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DISSECTING THE SAFETY BENEFITS OF PROTECTED INTERSECTION DESIGN FEATURES

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DISSECTING THE SAFETY BENEFITS OF PROTECTED INTERSECTION DESIGN FEATURES

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by

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ABSTRACT

DISSECTING THE PERFORMANCE SAFETY BENEFITS OF PROTECTED INTERSECTION DESIGN

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Protected intersections are an integral component of Complete Street networks and are used to facilitate and delineate the route cyclists should take while traveling along a protected network. The separation from the travel lane of automobiles, however, causes a decrease in driver attentiveness to cyclists. Rates of incidents of cyclists, specifically with right turning vehicles, have increased in recent years, leading to a desire to improve the safety benefits of existing protected intersections to increase the visibility of cyclists and driver awareness. This research used a simulated environment to test the effectiveness of different pavement markings and intersection radii on the speed and attentiveness of drivers. Participants were recruited to drive twelve scenarios in a simulated world and their speed, position, braking behavior, and glance pattern were analyzed to determine what combination of variables leads to the highest increase of safe interactions between cyclists and automobiles in a protected intersection. A speed and regression analysis were conducted to determine which variables influenced participants speeds the greatest, thereby improving the level of safety in the intersection. It was found that the size of the protected elements, the presence of a cyclist, and a participant's gender were all significant in influencing the speed at which drivers navigated the intersection ($p<0.05$) for right turns. The slowest speeds were recorded when a larger intersection radius was used in conjunction with a dashed white line through the protected intersection, suggesting that the combination of those two variables are effective in improving the level of safety for cyclists and motorists in a protected intersection.

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INTRODUCTION

Bicycle and pedestrians utilize roadways and intersections designed to easily accommodate automobiles, and these road users were typically an afterthought in terms of roadway design and construction with regards to existing infrastructure. With an increase in cyclists and pedestrians, coupled with the expiring lifespans of road networks, transportation planners and engineers are reevaluating, redesigning, and reimagining intersections to accommodate all users, with the intended goal of increasing the level of safety for everyone. One method to improving the safety of intersections is the creation of protected intersections through minor adjustments to the existing intersection design, and presently this is accomplished through the introduction of Complete Street projects and policies to encourage redevelopment along corridors suitable to all modes of transportation.

Streets and avenues in America have routinely been created to favor the fastest route for vehicles, while neglecting to provide an equitable alternative for pedestrians and cyclists within existing transportation systems. As towns and municipalities explore how to improve their infrastructure, planners are routinely turning to Complete Streets to design solutions for transportation in the 21st century. A physical barrier to the realization of Complete Street networks is the lack of connectivity between existing bike and pedestrian infrastructure, different networks, and the high costs associated with redesigning and improving existing streetscapes. In theory, Complete Streets work great when connected as part of a network system with seamless transitions from many origins and destinations. The reality is that Complete Streets are typically integrated on a piecemeal basis if a corridor or street is slated to be redesigned already, and rarely as a coherent network. The goal, of course, is to achieve such a network over time as more funding becomes available and demand for such accommodations increases, but that is expensive and time consuming for areas that have high conflict rates among bicycles and automobiles.

One solution to improving the network efficiency of complete streets are improvements which can be made to existing intersections in order to reduce congestion and improve the safety and visibility of pedestrians and cyclists. By modifying already existing infrastructure to a classification of ‘protected,’ cities and towns could potentially recognize some of the benefits of Complete Streets without redesigning the entire street. These improvements would be low cost and ideally not

require extensive construction work on the intersection, minimizing the planning and time required to install such benefits.

Enhancing existing intersections through the introduction of protected elements can lead to increased levels of safety for cyclists by improving their visibility and increasing driver awareness. Currently, these safety enhancements are found through the implementation of a Complete Streets project, where the complete redesign of the road network creates protected bicycle lanes and intersections for cyclists. A major benefit of Complete Streets is that they create protected areas for cyclists and pedestrians to use separate from cars. While these protected areas increase the safety of the users, the presence of such protected areas may decrease driver awareness of the presence of cyclists, leading to more incidents at intersections as drivers are not reminded on a frequent basis of the presence of cyclists.

