlotte Bikes, 2017). In fact, there are many benefits to cycling as a mode of transportation and reducing a community's reliance on private motor vehicles.

One primary benefit of cycling is its impact on human and environmental health. According to the National Health and Nutrition Information Survey, 34.9% of adults in the United States are obese (Ard, 2015), a statistic that could be radically reduced through the routine use of cycling and the cardiovascular exercise associated with it. Bicycles emit virtually zero air and noise pollution (Di Mascio, 2018). In an urban environment, this becomes increasingly important to ensure the health and well-being of the citizens.

Contrarily, automobile exhaust contains derivatives of ozone and particulate matter that can have detrimental effects on the respiratory system (Grabow, 2012). Studies in various cities around the world have modeled the impacts of switching a portion or all residents within a bikeable commute from automobiles to bicycles and found significant benefits to the health and longevity of the city (Grabow, 2012; Johansson, 2017). On a global scale, automobiles produce greenhouse gases and fine particulate matter, which have been scientifically proven to cause global climate change (Hill et al, 2009; IPCC 2018). With less gasoline consumption, users can minimize their carbon footprint and promote a more sustainable environment.

Cycling also promotes several economic benefits. First, cycling promotes mobility within a transportation network by taking private vehicles off the road (Di Mascio, 2018). When combined with public transportation, such as the new light rail line in Charlotte, cycling offers door-to-door access to replace the reliance on motor vehicles and increase capacity of the transportation network as a whole. As bicycles take up less space and public transit can carry more individuals, capacity is increased. Optimizing modal split decreases congestion by taking more vehicles off the road. Minimizing congestion benefits the economy because more time can be spent being productive, versus sitting in traffic. As quality-of-life improves within the city, businesses are more likely to want to relocate or open new branches in the area, further improving the local economy.

Another economic benefit of increased bike-ability involves social equity. Bicycles offer a much less expensive transportation option to low-income groups. Those who cannot afford a vehicle could bike to work, providing access and independence that the bus-system could not. To understand the significance of this affordability, Charlotte Bikes attests that after its initial purchase, a bicycle may cost its user less than $100 annually to supply daily transportation demands. By contrast, the American Automobile Association (AAA) estimates the cost of automobile ownership at $8,698 per year (Charlotte Bikes, 2017). Factoring in the cost of gas, taxes, maintenance and repairs, and registration, automobile ownership is a luxury many Americans cannot afford, yet many US cities are designed in a way that it is virtually impossible to live without one. Because of the potential improvements to the quality of life for low-income communities, access to safe bicycle facilities could be considered a social justice issue.

1.1 Problem Statement

Safety is a major problem affecting bicyclists and greatly influences mode choice. The Highway Safety Research Center reported 119 bicycle crashes in the City of Charlotte in 2017, four of which resulted in a fatality (Rodgman, 2017). Additionally, of all the U.S. bicycle-related fatalities from 2014-2016, 30% have occurred at urban intersections (Pedestrian and Bicycle Information Center, 2018). Though intersections pose a major threat to cyclists, few safety measures have been implemented to mitigate this threat. Striped bicycle boxes have increased safety for cyclists in Charlotte by raising driver awareness (NACTO, 2011; Dill et al. 2010). However, bicycle boxes do not offer physical protection to cyclists in the case of a distracted driver. The Protected Intersection design improves safety to cyclists by offering a corner refuge island to physically protect cyclists, offsetting the through cyclist trajectory from the through motorist trajectory, minimizing exposure time with a forward stop bar, and offering cyclist-friendly signal phasing. However, the safety and operational effectiveness of this design have not been tested or evaluated in the past.

1.2 Research Objectives

This research aims to evaluate the safety and operational effect of the Protected Intersection design at the intersection of Tyvola Rd and South Blvd in Charlotte, NC. Using microsimulation, trajectories of cyclists and motorists within the intersection can be modeled to measure potential conflicts and delays. This research compares the existing design of the intersection with the proposed Protected Intersection design under various vehicle composition scenarios. The composition of bicycles ranges from 0% to 15%, assuming a static demand for origin and destination pairs.

1.3 Organization of This Thesis

This thesis will proceed first with a literature review describing in more detail the demand for better bicycle facilities and relevant past research. Next, the specific background related to the study will be discussed, including details related to geography, microsimulation, and vehicle composition. Chapter 4 discusses the methodology of geometric design, microsimulation with PTV VISSIM, and safety assessment with SSAM. The discussion of microsimulation methodology is subdivided into the following categories: simulation, routing, traffic, driving behavior, calibration, and signal design. The results are discussed in Chapter 5, first by the effects to operations then by the effects to safety. Chapter 6 includes an analysis of these results, first by operational effects, then environmental impacts, then safety impacts. Effects to safety are subdivided into intersection-level and bicycle-level. Finally, Chapter 6 discusses the sources of potential error. Overall conclusions can be found in Chapter 7, along with suggestions for further study.

CHAPTER 2: LITERATURE REVIEW

The ultimate goal of this research is to improve the proportion of Charlotte commuters using bicycles as a regular mode of transportation. Thus, it is important to understand two major issues that may keep cyclists off the roads: mobility and safety.

"Mobility" describes the efficiency at which vehicles move when traversing the network. "Access" describes the user's ability to get onto the network, for example, from his or her residence. Both concepts are just as important to bicycle infrastructure as they are for motor vehicle infrastructure. Sparse or unconnected bicycle paths are unattractive for the same reasons unconnected and inefficient roads would not be acceptable for cars. Connectivity within a network is highly important in providing user-friendly travel. An isolated facility is irrelevant, regardless of how advanced the design, if it is not accessible through connected facilities. Copenhagen is frequently regarded as the most successful transportation network for multimodality and researchers have been curious to pinpoint specific ways to emulate the city. In his study of the great success of Copenhagen's cycling infrastructure, Carstensen (2015) points to the focus on the operations of the network as a whole. Bicycles should be able to cohesively travel from origin to destination. Integration with other modes, such as light rail, further optimizes this mobility. As connectivity is highly important in facilitating an efficient, reliable, and useable network, it becomes necessary to have lanes adjacent to major or minor arterials, instead of isolated to local or residential roads.

Further, demonstrating the importance of connectivity, Pedroso et al. (2016) found that increasing the total lane mileage in the bicycle network in Boston was correlated to a significant increase in the number of bicycle commuters. For every 1-mile increase in bicycle lanes per square mile, there was a 1% rise in the total number of bicycle commuters (Pedroso et al. 2016). One interesting phenomenon described by Pedroso et al. (2016) is the relationship between connectivity and safety. One might expect the number of bicycle crashes to increase proportionately as ridership increased. However, they found that as the number of bicyclists increased, no significant increase in injury-related accidents occurred. It is likely that the more often motorists see bicyclists, the more likely they are to be aware of their possible presence and practice behaviors such as checking over their shoulders before turning right on red. This same relationship between visual cues and crash rate might be an added benefit to bicycle infrastructure, as the sight of bicycle paths could raise awareness among motorists.

Safety is perhaps the most primary concern when a user chooses whether or not to bicycle, either for transportation or recreation. Perceived safety and comfort can be measured using either revealed preference or stated preference surveys. Revealed preference studies have shown that longer bicycle trips were associated with the provision of dedicated bicycle trails, concurrent with the previous discussion on connectivity. Other factors that have been found to positively correlate with bicycle use include residential density, buffering from street traffic, low crime rates, flat topography, and aesthetics. From a stated preference survey, Sener et al. (2009) found that the two most important factors contributing to bicycle use include travel time and motor vehicle traffic. However, when given the option of a direct route with un-marked on-street bicycle facilities versus an indirect, off-road bicycle path, users were willing to significantly increase travel time to use the safer path. (Tilahun et al., 2007; Majumdar, 2017). Majumdar (2017) found that safety was valued over travel time, and the factors that correlated most with perceived safety included marked facilities, lighting and visibility, and road width.

2.1 Bicycle Infrastructure

To improve safety and visibility for bicyclists, many different facility types have been used in the United States and abroad. The most widely known facility is perhaps one of the most inexpensive, the on-street bike lane (Gilpin, 2015). The lanes are designated by a painted stripe on the road, usually four or five feet wide. Bike routes also share the right-of-way (ROW) with motor vehicles but are designated by signage instead of a painted stripe. A buffered bike lane is similar to a bike lane in that paint is used to delineate the traveled way. However, a buffered bike lane includes a buffer space, usually about a foot or two of diagonally striped space to offset the bike traffic from the vehicle traffic (Charlotte Bikes, 2017).

The issue with bike routes, bike lanes, and buffered bike lanes remains that distracted motorists may drift into the bike lane at any time and there is no physical barrier protecting the cyclist. As a response to this predicament, many variations of a separated bike lane have been introduced. Charlotte Bikes refers to these as bi-directional paths, one-way separated bike lanes, or two-way separated bike lanes. Bi-directional paths have been frequently implemented in Charlotte as multi-use paths in greenways. These are typically not recommended in high-volume urban areas if many driveways are present (Charlotte Bike, 2017). Two-way separated bike lanes are typically utilized on a one-way street. Therefore, the best separated bike facility along an urban street would be the one-way separated bicycle lane. These separated facilities may also be referred to as “cycle tracks,” which describes a “bicycle path alongside a major city street that is separated from motorized vehicle traffic by a physical barrier" (Thomas et al., 2012).

One way to think about cyclist safety is in terms of the opportunity of contact or conflict with motor vehicles. How likely is it that traveled path of the cyclist and the motorist intersect? This measure can then be extrapolated to measure the likelihood of a crash between a cyclist and a motor vehicle. Because of the correlation between route conflict points and crashes, the safety created by the bicycle facility often deals with the physical barriers or proximity to the ROW.

A protected cycle track would be considered an over-engineered solution if implemented on every link in a network, such as local residential streets, but becomes more effective on higher volume roads. Charlotte Bikes developed a "Bicycle Facility Implementation Guide," ranking the facilities for safety and outlining situations in which specific facilities would be warranted (Charlotte Bikes, 2017). The Guide is in the form of a matrix between the average daily traffic (ADT) and the vehicular speed. By this guide, a shared roadway can be used only when vehicular speed is less than 25 mph and ADT is less than 3,000. In fact, at ADT less than 1,500 and speeds less than 20 mph, the road may give priority to cyclists and become what is known as a "bicycle boulevard" (Charlotte Bikes, 2017). A delineated bicycle lane may be required in areas with ADT between 3,000 and 6,000 and vehicular speeds between 25 and 30 mph. Much of the split between a bicycle lane and a separated bicycle lane is context-sensitive and may depend on other land-use and demographic characteristics. However, if speeds are much higher than 30 mph and ADT approaches 10,000, Charlotte Bikes suggests implementing a separated bicycle lane. If vehicular speeds are greater than 45 mph, a bi-directional path is warranted.

2.1.1 Intersection Facilities

Bicycle routes, bicycle lanes, and buffered bicycle lanes provide varying degrees of longitudinal protection. However, as soon as the cyclist enters an intersection, he or she is exposed to the most severe types of crashes and yet left virtually unprotected. Just as it is important to think of bicycle infrastructure as a network instead of a series of disconnected paths, it is important to think of safety along the route, instead of along individual links. Though cycle tracks present excellent safety options to cyclists along the length of a roadway, 2/3 of crashes involving a cyclist occur at an intersection (Thomas, 2012). This fact indicates the need for improvements to intersection design.

The City of Charlotte has installed a few intersection treatments known as "bicycle boxes." A bicycle box is a designated region at an intersection that allows cyclists to get ahead of queuing motorized traffic. They are often brightly painted to increase bicyclist visibility (NACTO, 2011). Bicycle boxes place cyclists in a shared ROW but displace the vehicle stop bar so cyclists can separate themselves. In some cases, the bicycle box stretches across all lanes of an approach, allowing cyclists a designated left-turn positioning. In a 2010 study in Portland, Oregon, Dill et al. (2010) found mixed results on the effectiveness of bicycle boxes. They found that encroachment into the pedestrian or cyclist areas was lower while vehicles were waiting. However, there was a significantly higher number of vehicles encroaching upon the bicycle lane while executing a right-turn. This finding indicates that a barrier to protect cyclists at intersection corners might be the best way to solve the intersection safety dilemma.

The Protected Intersection design is an answer to this dilemma. Introduced to the Institute of Transportation and Traffic Engineering (ITTE) as early as 1972, this design is often utilized in the Netherlands where cycling is a common form of commuter transportation (Gilpin et al., 2015). The primary benefits of a Protected Intersection are that users can bring the protection of a separated bicycle lane with them through the intersection. There is also very little room for ambiguity or confusion. Channelization with curbs directs cyclists through the intersection on a predetermined route.