Enhancing the existing level of safety and comfort protected intersections provide to cyclists and motorists is the goal of this research. These modifications to existing protected intersections will be created and tested in a simulated environment. A simulated environment will be created to test the effectiveness of different levels of treatment at existing protected intersections to inform planners and engineers of minor improvements that can be made to existing infrastructure. Participants in the simulation will encounter different types of pavement markings and varying sizes of intersection radii to determine what combination of changes can be made that will have highest level increase of safety for cyclists.

Research Motivation

This research seeks to determine the effectiveness of different treatment levels on the success of protected intersections. By improving the efficiency and safety of protected intersections, increases in network connectivity and bicycle trips can be realized as more users become familiar with navigating protected intersections. Ultimately, these minor adjustments to protected intersections are anticipated to lead to increases in safety, reductions in incidents between cyclists and drivers, cost savings to municipalities that wish to improve already constructed protected intersections, and the relative ease with which these modifications can be made to existing intersections to achieve benefits similar to that of a protected intersection.

Research Scope

The scope of this research will focus on answering the following questions:

- What effect do minor changes in a protected intersection radius have on driver behavior while performing turning movements?
- What effect do changes in the level of bicycle lane marking have on driver behavior while approaching, turning, and exiting a protected intersection?
- What combination of intersection radius and bicycle lane markings achieve the greatest increase in safe driving behavior for motorists and cyclists?

Existing protected intersections and relative design guidelines will be consulted in the creation and testing of different elements in a simulated environment.

LITERATURE REVIEW

This section will highlight the different resources consulted throughout the research process to construct the scenarios. The rationale for pursuing this research was examined through the use of relevant cyclists' literature to highlight the growing problem crashes between automobiles and cyclists is becoming in the United States. Existing levels of protected intersection and the specific elements that are implemented and installed to enhance cyclist safety and visibility were also reviewed. The effect that Complete Streets projects have had on protected intersections and cycling networks was explored to determine what practitioners are using in their redesign and reconstruction of streetscapes for all users. And finally, prior simulation work was consulted to examine what was tested, how the experiments were constructed, and what important decisions were made in the simulated environment to accommodate the participants while generating the most valuable data.

Cyclist Literature

Injuries arising from cyclist crashes with automobiles can be attributed to either collision with the ground or vehicle. There is, however, evidence to suggest that more serious types of injuries result from collisions with vehicles (Badea-Romero, A., & Lenard, J., 2013). Cyclist deaths due to traffic crashes have decreased slightly over the years, while the number of injuries has increased. According to the National Highway Traffic Safety Administration, cyclists accounted for 726 traffic deaths in 2014, down from 749 in 2013, while their rate of injury increased from 48,000 to 50,000 (DOT HS 812 246, 2016). Similarly, in the FARS dataset, fatalities have increased from a rate of 1.8% in 2000 (691/37,526 cyclists/fatalities) to 2.5% in 2015 (812/32,538 cyclists/fatalities) (US DOT, 2018).

This trend has continued in recent years, with the most recent data indicating that cyclists accounted for 2.2% of all fatalities in 2016 (840/37,461 cyclists/fatalities) across the United States. While one could argue that the overall rate of fatal accidents for cyclists is decreasing, the increase in overall traffic fatalities is a worrisome sign that American roadways and intersections should be made safer for all users (NHSTA, 2019).

Attempts have been made to measure the level of comfort of cyclists in urban environments using a static evaluation. Ghodrat et al. distributed an electronic survey to 342 participants seeking to understand their perceived level of comfort if they were the cyclist present in the image. The survey tested three different types of pavement markings as recommended by the National Association of City Transportation Officials *Urban Bikeway Design Guide*, three different levels of traffic volume, and two different signs (NACTO, 2011). The results of the survey indicated that truck traffic had the greatest effect on a cyclist's level of comfort, but the type of marking used did not drastically alter the comfort drivers experienced.

Various improvements for cyclists on bike lanes and intersections have been shown to be effective in improving the safety for cyclists and other road users. By reducing or eliminating conflict points between cyclists and automobiles, protected intersections and bike lanes enhance the comfort and safety of road users (Harris et al., 2013; Thomas and DeRobertis, 2013; Teschke et al., 2012; Lusk et al., 2011). Multiple types of treatment have been tested at intersections, such as the placement or continuation of bike lanes after a protected intersection (Schepers et al., 2017), signal phases for bicyclists (Furth et al., 2014), and protected intersection conflict points in mixing zones (Madsen and Lahrmann, 2017). While each of these treatments have their own benefits associated with them, this research will focus specifically on improving the already existing elements of protected intersections.

Protected Bicycle Elements

Cyclist deaths due to traffic crashes have decreased slightly over the years, while the number of injuries has increased. According to the National Highway Traffic Safety Administration, cyclists accounted for 726 traffic deaths in 2014, down from 749 in 2013, while their rate of injury increased from 48,000 to 50,000 (U.S. DOT, 2016 27,28). With the increase in bicycle infrastructure, the rate of right hook crashes between cyclists and automobiles has increased and become a focus of recent research (Warner et al. 2017). While increases in incidents can potentially be attributed to higher levels of comfort and safety experienced by cyclists, and an increase the amount of protected cycle features, there is a need for further research. States, such as Oregon, have noticed that right hook incidents between bicycles and motorists accounted for over 500 crashes and approximately 59% of all reported crashes (Hurwitz, D., Monsere, C., Jannat,

M., Warner, J., Razmpa, A., 2015. Towards Effective Design Treatment for Right Turns at Intersections with Bicycle Traffic. Oregon Department of Transportation (ODOT)).

In dense urban environments, commercial parking and loading zones are potentially high-risk areas for bicycle-truck conflicts (Conway, Thuillier, Dornhelm, & Lownes, 2013),
Colored pavement within a bicycle lane increases visibility of the facility, identifies potential conflict areas, and reinforces bicyclist priority in these areas. This treatment is commonly applied to conflict areas at intersections, driveways, and along nonstandard or enhanced facilities, such as cycle tracks (NACTO, 2011).

To reduce such collisions, there is a need to protect cyclists from such dangerous incidents by providing safe places for both cyclists and automobiles to operate at peak efficiency. Separating cyclists and automobiles has positive effects on cyclist safety and reducing points of conflicts between cyclists and vehicles. The following sections will detail two types of separated features that can be implemented to increase the comfort and safety level of cyclists.

Protected Bike Lanes

Protected bike lanes typically are created by moving on-street parking from the curb, opening up space for cyclists between the curb and roadway, at the expense of a lane of traffic (Schwartz, S. I., 2011). The sacrifice of a traffic lane does not represent a hindrance to regular traffic flow, as "closing roads, or narrowing streets, does not create more congestion" but rather tends to "cut the volume of traffic, especially in cities" (Silberstein, J., & Maser, C., 2014). In adopting a protected bike lane on a narrowed or close streets is one version of a road diet, whereby the capacity of a street is lowered in order to increase the overall flow of traffic and improve safety for turning vehicles (Laplante, John,PE, PTOE, & McCann, B., 2008).

A survey of 1402 current and potential bicyclists in Vancouver, Canada, indicated that one of the greatest motivators of an individual's decision to bicycle was whether a route was separated from traffic. Most respondents were more likely to ride on facilities that had low traffic volumes or separated bicyclists from vehicular traffic (Winters, Davidson, Kao, & Teschke, 2011).

Respondents rated protected bicycle facilities with physical buffers as offering greater PLOC than standard bike lanes (McNeil, Monsere, & Dill, 2015). Monsere et al. (2014), found similar results, noting that physical barriers provided more comfort for bicyclists than painted buffers.
Improving the perceived safety of a bicycling infrastructure is an important condition for increasing levels of bicycling (Dill & Mcneil, 2013).

Protected bike lanes created as a result of a road diet thus serve a dual purpose to transportation planners, as bikers become safer with a dedicated space to cycle, while improving traffic flow by reducing the ability of vehicles to use a street. If done successfully and with a high level of continuity, road diets and protected bike lanes can reduce conflict points for different modes of transportation and improve the overall level of service of a roadway (Knapp, et al., 2014). While protected bike lanes provide solutions to some conflicts between cars and bicycles, intersections are still problem areas that require better treatments to successfully reduce accidents.

Protected Intersections

Intersection geometry plays an important role in cyclist crashes due to poorly configured bike lanes and incomplete networks of bike only and protected lanes. The City of Philadelphia completed an in-depth analysis of pedestrian and bicycle fatalities in the City from 2009 to 2013. This report analyzed time of day, location, seasonal changes, and the frequency of incidents at intersections to determine what factors contributed to the fatality, and how accidents can be reduced in the future. By identifying existing pedestrian and bike infrastructure at each intersection known for high fatalities and noting major transportation issues that should be resolved to improve overall safety of the system, Philadelphia is exploring the benefits Complete Street initiatives could have on their intersections.