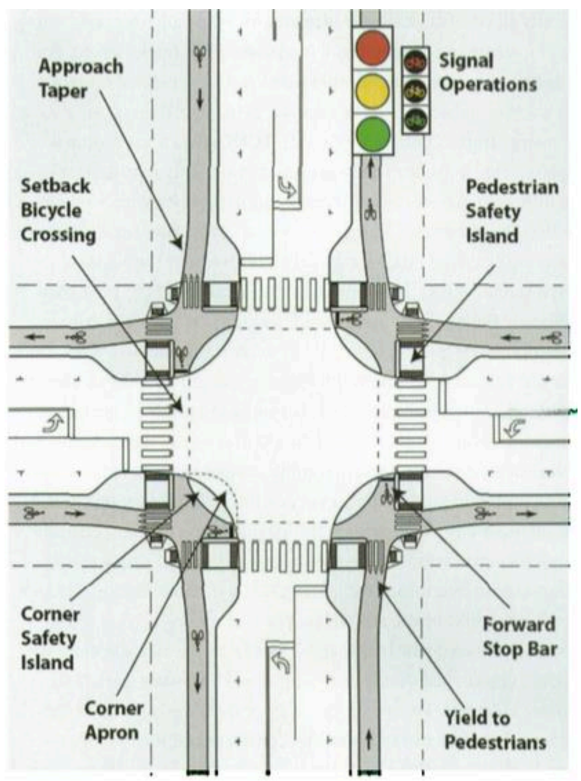

Figure 1 General geometric design characteristics of a Protected Intersection, (Gilpin, 2016).

The Protected Intersection design consists of four main features: a corner refuge island, a forward stop bar, setback bicycle crossing, and bicycle friendly phasing, which can be observed in Figure 1 (Falbo, 2014). The corner refuge island is probably the most notable feature. It physically separates cyclists from motorized traffic. It also allows for easy and protected right-turns for cyclists, who then never have to exit the barrier. Additionally, right-turning traffic faces the cyclist at about 90 degrees after having navigated the refuge island, promoting visibility. If the turning radius is as low as possible, cars will navigate the right-turn at a low speed, about 10 mph, further increasing safety.

With the forward stop bar, motorists yield to pedestrians and stop at a waiting area next to the refuge island. This decreases exposure time for cyclists crossing the intersection. Cyclists turning left also use this space to wait before making a left-turn. The forward stop location also further increases cyclist visibility to motorists, increasing their safety. In protected intersections, the cyclist travel lane tapers away from the motorized lane. By keeping the bicycle lane about a one-car length away from cars, the potential reaction time is increased. This is a contrast to conventional bicycle lanes where bicycles travel directly adjacent to cars. Tapering the cyclist approach also decreases cyclist speed and promotes user caution. One study found that bicyclists in a straight trajectory through an intersection were 3-6 times more likely to run the red light than cyclists in shared traffic. These cyclists were therefore 2.3 times more likely to sustain an injury (Thomas, 2012).

The final feature is bicycle friendly signal phasing, consisting of protected phases. In one case, only through movements are permitted for cars and bicycles, while turning movements are given their own phase. Another sequence involves a bicycle dedicated phase, where all motorized traffic is stopped once per cycle. However, this leading bicycle signal is explicitly prohibited by the FHWA.

2.2 Limitations of Previous Research

Several trade-offs exist between the various facilities. It is important to design a facility that will enhance safety while also minimizing cost and ROW acquisition. After all, if three bicycle facilities could be implemented at the cost of one, the bicycle network would receive added connectivity and access. In a study comparing safety between facilities with and without painted bicycle lanes on Charlotte streets, Pulugurtha and Thakur (2015) found mixed results on the statistical significance in safety improvements of bicycle lanes. Their findings indicated that the risks posed to bicyclists were three to four times greater on facilities without an on-street bicycle lane than roads with a bicycle lane. However, when looking at bicycle crashes per year per million vehicle miles traveled (MVMT), Pulugurtha and Thakur (2015) found no significant improvement in safety. This indicates a need for bicycle facilities beyond bicycle lanes, such as multi-use paths or cycle tracks.

Past research efforts, like by Pulugurtha and Thakur (2015), compared existing facilities with real-world data. Conducting such studies require a statistically large sample of existing facilities with multiple years of before-after data. Experimental treatments like the Protected Intersection design cannot be evaluated using such an approach.

In 2011, the National Association of City Transportation Officials (NACTO) released the "Urban Bikeway Design Guide." Comprehensive as it may have been, the guide did not include the Protected Intersection design. In order for NACTO to have included a facility treatment, it was required to pass three criteria; 1) the design must be in the United States or Canada, 2) there must be experimental data or research showing the impacts to safety or operations, and 3) the North American experience has "provided enough lessons learned to inform and improve future implementations of the design" (Gilpin et al, 2015). Though a degree of research and progress has taken place in the eight years since the release of the Urban Bikeway Design Guide, there is no evidence of safety and operational effects of Protected Intersection design. Therefore, experimental data related to safety and operation of Protected Intersection design would be highly valuable for future improvements and large-scale implementation plans.

CHAPTER 3: STUDY DESIGN

A discussion about study location, selected software for analysis, and bicycle scenarios for modeling is presented in this chapter.

3.1 Study Location

The study intersection is in south Charlotte, at the junction between South Blvd and Tyvola Rd. As no feature exists in isolation in the field of transportation engineering, the proximity of two adjacent intersections necessitated their inclusion in the analysis. These intersections include the Tyvola Rd with Old Pineville Rd and South Blvd with Seneca Place. The study intersection was selected because it would be highly valuable toward cyclists. It is 1.2 miles from entry to the Cross Charlotte Trail. The Cross Charlotte Trail is a project of Mecklenburg County to create 30 miles of trail and greenway for cyclists and pedestrians in a direct corridor across the city. It would allow the provision of increased safety and mobility to active-transport users, much like a freeway does for cars. Users must be able to safely access this corridor, which requires analysis and alterations of major nearby arterials. Additionally, there is a light rail station 0.2 miles away from the study intersection. Cycling could be used to create door-to-door transportation for users of the Lynx Blue Line light rail.

The study intersection sits in a mixed-use area. There are many restaurants, businesses, and shopping centers surrounding the intersection. The South Park Mall is 2.5 miles away. There are also many nearby apartment buildings, the closest of which serve predominantly low-income communities. Safe cycling infrastructure would offer affordable transportation to these residents.

Complexities with this intersection include a skewed angle of approximately 110 degrees. This effects the geometric design as concrete barriers are to be proposed at each corner of the intersection and the corners vary in size. Additional complications include the proximity of the intersection of Tyvola Rd and Old Pineville Rd. The intersections are approximately 350 feet apart, so they are operationally inextricable. Old Pineville Rd already has modest bicycle facilities in place, so connecting these facilities with the proposed intersection would be highly beneficial to the network.

3.2 Types of Analysis

For the sake of this research, it was important to employ a type of analysis that would lend itself to a testable hypothesis. The types of possible analysis included geospatial analysis, statistical analysis, and computer simulations. The geospatial analysis could include studying crash data or injury trends along various corridors to infer problem areas. Statistical analysis would be similar to that described by Pulugurtha and Thakur (2015), looking at a sample of specific existing facilities to make statistical conclusions about the facilities themselves.

As the use of protected intersections in Charlotte is mostly theoretical at the time of this study, it would be impossible to evaluate the difference in the performance of two existing intersections. Microsimulation allows factors such as ADT, intersection orientation, motorist familiarity, demographics, and topography to all be controlled. Any observed changes in safety can be attributed to the proposed design. Microsimulation software also allows the application of hypothetical traffic conditions, such as increased bicycle demand or overall population growth.

3.2.1 Microsimulation Software

VISSIM is a highly valuable and widely used traffic analysis software that uses microsimulation to project time-step traffic flows along a modeled network. Trueblood and Dale (2003) conducted a study on the "power and flexibility" of the VISSIM that has a significant impact on the study of a variety of facility types. The study implies that the features in VISSIM, such as the links and connectors, route decisions, reduced speed zone, and the priority rules, enable the traffic engineer to assess the complex systems effectively.

The Federal Highway Administration (FHWA) developed the Surrogate Safety Assessment Model (SSAM) as a response to the existing protocol of getting safety data from police reports, analyzing trends in the reports, and predicting future crashes from previous ones (Chen, 2009). Not only was the existing process slow and tedious, but it required crashes to occur in order to learn from them. Using simulation and automated conflict analysis to predict future crashes before they occur and even before a proposed design is constructed, saves lives, time, and money. SSAM works by analyzing the frequency of narrowly missed vehicle collisions in a microsimulation, such as VISSIM, to assess traffic safety. SSAM analyzes the trajectory of each vehicle for every tenth of a second. Each time a simulation is run in VISSIM, a TRJ file is produced. After several trial simulations are run, the series of TRJ files can be processed with SSAM.

Vasconcelos et al. (2014) studied the validity of SSAM predictions through two different methodologies, each examining various types of intersections (2014). They first compared SSAM conflict points with the predicted number of injuries from analytical models. The second method compared the SSAM conflict points with crash data gathered from existing intersections. They found that though SSAM seemed to underestimate the number of conflicts for each location, the model accurately predicted the types of conflicts that would be observed. Though some caution is necessary when relying on any model, Vasconcelos et al. (2014) concluded that SSAM offers "a promising approach to assessing the safety of new facilities, innovative designs, or traffic regulation schemes."

3.3 Bicycle Scenarios

In this study, bicycle compositions were modeled at 0%, 1%, 5%, 10%, and 15% of overall vehicles on the corridor. These levels were chosen as important real-world scenarios. Zero percent allows a control value to focus primarily on motor vehicle traffic and mostly fits the composition at the intersection today. One percent is consistent with the national average share of commuter mode choice by cyclists (McLeod, 2017). According to the League of American Bicyclists 2017 survey, the highest share of cycling in the United States is in Davis, California with 15.5%. Washington D.C. and Portland, Oregon have 5.0% and 6.7%, respectively. Boulder, Colorado has 10.7% cyclists. In other parts of the world, 41% of work related trips in Copenhagen were made by bicycle, compared to just 24% by car, though distance may play a factor in mode choice (Petersen Weihe, 2017). One to 15% appears to be the range for similar sized cities in the US, and therefore has been the chosen range for this study.

A survey by the City of Charlotte found that 51% of Charlotte residents stated they would like to bicycle more than they currently do (Charlotte Bikes, 2017). The demand for cycling exists, but the supply of a safe and reliable network is still needed.

CHAPTER 4: METHODOLOGY

For the purpose of clarity and succinctness, the two geometric design scenarios will be referred to as "existing" and "proposed." The existing design refers to the infrastructure as it is currently seen today. The study intersection, Tyvola Rd and South Blvd, has no bicycle accommodations at all. Bicycle lanes exist along Old Pineville Rd and Seneca Pl, included in the model. The proposed design consists of a Protected Intersection design. It includes the concrete barriers at curves to allow for safe queueing of bicycles and clear delineation of movements. Each design scenario was subjected to varying traffic scenarios, as discussed further in the VISSIM subsection.

4.1 Design

The first step in evaluating a Protected Intersection was to design it. The geometric design was done in Bentley Microstation according to the guidelines expressed by Alta Planning and Design and Joe Gilpin in "Evolution of the Protected Intersection" (2015).

In order to provide the barriers necessary for a Protected Intersection, longitudinal cycling facilities had to be developed as well. In a professional setting, a survey would be conducted to find the ROW delineations, parcel boundaries, grade, and feature delineations like curb and gutter and lane width. This could also be reconstructed as best as possible from aerial photos gained from NC OneMap.

Visually overlaying features and measuring offsets using Google Earth were used to reconstruct the geometric design of the existing intersection. No data was gained for grade or ROW. Instead, ROW acquisition was minimized as much as possible. Therefore, barriers, lane widths, and crosswalk widths were designed to minimum specifications when necessary. As the goal of this research is to improve safety, it was important to judge the trade-off between the safety of large offsets from traffic and the cost of using more space. Many of the businesses surrounding the study intersection are placed close to the road, indicating a narrow ROW. Acquiring ROW much into the surrounding parcels could have caused unnecessary inconvenience to those businesses, many of which are small and family-owned. Lane widths and buffers were therefore decided as the appropriate compromise between safety and cost and may vary by the approach.

4.1.1 Typical Section

All elements of the Protected Intersection were derived from chapter five of "*The Evolution of the Protected Intersection*" by Gilpin et al. (2015). Figure 2-A shows the dimensions of the proposed intersection. Roadways each have a design speed of 40 mph and the posted speed limit of 35 mph. The existing typical section on each approach is a 5-lane divided arterial. The ADT during 2016 was 42,000 on Tyvola Rd and 25,000 on South Blvd.