Various types of and levels of protected intersection exist around the world. Nick Falbo, planner for Alta Planning + Design has created multiple renderings of protected intersections for implementation in American cities by utilizing design elements used in other countries. Cities around the world have adopted various levels of protected intersections to enhance the safety benefits for cyclists. In Seville, Spain, for example, a combination of dashed white lines and solid green pavement is used to delineate and emphasize the location that bicycles should cross, Figure

1. Other designs for protected intersections can incorporate waiting area for cyclists, protected islands and larger crosswalks, and bump outs to increase the visibility of cyclists and pedestrians, Figure 2, Figure 3, and Figure 4 respectively (Falbo, 2014).

Figure 1: Protected intersection from the cyclist perspective in Seville, Spain

Figure 2: Protected intersection in Quebec, Canada, with a bump out area for cyclists to wait before crossing the intersection

Figure 3: An aerial rendering of a potential protected intersection utilizing green pavemen markings

Figure 4: Another rendering of a protected inte design, this time with dashed markings and larg outs for cyclists and pedestrians

Recently, new guidance documents published by the Federal Highway Administration (FHWA) and the Massachusetts Department of Transportation (MassDOT), have focused extensively on cyclist planning for protected bike lanes and intersections (FHWA, 2015; MassDOT, 2015). Both of these guides rely heavily on protected intersection designs constructed in other countries and use comparisons to existing infrastructure in Boston and the rest of the country to highlight the potential improvements that can be made for cyclists in America. These guidelines have been widely distributed and adopted by transportation agencies and municipalities across America, seeking to improve the street experience for all road users. Adopting the guidance presented in these documents is benefiting complete streets initiatives as municipalities and towns turn their attention towards improving the safety of all road users.

Complete Streets attempt

Streets are the circulatory system of cities, they are the arterials and veins which move goods to market, people from home to work and back again, and create the web of passageways which connect regions to one another. Complete Streets are a relatively new idea in the field of Transportation and Regional Planning. The idea of Complete Streets is young in the United States, emerging in the early 2000s by cycling advocates seeking to replace and enhance the meaning of the original term 'routine accommodation', coined in the 1970s by advocacy groups to force consideration of cyclists and pedestrians alongside regular roadside improvements (Lawler, R. E., Carr, K., & Fish, J., page 2-2, 2012). The first bike bill was enacted in 1971 in Oregon and required "new or rebuilt roads accommodate bicycles and pedestrians" (Lawler, R. E., Carr, K., & Fish, J., page 2-1, 2012). Similar bills were enacted throughout the 70s and 80s across the United States and culminated in 2003 with the coining of the phrase 'Complete Streets' by the National Complete Streets Coalition (Lawler, R. E., Carr, K., & Fish, J., page 2-1, 2012).

These integral parts of cities and regions, however, do not serve each segment equally, as there are streets designed for the automobile and not for the bike, or those designed for the pedestrian, but not the car. To bridge this divide between accessibility of modes to each street, the idea of Complete Streets has emerged as a way to improve existing streets and intersections. When followed, these guidelines for future roads create spaces so that cars, bikes, and pedestrians may occupy the same space safely and efficiently so that streets are made less dangerous by design (Atherton, E., Chang, Y., Davis, S., Dodds, A., Sklar, S., & Zaccaro, H., 2017).

Enhancing the complete street intersections by modifying or replacing elements can lead to positive changes for cyclists and motorists alike. Municipalities and transportation agencies are focused on reducing the number and severity of crashes between cyclists and automobiles, and thus are utilizing and constructing protected intersections in an increasing fashion across the United States. One such analysis conducted in 2015 by Alta Planning identified six protected intersection installations in North America, one each in Salt Lake City, Chicago, Austin, Vancouver, Montreal, and Davis (Gilpin, 2015). Naturally, due to the geographic and geometric differences for each location, the design and elements included in the protected intersection vary, but each intersection focuses on improving the experience for cyclists by providing safety enhancements at all approaches, increasing cyclist visibility and making the street more complete.

Previous Simulation Work

Right hook crashes have been a focus of simulation experiments at the University of Oregon for a while now. Experiments conducted in 2015 focusing on effective design treatments for right turns and bicycles was completed by Hurwitz et al, and focused extensively on motorists' visual attention to cyclists approaching from different directions. The causal factors identified from this research was then built upon by Warner et al. (2015), through the design and completion of additional experiments focused on various levels of treatment available for intersections.

This next level of research focused on the different variables associated with an intersection and how those variables influenced motorists' situational awareness and visual attention. By changing the level of signage, pavement marking, curb radius, and protected intersection design, Warner et al. (2017), focused on four different categories of right hook crash treatments. The results of the experiment indicated that a level one sign, the presence of through intersection markings, a smaller curb radius, and protected intersections with islands provided the best positive influence on driver behavior. These results were influential in determining the direction that this research would take.

Simulating vehicle and cyclist interactions at intersections can be challenging due to the speed disparities between which cyclists and automobiles typically travel. In their research in Sweden, Boda et al. (2018) attempted to produce these interactions with the use of a driving simulator and a test track to measure and record these interactions. This study specifically sought to understand

how drivers responded to cyclists crossing their paths at an intersection. Boda et al found that the speeds of the bicycle and automobile had no direct effect on the response of the driver in the simulation, and that that the greatest influencer on the interactions was the point in time when the cyclist was visible and the crossing configuration that was used.

Similarly, Jannat et al. (2018) studied the effect of driver's situational awareness on right-hook accidents between motorists and cyclists in a simulated environment. Their experiment utilized a driving simulator and tested the awareness of motorists to an oncoming cyclist on right turns, and to measure the awareness of drivers the Situation Awareness Global Assessment Technique was used. Jannat et al. found that participants were significantly influenced by the cyclist's position relative to their vehicle, and that drivers tended to suffer from detection error, leading to greater rates of incidents between driver and cyclist.

Recent simulation work has been completed at the University of Oregon by Mafruhatul et. al (2018), focusing on right hook crashes related to driver's situational awareness while navigating through an intersection. This experiment focused on changing the bicyclist's relative position and oncoming left-turning vehicle presence to determine motorists' situational awareness in each scenario. The researchers found that motorists tended to focus more on the surrounding vehicles rather than the bicyclists, specifically the cyclists approaching from behind the motorist.

METHODS

This section details the methods used throughout the course of the research to determine the safety benefits of different protected intersection elements. A 3D world was created using Google Sketchup, and this world was ultimately inserted into the full body driving simulator in the Human Performance Lab in the engineering department. Participants were recruited and run for this research over a two week period, and each participant wore an eye tracking device to monitor their pupil movements throughout the course of their experimental drives. Participant data was recorded for each drive and was used to answer the following research questions:

- What effect do minor changes in a protected intersection radius have on driver behavior while performing turning movements?
- What effect do changes in the level of bicycle lane marking have on driver behavior while approaching, turning, and exiting a protected intersection?
- What combination of intersection radius and bicycle lane markings achieve the greatest increase in safe driving behavior for motorists and cyclists?

Driving Simulator

To dissect the performance safety benefits of protected intersection design on driver behavior, a driving simulator experiment was developed and conducted in the Arbella Human Performance Laboratory at the University of Massachusetts, Amherst. The driving simulator used for this study is a full-body 2013 model Ford Fusion Sedan fixed-base simulator. The vehicle is surrounded by six projectors, displaying the simulated environment to the driver. The main projectors have a resolution of 1920 x 1200 pixels and an image display refresh rate of 96 Hz. The rear projector has a resolution of 1400 x 1050 pixels, also with a display refresh rate of 96 Hz. These six projectors together generate an approximate 330-degree field of view around the driver, allowing the driver to be immersed in the simulated environment. The sound system consists of a five-speaker surround system plus a sub-woofer for exterior noise, and a two-speaker system plus a sub-woofer for interior vehicle noise. A rendering of the simulator set up in the Human Performance Laboratory is displayed in Figure 5.