The proposed longitudinal bicycle facility was a one-way separated cycle track on each approach. A typical section can be viewed in Figure 2-B. The minimum width of the concrete buffer was 15 inches, though 3' buffer was used when possible. Bicycle lanes were 7' wide and sidewalks were 6' wide. A 4.5' planting strip was designed between the bicycle lanes and sidewalks, to promote safety and aesthetics. A 1' 6" curb is proposed between the cycle track and planting strip.

Each approach tapers away from the edge of travel at least 100’ from the proposed crosswalk. This taper creates an offset approach of at least 8 feet, acting as bicycle storage length or pedestrian refuge.

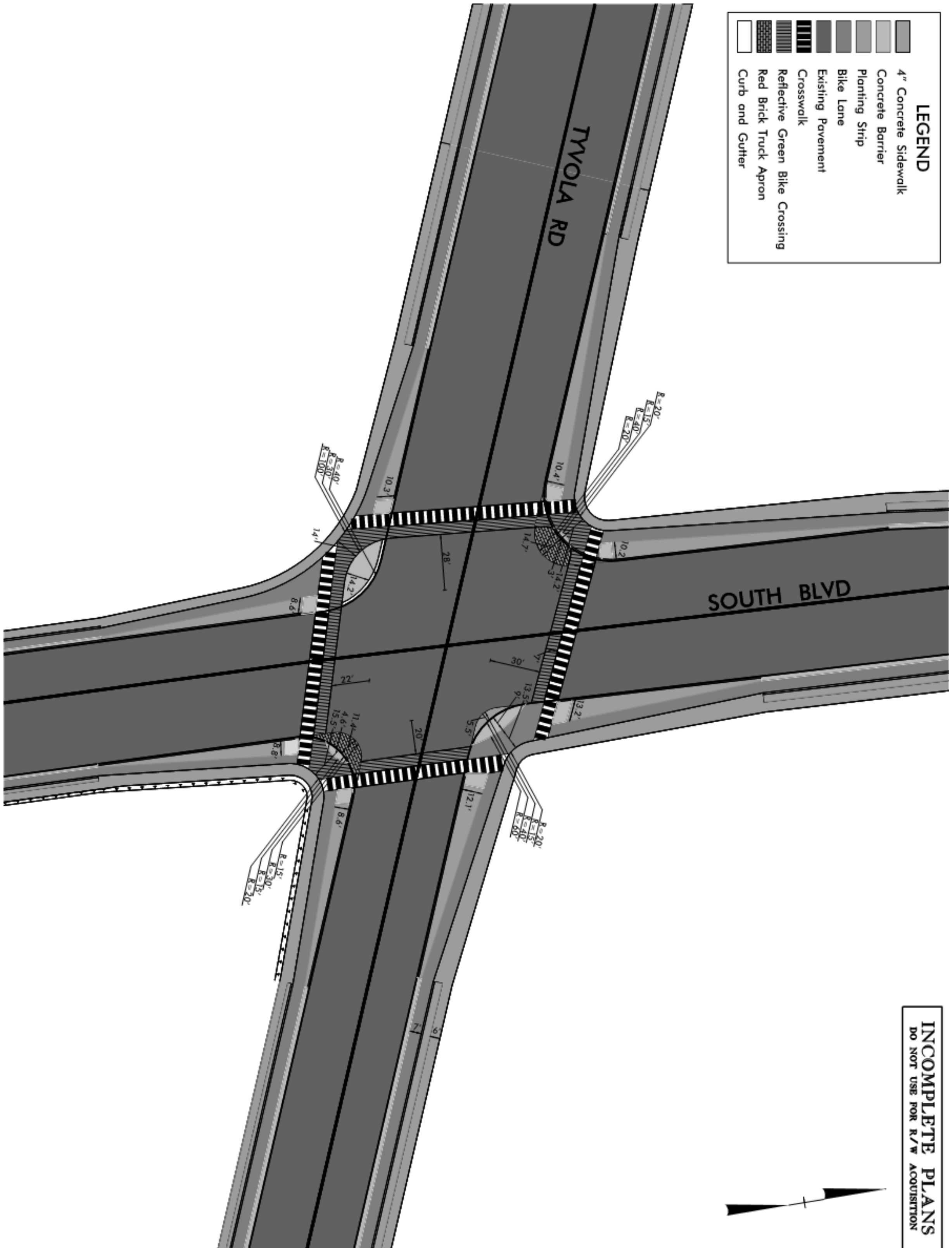

Figure 2-A Proposed Protected Intersection, plan view

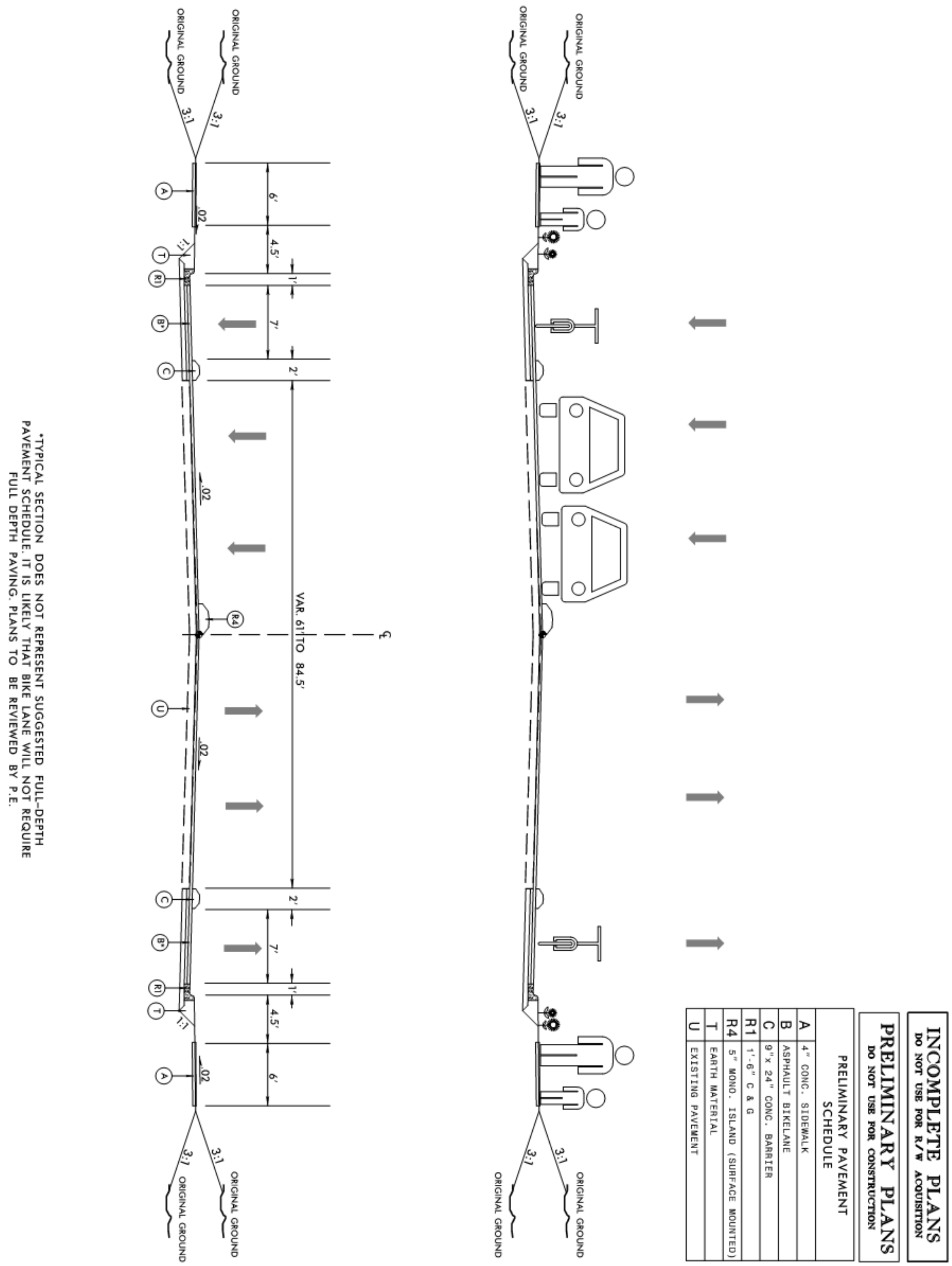

Figure 2-B Typical cross section of the proposed cycle tracks approaching the Protected Intersection

A minimum truck apron radius equal to 15'is proposed. This guides cars away from the refuge island as much as possible. If a truck or bus cannot execute this turn, the apron is mountable up to the concrete refuge island. The refuge island itself has a minimum radius of 40', in order to accommodate heavy vehicles up to WB-40, which is consistent with the existing corner radius. It is proposed that the apron is constructed using a different material from the island and the street, such that the street is asphalt, the apron is laid brick, and the island is concrete. Similarly, the bicycle crossing lane is painted in reflective green in the model. The variation in materials improves aesthetics but also acts as a visual cue to orient motorists in the current path. The corner radius has been designed so that a 30' radius exists from the corner sidewalk to the edge of the apron.

Once cyclists navigate around the refuge island, they are approximately 40' in front of the vehicle stop bar, allowing improved start-up time and minimizing exposure time. The bicycle through traffic is setback at least 20' away from motorized through traffic, preventing lane-change conflicts.

4.1.2 Assumptions

An 11 mph design speed was used for bicycles. However, this is only relevant to curves along the links. As bicycles approach the stop bar at an intersection, it is assumed that their speeds will be minimal and they will be able to navigate curves of small radii.

4.2 Microsimulation Software

PTV VISSIM was used to simulate traffic along the corridor and through the intersection. The designs discussed in the previous section were imported as aerial images and oriented so streets aligned correctly with the software's base map. Links were constructed along each corridor to the correct dimensions. Two models were built using the microsimulation software; existing and proposed. The primary corridors, Tyvola Rd and South Blvd were made to extend at least 0.5 miles from the stop bar at the intersection. The supplemental corridors, Old Pineville Rd and Seneca Pl extended at least 0.25 miles from their intersections. Because the westbound approach to the study intersection developed extensive queue lengths, the link was extended to Marion Diehl Center Dr, approximately 1 mile from the intersection.

Vehicle inputs for the model were made from data obtained from the city of Charlotte Department of Transportation (CDOT). The data input for Tyvola Rd and Old Pineville Rd was gathered on 1/13/15. A 1.8% annual growth rate was applied to gather approximate 2018 values. The data for Seneca Place and South Blvd was collected on 10/15/2014 and was similarly projected to 2018 values. In addition, only peak hour flows for the two supplemental intersections were provided, so the volumes for the remaining time intervals were calculated by applying the rate of change from the main intersection to the corresponding flow in the minor intersections. For example, to calculate the volumes for Tyvola Rd eastbound at Old Pineville Rd, the rate of change from 4:15 to 4:45 was calculated for the eastbound traffic with South Blvd, then applied proportionally to the first intersection.

4.2.1 Simulation

A total of ten scenarios were modeled with varying traffic conditions and vehicle compositions. Vehicle compositions were modeled at 0%, 1%, 5%, 10%, and 15% bicycles. These five compositions were applied to the existing model and to the proposed model. Each of these ten models was ran with 3 different random seeds; 4, 22, and 42.

Four runs were conducted for each random seed. Therefore, 12 simulations were conducted for each of the ten conditions for a total of 120 simulations. The simulation was 8100 seconds long, or 2 hours and 15 minutes. It started at 4:00 PM and ran until 6:15 PM. The first fifteen minutes of run time was used for saturating the model with traffic, so evaluations were conducted from 4:15 PM to 6:15 PM, or 900-8100 seconds.

Table 1 Summary of Simulation Scenarios

PARAMETER	NUMBER OF TREATMENTS	DESCRIPTION
MODEL	2	Existing and Proposed
VEHICLE COMPOSITIONS	5	0%, 1%, 5%, 10%, 15% bikes
RANDOM SEEDS	3	4, 22, and 42
RUNS	4 per random seed	12 per vehicle condition scenario, 120 total

4.2.2 Routing

CDOT data was very important for developing the relative flows for the routing options. In order to reconstruct traffic flows, estimated origins-destinations had to be considered. As this data was not given, several assumptions had to be made. The first major assumption was that vehicles only make one turn. For example, a vehicle going southbound on Old Pineville Rd could not turn left onto Tyvola Rd and then left onto South Blvd. Certainly, these types of routes exist in a real setting, but it would be impossible to know the relative flow with the given data. Another assumption was that relative flows remain constant over the two-hour study interval. In reality, relative flows are dynamic. A greater portion of cars may be turning left when school releases than an hour later. However, for the purposes of this model, relative flows were held constant. Similarly, it was assumed that the relative flows for the bicycle facility on a given approach would match those of the vehicular facility.

At intersections without the proposed protected design, a lot of assumptions had to be made. Though Old Pineville Rd has bicycle lanes, absence of pavement markings and signage make it unclear how users are supposed to navigate the intersection, and ambiguous engineered trajectories may lead to increased confusion and conflicts for both motorists and cyclists. Because the model omits pedestrians, left-turns on bicycles was simulated with traffic as a shared lane. This is an alternative to bicycles taking up pedestrian space, either by riding through the crosswalk illegally or by getting off the bicycle and walking, then getting back on the bicycle. This intersection was simulated according to how a user might navigate it, traveling with left-turning traffic when possible, traveling along the crosswalk when necessary. Additionally, the transition from shared lanes to designated bicycle facilities tends to be awkward. Often, engineers and planners leave no transition for cyclists at all, and a lane ends at an arbitrary point.

4.2.3 Traffic

For speed decisions, it was assumed that cars travel approximately at the posted speed limit, maybe slightly faster. Speed inputs were limited in options as km/hr in increments of 5 or 10 at higher speeds. Buses and heavy vehicles travel slightly below the speed limit. Turning vehicles travel about 5 mph slower for left-turns and 10 mph slower for right-turns. Integer miles per hour speeds were not possible because VISSIM only allows speeds to be set in terms of kilometers per hour, despite base settings being set to English units. Bicycle speeds were therefore set to 9.32 mph or 15 kmph.

Motor vehicle composition was set to 7% buses, 4% heavy vehicles, and 89% cars. This composition remained constant in the proposed simulations because bicycles were added to separate links. However, in the existing simulations, vehicle compositions were modified according to the respective traffic scenario. In this case, the existing model with 15% bicycles had 2% heavy vehicles, 4% buses, and 79% cars. As a whole, motorized vehicle composition was somewhat arbitrary as this was not a measured data set. As vehicle composition was held constant and only varied as pertaining to bicycle percentage, it should not affect the comparison of existing and proposed intersections. In an ideal scenario, only passenger cars would be reduced and substituted with an increase in bicycles to represent a change in mode choice. However, as vehicle compositions were not measured in the field, there is no context for maintaining heavy vehicle concentrations. Because vehicle compositions were consistent between the two models, a comparative analysis reveals changes specifically related to the effect of bicycles on the system, dependent on geometric design. Percent heavy vehicles and buses was a parameter manipulated to calibrate the model to field conditions. Therefore, the motorized compositions were decreased proportionally.

4.2.4 Driving Behavior

Driving behavior was set following guidelines provided in the VISSIM version 9 Manual (p. 265). It was important to model the driving behavior of bicycles and cars sharing a link and to parametrize the specific “lateral” behavior. The basic characteristics are as follows (direct quote from p. 265);

- bicycles must drive on the right side
- bicycles may be overtaken by cars only on the left

- bicycles may overtake cars only on the right
- bicycles may overtake other bicycles only on the left

The urban motorized driving behavior was modified by “look ahead distance” and “lateral behavior.” Step-by-step procedure for this modification can be seen in the VISSIM Manual. The urban lateral behavior and bicycle driving behavior were applied to any link shared between bicycles and cars. This includes most of the links in the existing model and Tyvola Rd eastbound towards Old Pineville Rd in the proposed model. As a default parameter for urban arterials, a Wiedmann 74 car following model was applied to all modeled scenarios.

4.2.5 Calibration

The vehicular components of the model were calibrated using queue lengths at specific time intervals. Eastbound and southbound traffic was omitted because the signals at Old Pineville Rd and Seneca Pl prevent a true, unobstructed queue from being measured. Queue lengths were estimated by comparing landmark placeholders with aerial photos and manually marking locations where queues ended. Then, queue lengths were determined by using Google Earth to measure the distance from the marked queue ends to the STOP bar. Five samples were taken per approach over ten-minute intervals on one afternoon. Error from the model was calculated as 20% for each approach, which is reasonable given the small sample size for calibration.

4.2.6 Signals

Three signals were modeled; Seneca Pl with South Blvd, Tyvola Rd with South Blvd, and Tyvola Rd with Old Pineville Rd. Signal timing plans were obtained from CDOT. The close proximity of the intersections necessitated their coordination. All three signals ran as “pre-timed” versus semi-actuated. Signal communication was set in VISSIM between all the adjacent signals. A model signal head was placed on each lane. Priority rules were defined to force permitted turners to yield to through traffic. Right-turn-on-red (RTOR) was allowed in the existing condition, but not in the proposed condition. This is because RTOR poses safety concerns for cyclists and pedestrians and should be prohibited as part of a protected intersection (Gilpin, 2015). To model this change, RTOR behavior in the existing model placed a stop sign on the right-turn lane instead of a signal head. However, signal heads were placed on right-turn lanes in the proposed model. In addition, signal compliance was set to 97% for motorized links and 100% for a cycle track. No changes were made to the existing signal plan.

4.3 Safety Assessment

SSAM was used to analyze the model projections for potential conflicts. Conflicts represent overlapping trajectories that may indicate a real-world collision if the driver does not take action to alter the trajectory. A TRJ file was produced in VISSIM for each simulation run. A TRJ file can then be input into SSAM, which analyses the trajectories within the output file for conflicts. It also categorizes the conflicts based on the type of crash it could correlate to. These incidents include crossing-type (T-Bone), rear-end type, and lane-change type. Only one TRJ file per scenario was analyzed. To promote consistency between scenarios, the last run from random seed number 4 was used. The outputs from SSAM are useful for comparing the crashes between scenarios.

The default settings in SSAM were used in the analysis. This includes max TTC= 1.5 and PET=5. TTC stands for “time to collision” and represents the number of seconds required for overlapping trajectories to be considered a conflict. PET represents “post encroachment time," and is defined as "the time between the moment that the first road-user leaves the path of the second and the moment that the second reaches the path of the first" (Allen et al, 1977). Conflict angles were set so that rear-end crashes occur at less than 30 degrees and crossing angle is 80 degrees.

CHAPTER 5: RESULTS

The results related to operational and safety effects for the existing intersection and proposed Protected Intersection are discussed in this chapter.

5.1 Operational Effect

There are several objectives with this research. First, it aims to improve the bikability of the area by adding safe and attractive features, thereby increasing the number of bicycle commuters. It is also important to reduce fossil fuel emissions in the area and make the intersection more environmentally friendly. However, mobility and efficiency are also of major importance to transportation engineering. Therefore, the results of this research consider the operational performance, safety performance, and environmental impacts of the proposed changes to the intersection.

5.1.1 Delay

Figure 3 shows that the overall delay per vehicle is much higher for the proposed intersection design than the existing intersection design. The average vehicle delay over the two-hour period is 55 seconds with zero percent bicycles. This delay increases as relative bicycle volume increases, at a rate of 1.37 seconds for every additional percent of added bicycle volume. Because bicycles are on a shared lane and travel at a slower speed than cars, their presence on the roads disrupts the flow and causes increased delay, despite fewer cars being on the roads.

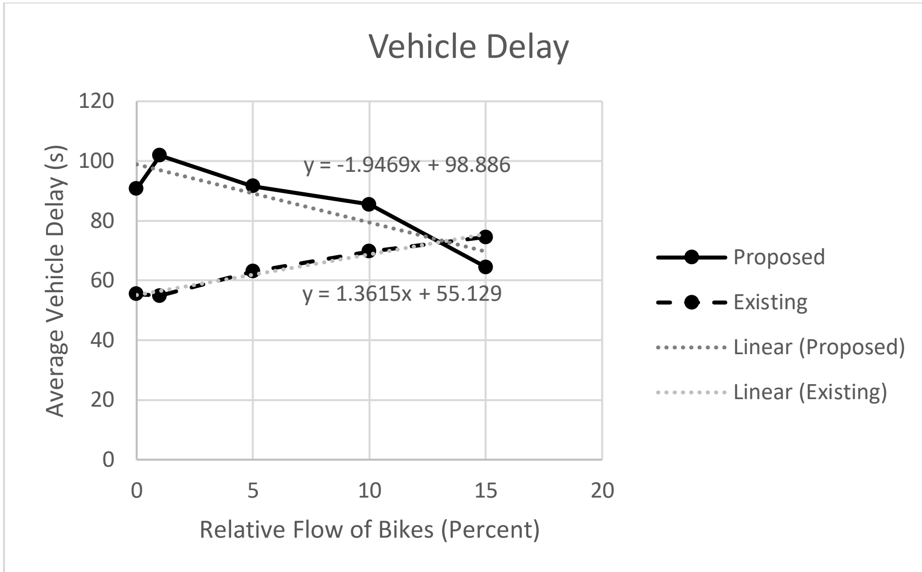

Figure 3 Average vehicle delay as a function of the increase of relative flow of bicycles.

However, when bicycles are given their own ROW, delay steadily decreases as bicycles make up more of the vehicle composition. The proposed Protected Intersection with zero bicycles had an average delay of 91 seconds per vehicle. This delay was not caused by bicycles, as none were present. Instead, this is most likely caused by the removal of RTOR behavior. One can see that this change increased the delay by 36 seconds. However, after the initial delay of removing RTOR privilege, the delay decreased steadily. Figure 3 shows that the delay of the proposed Protected Intersection equals that of the existing intersection at roughly 13% bicycles. After which, bicycles improve system delay. At 15% bicycles, the existing intersection had a delay of 75 seconds per vehicle and the proposed Protected Intersection had a delay of 65 seconds per vehicle. At the proposed Protected Intersection, vehicle delay decreases by 2 seconds per vehicle for every percent increase in bicycle composition.

5.1.2 Level of Service (LOS)

Level of Service (LOS) is a qualification used by traffic engineers to label the overall effectiveness of a facility. Like a school grade, LOS ranges from A to F. LOS is measured by various parameters depending on the type of feature and intersections are qualified by the delay. Therefore, LOS results should match those of general delay results. Figure 4 shows that, like Figure 3, the proposed Protected Intersection had a higher initial LOS than the existing intersection. The LOS conditions in both scenarios are considered unacceptable, with the existing condition at LOS E and proposed Protected Intersection at LOS F. The existing intersection had a steady increase to LOS F as more bicycles were added to the system, whereas the proposed Protected Intersection improved from LOS F to LOS E. Figure 4 shows LOS as numeric values, such that LOS A is represented as "1" and LOS F is represented as "6."

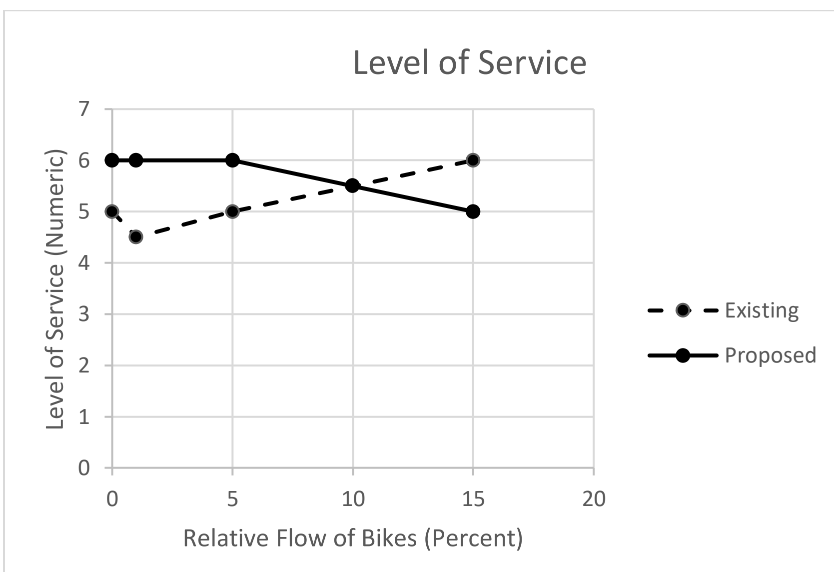

Figure 4 Level of service for the existing and proposed models as a function of the relative flow of bicycles.

5.1.3 Environmental Impact

Environmental impact is determined by VISSIM's estimation of fuel consumption. The software gives little information about how this value is calculated, though it is most likely determined by a combination of vehicle composition and the vehicle travel time through the system. The results pertaining to fuel consumption appeared somewhat skewed. As demonstrated in Figure 5-b there was a significant difference in fuel consumption between the existing and proposed models, regardless of the vehicle composition. In fact, at zero percent bicycles, unadjusted fuel consumption was 337 gallons per hour for the existing model and 143 gallons per hour in the proposed model. It is likely that this error stems from the difference in driving behavior, as RTOR privilege would not cause such a drastic increase. Further, the delay was greater at zero percent bicycles for the proposed model, so one would anticipate a positive correlation between delay and fuel consumption. Therefore, data were adjusted to compensate for the difference in driving behavior, so that fuel consumption with zero percent bicycles would be equal between proposed and existing models. Figure 5-A displays this adjusted data.

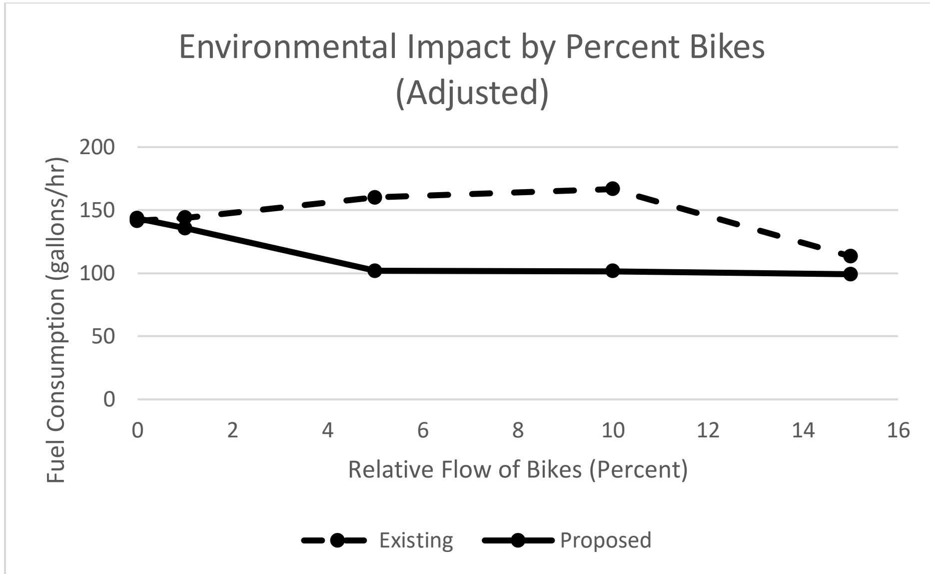

Figure 5-A Adjusted fuel consumption in gallons per hour as a function of the relative flow of bicycles.

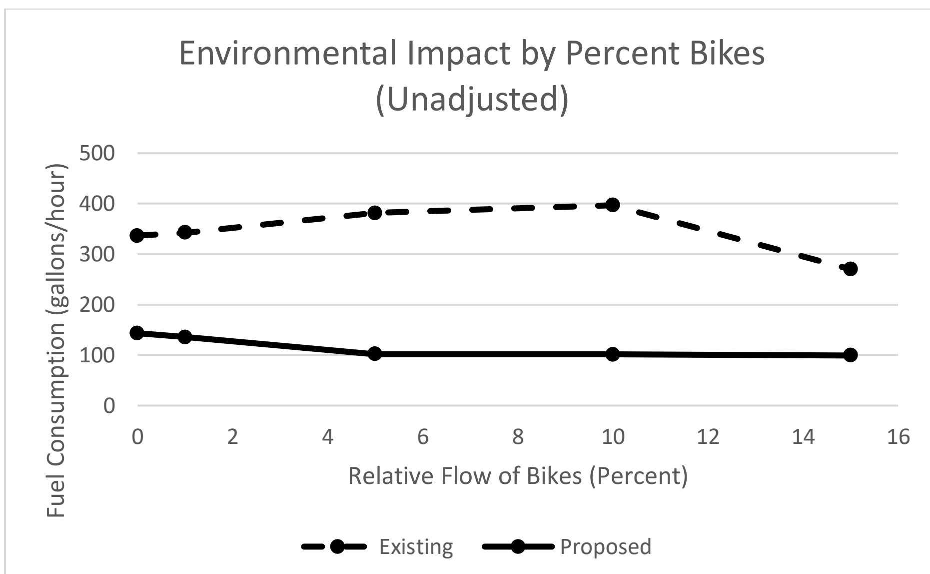

Figure 5-B Unadjusted fuel consumption as a function of the relative flow of bicycles, as produced by the microsimulation.

After adjustment, it is clear that the addition of bicycles leads to an increase in fuel consumption in the existing model and a decrease in fuel consumption in the proposed model. At zero percent bicycles, traffic in both models produced 142 gallons per hour. The fuel consumption peaked at ten percent bicycles, at roughly 167 gallons per hour in the existing model. The fuel consumption was highest in the proposed model with zero percent bicycles and decreased until it approached what appeared to be an asymptote at 100 gallons per hour.

Table 2 Summary of Operational Results

MODEL	% BIKES	AVERAGE VEHICLE DELAY (S)	LOS	FUEL CONSUMPTION (GALLONS/HR)
EXISTING	0	55.45	E	141.47
	1	54.95	D- E	143.83
	5	63.08	E- F	160.18
	10	69.78	E- F	166.71
	15	74.58	F	113.45
PROPOSED	0	90.66	F	143.45
	1	101.82	F	135.82
	5	91.64	F	101.96
	10	85.43	E- F	101.59
	15	64.52	E	99.24

5.2 Safety Effect

SSAM processes trajectories generated in VISSIM to analyze for conflicts. It then sorts these conflicts into categories based on the angle at which a potential crash might occur. The conflicts presented are useful as a relative comparison. They serve as an indicator of a potential crash if a motorist does not alter his or her trajectory to avoid a crash. The data do not indicate that 42 crashes per vehicle will occur, rather that there is a greater potential of a crash because of the large number of conflicts.

5.2.1 Conflicts on Each Model

All the SSAM generated outputs have been divided by the average number of vehicles at the Tyvola Rd and South Blvd over the two hour period, which is 6,896. This changes the unit type from "the total number of conflicts at the intersection" to "the average number of conflicts experienced per vehicle at the intersection".

Figure 6 shows the total number of conflicts. Vehicles on the proposed model clearly experienced significantly fewer total conflicts than vehicles on the existing model. At zero percent bicycles, the existing model showed an average of 6.8 conflicts per vehicle whereas the proposed model showed 1.0 conflict per vehicle. The conflicts in the proposed model stayed relatively consistent, ranging between 3.3 and 9.0 conflicts per vehicle. By contrast, the total number of conflicts in the existing model increased at a linear rate, reaching a maximum at fifteen percent bicycles of 42.3 conflicts per vehicle.

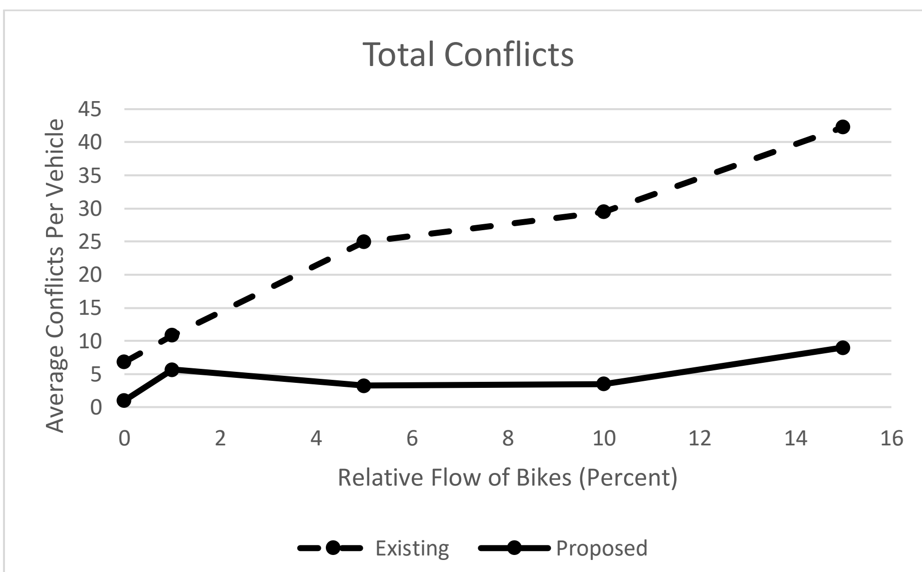

Figure 6 Total conflicts per vehicle as a function of the relative flow of bicycles.

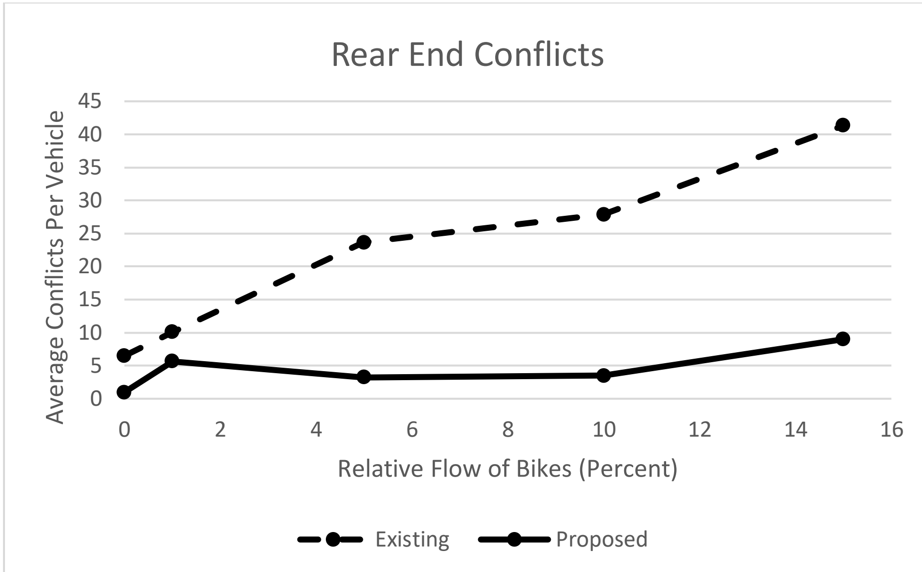

Figure 7 Average number of rear-end conflicts per vehicle as a function of the relative flow of bicycles.

The trends shown in Figure 7 are almost identical to those shown in Figure 6, as rear-end conflicts make up about 92% of total conflicts. As previously discussed, the two models start with variation in the number of rear-end conflicts at zero percent bicycles. The number of rear-end conflicts increases linearly for the existing model whereas little change occurred in the proposed model. The average maximum rear-end conflicts experienced per vehicle in the existing model and the proposed model are 41.3 and 8.3, respectively.

The crossing type conflicts can be observed in Figure 8. The data shows a large degree of variation for each model, although crossing type conflicts are relatively rare. There is no significant difference between the two models pertaining to crossing type conflicts. Both models had 0.1 conflicts per vehicle at zero percent bicycles and 0.4 conflicts per vehicle at fifteen percent bicycles. Trends displayed in Figure 8 are insignificant. A linear best fit regression on the existing model shows an R^2 value of 0.589. The proposed model regression was a slightly better fit, with an R^2 value of 0.899.

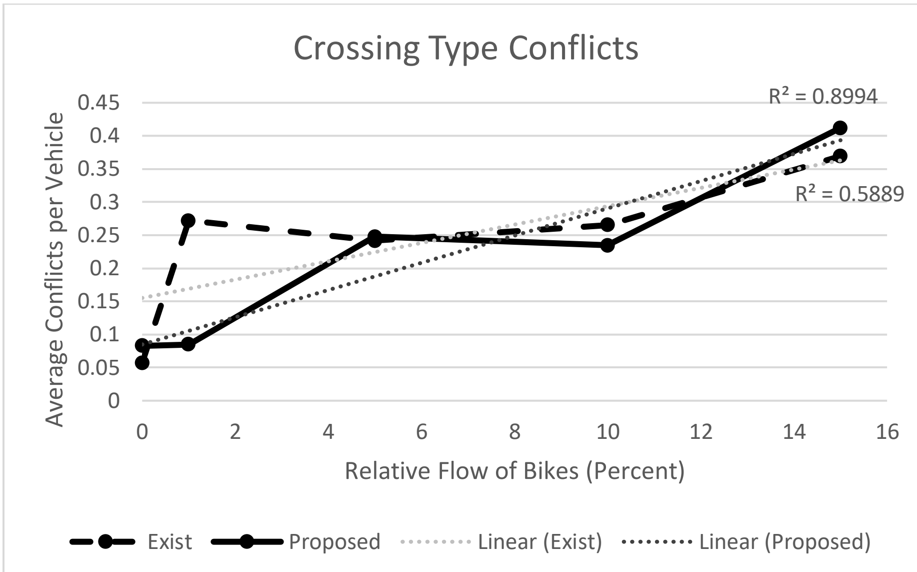

Figure 8 Crossing type conflicts experienced per vehicle, averaged, as a function of the relative flow of bicycles.

The lane change conflicts can be observed in Figure 9. The proposed model had very few lane change conflicts, ranging only from 0.1 at zero percent bicycles to 0.3 at fifteen percent bicycles. However, the existing model showed a great degree of variation, increasing from 0.3 conflicts per vehicle at zero percent bicycles to 1.3 at ten percent bicycles. This represents a 400% increase in lane change conflicts as more bicycles were present on roads. However, lane change type conflicts decreased in the existing model at fifteen percent bicycles, at 0.6 conflicts per vehicle. A polynomial regression can be fit to the lane change conflicts in the existing model with an R^2 value of 0.978.

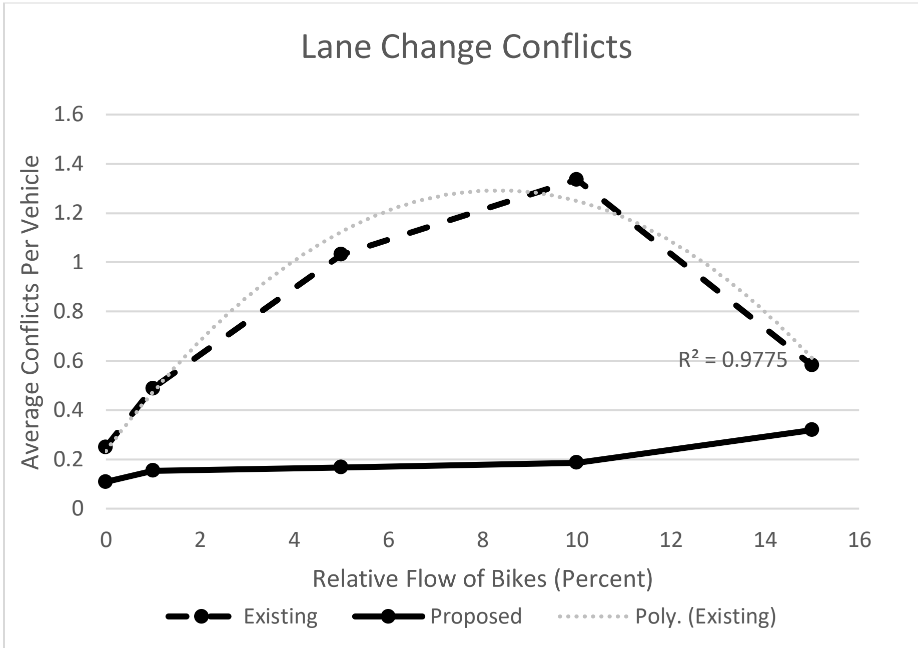

Figure 9 Average number of lane change conflicts experienced per vehicle as a function of the relative flow of bicycles.

Table 3 Number of Conflicts by Type, System-wide

MODEL	PERCENT BIKES	CROSSING	REAR END	LANE CHANGE	TOTAL
EXIST	0	0.06	6.49	0.25	6.79
	1	0.27	10.10	0.49	10.86
	5	0.24	23.66	1.03	24.93
	10	0.27	27.90	1.34	29.50
	15	0.37	41.32	0.58	42.27
PROP	0	0.08	0.79	0.11	0.98
	1	0.08	5.42	0.15	5.66
	5	0.25	2.84	0.17	3.25
	10	0.23	3.08	0.19	3.50
	15	0.41	8.27	0.32	9.00

5.2.2 Cycling Conflicts

Unfortunately, there is no option in SSAM to sort conflicts by vehicle type. Therefore, comparing the safety of cyclists in each model was difficult. However, the intersection at Old Pineville Rd offers a comparison to the proposed intersection at Tyvola Rd and South Blvd. Old Pineville Rd has designated bicycle lanes, so links were constructed to only accommodate cyclists. The data output by SSAM offers conflict information for each link, which offered a proxy of bicycle-related conflicts. Therefore, we can compare the total number of conflicts occurring on the proposed Protected Intersection against a traditional Intersection with on-street bicycle lanes. It is important to note that these intersections have differing volumes, which could have an impact on the total number of conflicts. As volumes are higher around the Protected Intersection, controlling for volume would only improve the degree to which the Protected Intersection outperforms the traditional intersection. SSAM results were taken from two approaches at the traditional intersection and four approaches at the Protected Intersection. In order to compare values along the same number of links, the conflict data at the Protected Intersection was divided by two.

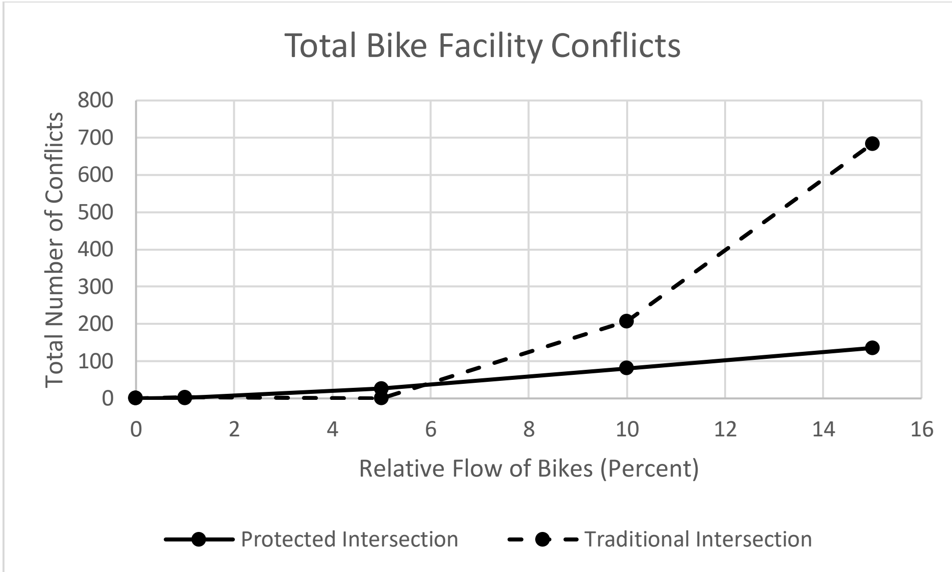

Figure 10 Total number of conflicts on bicycle facilities, compared at each intersection.

All bicycle facility links started with no conflicts, as zero bicycles were on the links in the first scenario. Figure 10 shows that the number of conflicts at the Protected Intersection increased at a linear rate of approximately 9 conflicts for every one percent bicycles. However, conflicts at the traditional intersection increased as a power function and thus, the number of conflicts increased at an increasing rate as bicycles were added. The resulting difference in safety was staggering. At fifteen percent bicycles, the traditional intersection showed 684 total conflicts, whereas the Protected Intersection showed 136 total conflicts. This shows that the Protected Intersection can reduce bicycle-related conflicts by as much as 80%.

The difference between the two intersections in rear-end conflicts is even greater. Again, the number of conflicts at the Protected Intersection increased linearly, but the number conflicts at the traditional intersection seem almost exponential. Figure 11 shows that at fifteen percent bicycles, the traditional intersection had 93 rear-end conflicts and the Protected Intersection had 36 rear-end conflicts. Below fifteen percent, the Protected Intersection had a slightly higher rate of rear-end conflicts.

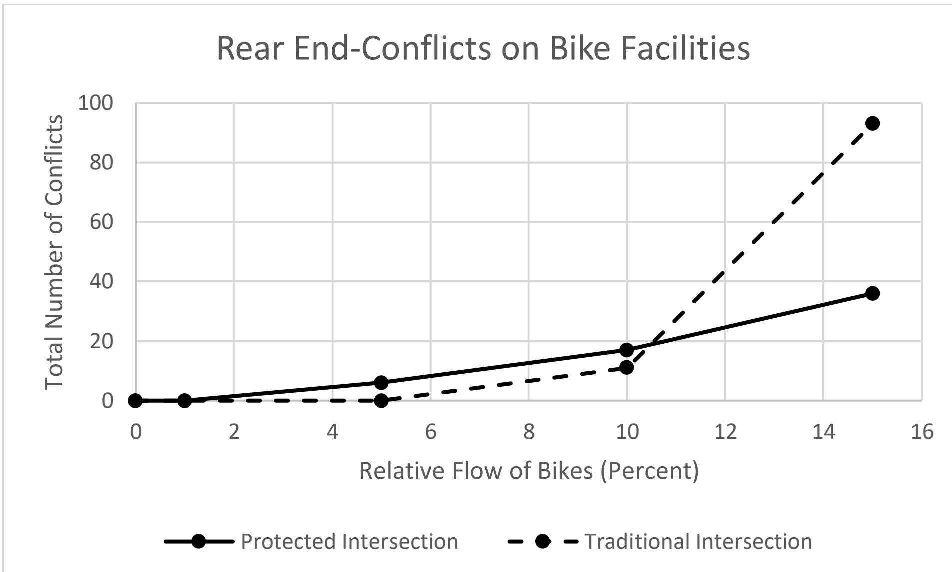

Figure 11 Rear-end conflicts on bicycle facilities compared between two adjacent intersections of different types.

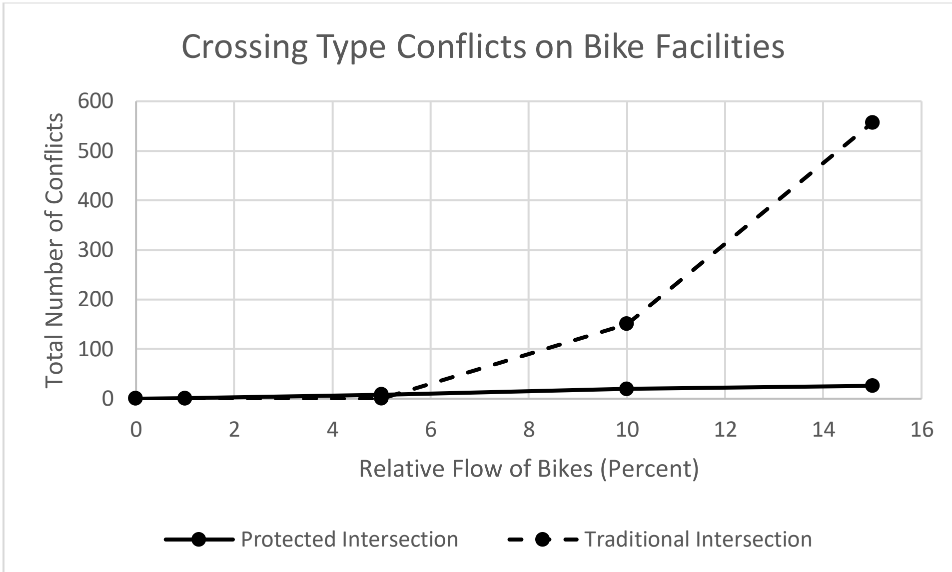

Figure 12 Crossing type conflicts at the two intersections as a function of the relative flow of bicycles.

The difference in crossing type conflicts between the two intersections was also highly significant. The Protected Intersection had only 26 crossing-type conflicts at fifteen percent bicycles. By comparison, the traditional intersection at Old Pineville Rd showed as many as 557 crossing-type conflicts at fifteen percent bicycles, twenty times greater than at the Protected Intersection. Even at ten percent bicycles, the proposed intersection showed only 20 conflicts when the traditional intersection had 151 conflicts.

The lane change conflicts presented a deviation from the previously mentioned patterns in conflicts. The protected intersection at Tyvola Rd and South Blvd still maintained a linear increase in the number of conflicts as the relative flow of bicycles increased. The traditional intersection at Tyvola Rd and Old Pineville Rd had much more variation. At ten percent bicycles, both intersections showed 45 lane change conflicts. The rate then decreased at the traditional intersection and increased at the Protected

Intersection. At fifteen percent bicycles, the proposed Protected Intersection showed 74 lane change conflicts while the traditional intersection showed 34 conflicts. This variation can be observed in Figure 13.

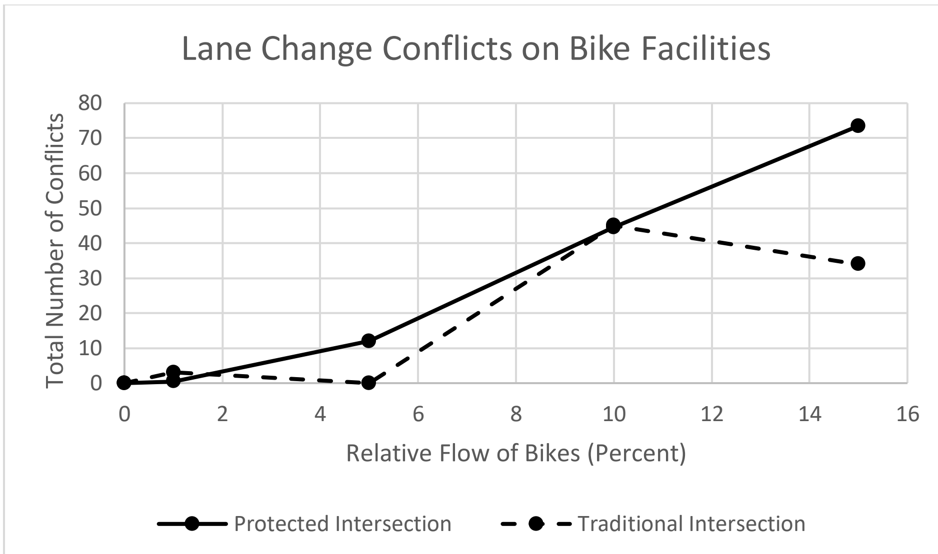

Figure 13 Lane change conflicts at the protected intersection versus the traditional intersection, as a function of the relative flow of bicycles.

Table 4 Number of Bicycle-Related Conflicts by Type

INTERSECTION TYPE	PERCENT BIKES	CROSSING	REAR END	LANE CHANGE	TOTAL
PROTECTED	0	0	0	0	0
	1	1	0	0.5	1.5
	5	8	6	12	26
	10	19.5	17	44.5	81
	15	26	36	73.5	135.5
TRADITIONAL	0	0	0	0	0
	1	0	0	3	3
	5	0	0	0	0
	10	151	11	45	207

	15	557	93	34	684

CHAPTER 6: ANALYSIS

The relative flow of cycling was modeled at 0%, 1%, 5%, 10%, and 15% in order to model varying scenarios seen in bicycle-friendly cities across the United States. These flows were modeled on the existing geometric design of the Tyvola Rd and South Blvd intersection, as well as the proposed Protected Intersection design. It was hypothesized that the Protected Intersection design would improve safety at the intersection, as measured in potential conflicts in modeled trajectories. It was also hypothesized that operation would show at least marginal improvement as bicycles users switched mode choice and fewer cars were on the road.

6.1 Operational Effect

As a whole, it cannot be confirmed that the proposed Protected Intersection improves operational performance. As more bicycles were added to the proposed intersection, delay decreased. However, this is only due to the fact that the relative share of bicycles was increasing, by which the relative share of motor vehicles decreased. Decreasing the number of motor vehicles on the road leads to a decrease in the delay. As more bicycles were added to the shared lanes of the existing intersection, delay increased. As any motorist has observed, one bicyclist on the road can result in a long queue of vehicles behind him or her, particularly under congested conditions. Bicycles travel at a slower speed and cause the speeds of the vehicles queuing behind them to slow significantly. When cyclists are on a shared lane, delay increases even if there are fewer motorists.

Apart from delay, there are additional hazards associated with cyclists on a shared lane. Motorists seeking to pass other users create lane-change hazards, as demonstrated in

Figure 9. Delayed traffic promotes motorist anxiety and frustration. Several studies, as well as a shared experience, support that congested roads can increase road rage and aggressive or reckless behavior (Smart et al., 2004). A 2018 study by Delbosc et al. (2019) discussed hostility and violent behaviors toward cyclists in Australia. The study shows that on-road cyclists are often dehumanized or viewed as “less than human.” Aggression from delay combined with a lack of respect for cyclists may lead to exacerbated safety hazards for cyclists. If cyclists are seen as a burden or faced with aggression, hostility, or even violence, they will be much less likely to use the facility.

It is important to note that data is not separated by vehicle type. This is somewhat irrelevant for the existing model because cyclists and motorists are together. However, it is likely that cyclists and motorists could experience differing amounts of delay when traveling on separate facilities. In fact, it is likely that cyclists would experience less delay as cycle paths are less congested and offer a better LOS, particularly toward the left of Figure 3, when the relative flow of bicycles is low and delay is high. The sight of an unhindered bicyclist driving past the quarter-mile of queued vehicles may lead to increased bicycle mode choice.

The initial increase in delay in the proposed Protected Intersection model is due to the elimination of RTOR privilege, or “right-turn-on-red.” This is strictly prohibited in the Evolution of the Protected Intersection (Gilpin, 2015). RTOR is rare in other developed countries with more diversity among mode choice. In the US, it is uncommon for RTOR to be prohibited. Restricting RTOR increases safety for pedestrians, cyclists, and through traffic (Preusser et al., 1981). Though delay could be minimized, the practice of allowing RTOR behavior at crowded, multimodal intersections should be carefully considered on a case-by-case basis.

The operational performance at the proposed Protected Intersection will not improve until the relative flow of bicycles reaches 15%, at which point delay could be almost equal to that of the existing, zero-bicycles intersection. This means that a 15% reduction in motor vehicles is required in order for the added delay in removing RTOR to be mitigated. It is clear that the Protected Intersection design does not improve operations for all users, as measured by the delay. However, allowing cyclists their own lane versus shared lane results in improved operational performance over time.

As the LOS at an intersection is determined by delay, it is reasonable that the patterns shown in Figure 4 mirror those shown in Figure 3. Though seemingly redundant, it is important to consider LOS because it qualifies the overall function of a facility. Under current conditions, the existing intersection operates at a LOS E. The LOS E is associated with at-capacity conditions and improvements will need to be made immediately. The observed operational performance is not specific to the proposed Protected Intersection, but rather to the relative flow scenarios chosen and simulated.

One could argue that on-street bicycle lanes could offer the same operational performance as bicycles and motor vehicles do not share the same lane. However, implicit in the concept of vehicle composition and relative flow is the mode choice. The facility must be attractive enough to the user in order to be chosen. Mode choice, and therefore revealed preference is the primary difference between on-street bicycle lanes and separated bicycle lanes. Nguyen et al. (2018) compared revealed preference of cyclists on on-street and off-street facilities and found that women and inexperienced riders almost always choose off-street facilities. Experienced male cyclists may prefer on-street facilities when given the choice between a bicycle lane and off-street shared path with pedestrians. However, they found that traffic conditions play a major role in a user's perceived safety and that high volume roads discourage on-street riders. This research reiterates the policies outlined by Charlotte Bikes (City of Charlotte Department of Transportation, 2017). The City of Charlotte recommends a separated bicycle facility for roads with vehicle speeds greater than 30 mph and volumes greater than 4,000 ADT. The intersection at Tyvola Rd and South Blvd far exceed these thresholds, so a separated bicycle lane would be the only recommended bicycle facility to install. It is therefore imperative to provide the safest facilities possible, especially at an intersection as major as this. The facility type promotes safety, which promotes mode choice, which then leads to operational performance improvements.

6.2 Environmental Impact

State or local governmental investment in alternative and eco-friendly modes of transportation is imperative for the well-being of our planet. The 2018 Intergovernmental Panel on Climate Change Special Report states that in order to prevent the catastrophic events associated with global warming in excess of 1.5°C, global net anthropogenic CO_2 emissions must be reduced by 45% by 2030 (IPCC, 2018). Transportation is one of the primary sources of CO_2, associated with nearly one-quarter of the total CO_2 emissions (Wang et al., 2018). As a whole within the national economy, the transportation sector contributes 29% of the total greenhouse gases (GHGs), though it is perhaps the most dominant source of GHGs on a household basis (Desai and Camobreco, 2019). The Environmental Protection Agency (EPA) reports that each gallon of gasoline burned creates 20 pounds of GHGs. This equates to roughly an average of 4.7 metric tons of GHGs per year per vehicle (Office of Transportation and Air Quality, 2014).

With reports such as these, many people have been seeking to reduce their own carbon footprints by switching to a more sustainable mode of transportation. Unfortunately, efforts on an individual basis are not enough. Figure 5-A shows that as bicycles are added to the system, fuel consumption actually increases, even up to ten percent bicycles. Cycling without the right infrastructure is not only dangerous but can cause delays to the system, which actually has an adverse environmental impact. The slowing, then accelerating required of the passing behavior of a vehicle on shared lane results in increased fuel consumption, not to mention the overall increase in travel time. The phenomenon of increased fuel consumption on the existing model despite fewer cars illustrates why efforts meant to be environmentally conscious must stem from a state or city level. Even after adjusting the data to compensate for potential model-rated errors, there is still a significant difference between the amount of fuel consumed in the existing and proposed Protected Intersection designs.

At ten percent bicycles, vehicles on the existing model consumed 167 gallons of fuel per hour and vehicles on the proposed Protected Intersection model consumed 101 gallons of fuel per hour. Over a single 2-hour evening peak, this results in 3.3 tons of GHGs produced on the existing model, compared to 2.0 tons produced on the proposed Protected Intersection model. This results in 339 more tons of GHG produced per year on the existing model versus the proposed Protected Intersection model. This calculation only includes weekday traffic, specifically at the Tyvola Rd and South Blvd intersection, and only considers 2 hours of traffic. When considering the whole day, the difference between the existing and proposed models would be over twice this calculation.

Looking at a less extreme scenario, 141 pounds of fuel per hour is currently consumed on the existing model, with zero percent bicycles. If the proposed Protected Intersection were constructed and bicycles made up only one percent of the vehicle composition during the weekday evening peak hour, nearly 30 tons of GHG emissions would be saved over the course of the year. This value considers only one intersection over two hours. If the City of Charlotte as a whole promoted safe cycling infrastructure, massive amounts of GHG emissions could be prevented. But to reiterate, these changes must take place at an infrastructure level. Cycling without proper infrastructure could result in delays that increase fuel consumption by up to 20%.

6.3 Safety Effect

Safety can be analyzed in two separate contexts. The first is along the system as a whole, with all vehicle types equally considered. The second analysis focuses on bicycle lanes in particular, as a proxy for the ways in which cyclists themselves might encounter conflicts.

6.3.1 System Conflicts

From a safety perspective, the more bicycles placed on a shared lane, the more conflicts will occur. Bicycle speeds averaged about 11 mph, whereas vehicle speeds averaged around 35 mph when not queuing. The delay produced by bicycles on a shared lane drastically alters the trajectory of a vehicle. The vehicle must either slow to queue behind the bicycle or change lanes to pass the bicycle. Both of these maneuvers can produce a conflict in the model. Looking at Figure 6, it is clear that from a system perspective, the proposed model presented fewer conflicts and was safer than the existing model. The margin of this difference increases as more bicycles are added to the system.

The rear-end type conflicts demonstrated in Figure 7 are most likely caused by excessive amounts of queuing. The greater the number of bicycles on the shared lane, the more queuing and the number of rear-end conflicts. The existing model shows a pretty linear rate of increase in conflicts per vehicle as to the relative flow of bicycles increases. The proposed model shows a little more variation. Much fewer rear-end conflicts occurred on the proposed model. After one percent bicycles, the number of conflicts per vehicle decreases. This can be attributed to the lower volume of vehicles on the roads as a result of the change in vehicle composition. However, after 10 percent bicycles, the number of rear-end conflicts in the proposed Protected Intersection model begins to increase. Unfortunately, SSAM does not allow conflicts to be analyzed by vehicle type. It is likely that the increase in conflicts occurred among bicycles and that the bicycle lanes themselves became more congested. From a perspective of rear-end conflicts, the optimum safety performance on the system occurs when bicycles make up ten percent of the traffic on the proposed design.

Lane change type conflicts are related to side-swipe and passing behavior. Crashes of this conflict type tend to be less severe and may result in property-damage-only. The safety optimum for rear-end conflicts in the proposed Protected Intersection model occurred at ten percent bicycles. Ironically, ten percent of bicycles represent the peak in the number of conflicts for lane change conflicts. The parabolic nature shown in Figure 9 illustrates that there are multiple factors affecting the number of lane change conflicts. The number of bicycles on the existing system is increasing, resulting in an increase in the number of passing maneuvers. This would cause an increase in the number of lane change conflicts. Simultaneously, the number of motor vehicles on the system is decreasing. This would cause a decrease in the number of lane change conflicts as it becomes easier to find gaps. These two phenomena occurring simultaneously results in the parabolic curve, and the sharp decrease in the number of lane change conflicts on the existing model at fifteen percent bicycles. As previously discussed with rear-end conflicts, the rate of lane change conflicts in the proposed Protected Intersection model increases at fifteen percent bicycles, which could indicate near-capacity conditions.

It is difficult to make inferences related to crossing type conflicts. Figure 8 shows an insignificant difference in the number of conflicts between the existing and proposed Protected Intersection models. The proposed Protected Intersection is intended to significantly improve crossing type conflicts, as these are one of the most severe crash types. It is important to consider that the SSAM data was not aggregated by intersection but instead looks at the whole system. Only one of the three simulated intersections had improvements modeled. If the number of conflicts increased in one area of the model but decreased at another, SSAM would not indicate a net change. It is clear that as a whole system, the SSAM data does not indicate safety improvements as pertaining to crossing type conflicts.

6.3.2 Bicycle Specific Conflicts

Though vehicle specific conflict data could not be analyzed, there is significant data supporting that bicycles were much safer at the Protected Intersection, as observed in Figure 10. The linear increase in all the conflict types along the Protected Intersection (figures 8-11) indicates that bicycles conflicts occurred with other bicycles. Bicycle-to-bicycle crashes may result in some injury, but they are nowhere near the severity of a bicycle-to-vehicle crash. Conflicts by type on the Protected Intersection appear to increase proportionally as bicycles are added to the system and the volume approaches the facility capacity.

Channelization is likely correlated to the instances or rear-end and lane-change conflicts, as bicycles are forced on a specific path. Capacity is limited because the lanes have clearly delineated, inflexible barriers. Bicycle lanes were 7' wide throughout the intersection. The curb-to-curb distance between the refuge island and the sidewalk was roughly 14' and varies slightly for each corner of the intersection. Because of the skewed angle of the intersection, bicycle storage lengths were much greater at the obtuse-angled approaches, at the westbound and eastbound approaches. Storage at the southbound approach is as low as 10-14'. If the 7' lane allows two bicycles to wait side-by-side, the approximate storage capacity could be as low as 3 or 4 bicycles at the southbound approach. By contrast, storage at the eastbound approach is as high as 42,' and could accommodate as many as 8-10 bicycles. Greater storage would limit the number of conflicts between cyclists and increase capacity.

It is likely that bicycles could navigate around each other better than cars might, as they travel at low speeds, take up less space, and can make easier eye contact. The capacity could be greater than simulated, as the vehicle characteristics in the model may not have been the most accurate.

One drawback of channelization is that bicycles are forced to stick to a specific path, and might be hindered in their navigation around each other. However, bicycle-to-bicycle conflicts are far less of a safety concern than bicycle-to-vehicle conflicts, so channelization is preferred.

The most important improvement observed with bicycle safety was the difference between crossing-type conflicts on the bicycle lane intersection versus the Protected Intersection. Crossing type conflicts are the most dangerous because they occur at approximately 90° so the full force of the impact is felt by each party if a crash occurs. When the full force of a vehicle traveling at 35 mph is felt by a bicyclist, the resulting crash could lead to severe injury or even death. Therefore, the primary focus of the Protected Intersection is to prevent crossing-type conflicts. The Protected Intersection works because concrete refuge islands force vehicles and bicycles into their own separate trajectories. Unlike a painted stripe on a bicycle lane, motorists risk causing damage to their own vehicles if they are incompliant.

Crossing type conflicts are also minimized because of the forward stop bar. This decreases exposure time by lessening distance required to cross the intersection. In the proposed Protected Intersection, the distance from the outer edge of each crosswalk is approximately 165’ for each approach. This is the minimum distance a vehicle would have to travel to cross the intersection. By contrast, the path for cyclists to cross is only 84’ to cross South Blvd or 65’ to cross Tyvola Rd. If a cyclist travels at 8 mph, or 11.7 feet/sec, his or her exposure time would be 7.1 seconds along the Protected Intersection path versus 14.2 seconds along the road. The exposure time at the Protected Intersection is half of that along the road. Across Tyvola Rd, the exposure time is even lower at 5.6 seconds. Reducing exposure time by this magnitude greatly reduces the likelihood of an incident to occur, helping cyclists feel safer and therefore promoting cycling as a viable and attractive mode of travel.

Though changes to the signal would be recommended in further study, no changes were made to the signal plan for this study. Despite this fact, bicycles were able to clear the intersection during the yellow and all-red clearance interval. Though they travel at a slower speed, the shorter required distance across the intersection allows for shorter clearance intervals. This allows the signal to run more efficiently with less lost time. It is important to note that no changes were made to the intersection at Old Pineville Rd. The bicycle lanes along this road are an existing condition and the conflicts presented in the data represent possible conflicts of bicycles currently crossing the intersection.

Currently, the percent of bicycles on Old Pineville Rd during the evening peak hour is very less. Therefore, the number of crossing-type conflicts is lower in number. However, this is a very real safety hazard. Few cyclists currently use these facilities because they simply are not safe to use.

Clearance intervals are calculated based on the grade, width, and design speed of an intersection. Along Old Pineville Rd, the total clearance interval, including yellow and all-red times is 6.6 seconds on the northbound approach and 6.2 seconds on the southbound approach. The width of the intersection is 158' and the average length of a bicycle is 6'. If a cyclist is traveling at 12 feet/second, it would take the cyclist roughly 14 seconds to clear the intersection. This means that cyclist could pass the stop bar when the light is still green, cross during the yellow and all-red phases, and still have another 8 seconds of travel time before he or she is safe. This is why over 500 crossing conflicts were simulated on bicycle paths at the Old Pineville Rd intersection for fifteen percent bicycles.

Not enough of our current roadways are designed with cyclists in mind. Roads are designed for vehicles and using the speeds of vehicles for their calculations. If bicycle lanes are delineated, they are thrown in as an obligatory after-thought. Designing this on-street, painted bicycle lanes is frankly a waste of city and state funding because few people are ever going to use them. They are not safe. Bicycle facilities are not designed to the same rigorous safety standards as motorized facilities. So often, bicycle lanes are drawn onto a street and the lane ends at an arbitrary point with no clear thought about the path of the cyclist. It is possible that the engineers who designed the intersection of Old Pineville Rd and Tyvola Rd anticipated that cyclists would get off their bicycles and cross the street as a pedestrian, but this is in no way indicated to the user. In fact, the current pavement markings indicate that a cyclist is intended to cross the intersection like a vehicle because the stop bar crosses the bicycle lane in the same way as the motorized lanes. The bicycle lane does not appear to be in any way connected to the crosswalk. In the intersection itself, there is no striping whatsoever. The result is a confusing and ambiguous path for cyclists that can result in conflicts with vehicles.

The intersection at Old Pineville Rd and Tyvola Rd demonstrates why planners and engineers need to move beyond the painted, on-street bicycle lane and consider intersection treatments for cyclists to the same level that they would consider intersections for vehicles. The difference in total conflicts comparing the traditional, bicycle lane intersection and the proposed Protected Intersection is astounding. If conflicts occurred at the Protected Intersection, they most likely occurred between bicycles and would have been minimally severe. A significant number of the conflicts that occurred on the bicycle lanes at the traditional intersection most likely occurred between bicycles and motor vehicles due to possible oversights on intersection design.

6.4 Potential Error

There are several potential sources of error related to this research, most stemming from the use of PTV VISSIM. It offers an incredibly detailed microsimulation platform, and a system can be programmed down to the level of detail of the number of Ford F-150's using the roads. Because of limited resources, this simulation did not parametrize each and every vehicle on the road. As PTV is a German company, vehicles modeled in this research most likely resembled the types of vehicles one might see on the road in Germany. It is likely that vehicles in the model would have been more compact than those existing on the intersection in reality, resulting in an over-estimating of intersection capacity. Additionally, speed distributions were not parametrized, which would have added accuracy to the model. Instead, vehicles were modeled to drive slightly above the speed limit and buses and heavy vehicles were modeled to drive slightly below the speed limit.

There were some concerns with the driving behavior utilized on shared lanes. It was important to model the lateral behavior of vehicles passing slow-moving bicycles, so the procedure recommended in the VISSIM Manual was used. However, the "look ahead" distance specified by the Manual may not have provided sufficient stopping sight distance for vehicles, leading to a major influx of rear-end type conflicts.

As previously mentioned, it appeared that fuel consumption related to this driving behavior was erroneous, as the model showed roughly twice the fuel used on the existing model than on the proposed model, even when no bicycles were present. Controlling for this discrepancy was attempted by reducing all the fuel consumption values in the existing model by 42%, in order for fuel consumption at zero percent to be equal on both models.

Models may not operate like humans unless each specific behavior under each specific scenario is defined. For example, priority rules had to be laid out at each intersection, despite the use of a signal. This is because the system was operating at capacity. The westbound queue from the intersection of Old Pineville Rd and Tyvola Rd sometimes backed up into the intersection of Tyvola Rd and South Blvd, resulting in vehicles blocking the intersection. Though this is often seen in real-world situations, motorists know that even though they may have a green light, they must yield until the intersection becomes unblocked. The model will not facilitate this yielding behavior unless traffic on each and every lane is programmed to give priority to vehicles in the intersection.

CHAPTER 7: CONCLUSIONS

Bicycles provide a sustainable and inexpensive form of transportation that can improve the overall quality of life within a city. They have the potential to improve public health by offering active transport and reducing the amount of air pollution. They provide a mode of transportation to low-income residents who might not be able to afford a car and supplement the Charlotte light rail system by providing door-to-door accommodation. In order to offer a viable alternative to motorized vehicles, bicycle networks must provide a safe and connected path from origin to destination. Though the City of Charlotte has made efforts to construct bicycle facilities when possible on roadway improvement projects, much of the bicycle network is fragmented and unsafe. The City of Charlotte Bike Plan states that "The City will create a safe, comfortable and convenient network of bicycle facilities that aid and encourage cycling for people of all ages, abilities, and interests, in all areas of Charlotte" (p 26). Though a noble vision, the City has many improvements to make before it accomplishes this goal.

This research provides evidence that the Protected Intersection design can reduce bicycle-related conflicts by as much as 80%. As thirty percent of all bicycle-related fatalities occur at urban intersections, it is essential that intersections receive just as much, if not more consideration by planners and engineers than longitudinal facilities (Pedestrian and Bicycle Information Center, 2018). Intersections are an integral part of any transportation network. If cycling infrastructure is to be designed, it should be given the same attention that one gives to infrastructure for motor vehicles. Infrastructure should be looked at from a connected network level and safety should be at the forefront of design along every link and node in the network.

The Protected Intersection offers promising results for reducing GHG emissions, even if only implemented in select areas. If implemented throughout the city, the possible reduction in GHGs would be astronomical. Like network connectivity, GHG reduction is only possible if implemented from an initial design standpoint. This research demonstrates that when bicycles are on a shared network, they can have an adverse effect on total fuel consumption by causing vehicle delays. In fact, by separating bicycles from on-street traffic, emissions can be reduced by up to 40%.

This research did not find evidence that the Protected Intersection improved overall operations at the intersection. Delay was reduced when bicycles were separated from motor vehicle lanes, but the removal of RTOR privilege negated any delay savings.

The City of Charlotte is growing by approximately 1.8% each year and the roads are nearing or exceeding capacity, resulting in more congestion, more crashes, and more delays. The greater metropolitan region is projected to reach 2.74 million residents by 2030 (World Population Review, 2019). It is physically impossible and extremely inefficient to transport all of these commuters by private vehicle. By investing in alternative modes of transportation, the city can more efficiently transport its residents and improve the total system capacity. Studies have shown that Charlotte is the 4th fastest growing city in the United States and the 1st in the growth of the number of businesses (Jensen, 2018). As a result, city planners will have to carefully consider how to make the city an attractive and socially sustainable place to live.

The intersection of Tyvola Rd and South Blvd currently operates at a LOS E or F, demonstrating that volume currently meets or exceeds capacity. To mitigate the effects of increased demand, this intersection will have to receive dramatic improvements in the next few years. If the intersection will be under construction to improve operation anyway, it is highly recommended that the Protected Intersection and longitudinal bicycle facilities be installed as well. Cycle tracks improve LOS by reducing demand on the roadways. Planners can install cycle tracks to increase capacity and further augment the operations of the system. Though RTOR would need to be restricted, the system would be able to serve a greater number of users.

7.1 Limitations and Scope for Further Study

The ROW was not specifically considered during the design process as the survey was not available. However, the encroachment onto properties, and therefore the proposed ROW acquisition was minimized. One significant issue was that some buildings appear to be within the existing ROW. Some building conflicts were avoided by using minimum bicycle lane and sidewalk widths and removing the planting strip. For example, in the Southwest corner of the intersection, approximately 200’ down South Blvd, the Kidz Dental building was placed close to the ROW. However, the bicycle lane was able to fit within the existing planting strip. Unfortunately, the same procedure was not possible at conflict in the northwest corner of the intersection. The edge of the building for Maria’s Mexican Restaurant was only 12’ from the existing edge of travel, probably within the existing ROW. Further, the study proposes ROW acquisition of the restaurant and relocating to another section of the lot. Further, the mobility improvements for pedestrians and cyclists will improve access to the area, possibly improving business and increasing property values. Because the conflict with the building was unavoidable, the standard typical cross section was used instead of a minimized typical. The financial cost of the construction of the Protected Intersection was not within the scope of this study but should be researched further.

Suggestions for other further study include simulations of future traffic volumes and simulations of other intersections in Charlotte. The study intersection operated at LOS E or F during existing conditions. The effect of a Protected Intersection on safety, operation, and emissions should be studied in areas operating at a more favorable LOS, such as B or C. This study did not look into changes of the existing signal, though results show that the effects of this were minimal. Further, future study should consider optimizing signal control for bicycle infrastructure.

Another source of further study is the Cross Charlotte Trail Project. The project promotes many of the benefits discussed in this research, such as equitable transportation, safe bikeways, and more environmentally sustainable solutions. The trail could also require intersection improvements when approaching an urban setting as opposed to the typical greenway setting. The Cross Charlotte Trail has recently received criticism for its lack of funding. However, the findings of this research support that funding and design for the Trail and other safe bicycle projects need to be implemented as soon as possible.

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