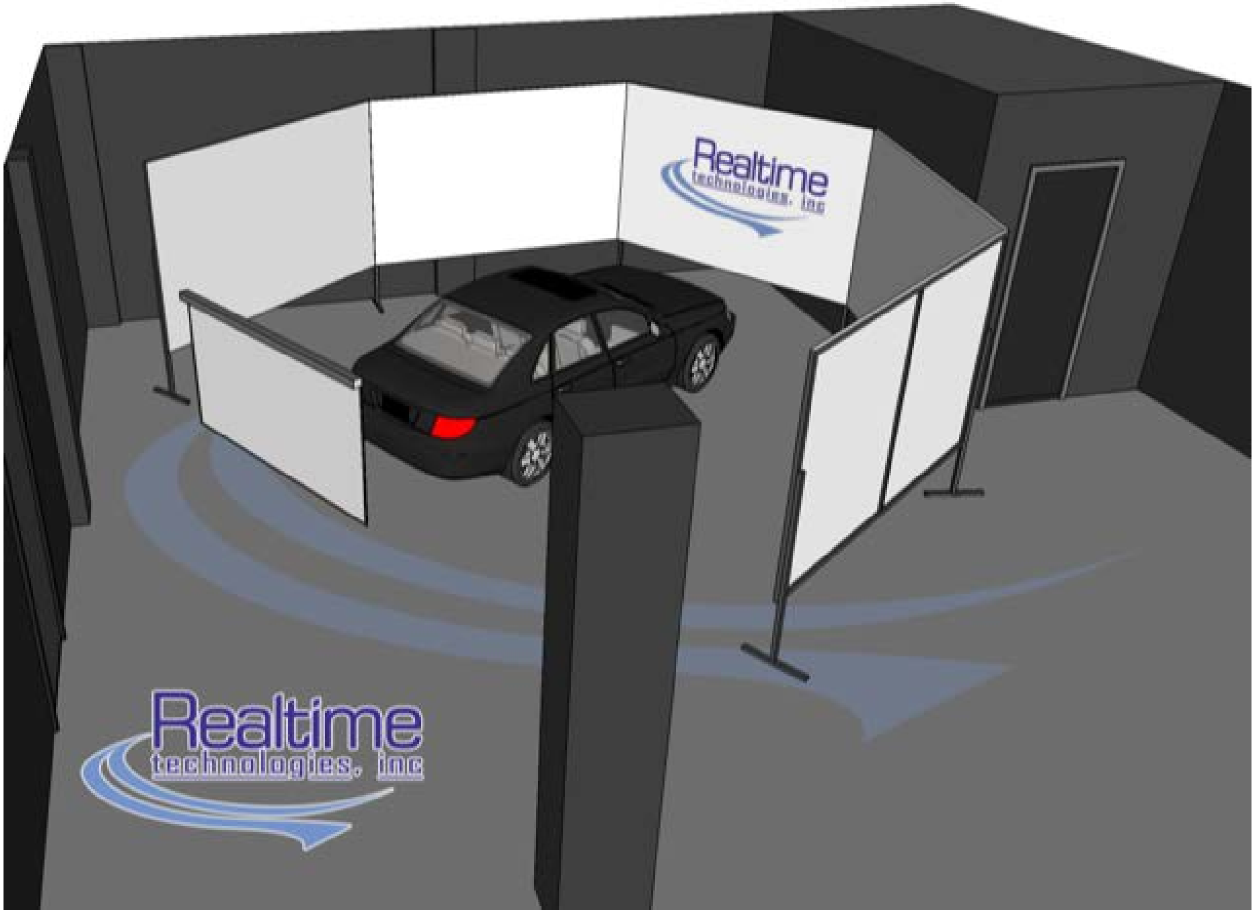


Figure 5: A rendering of the driving simulator and the surrounding screens

A portable ASL Mobile Eye XG eye tracker system recorded drivers' eye movement for analysis throughout the simulated drives. This eye tracker samples the position of the eye at 33 Hz with a visual range of 50 degrees in the horizontal direction and 40 degrees in the vertical direction. The system's accuracy is 0.5 degrees of visual angle. The eye tracking data recorded was used to compare the driver's behavior to what the driver was glancing at as the turning movements were performed throughout the experiment. Emphasis was placed on participant's glances at protected intersection elements throughout the experiment.

Experimental Design

To conduct the experiment, approximately half a mile of simulated roadway was developed in Google Sketchup 2014 to record driver interactions at protected intersections. The 2014 version of Sketchup was used as this software was the most compatible with the driving simulator software available at the University. Twelve different scenarios were constructed using the Realtime

Technologies Inc., Sim Vista Version 3.2 software available in the Arbella Human Performance Laboratory. These scenarios will look at the effect that the different combinations of variables identified in Table 1 may have on driver behavior at protected intersections. To generate the combinations, three variables were used throughout the experiment: the level of roadway marking for bicycle lanes, the radius of the protected element at the intersection, and whether a bicycle was attempting to cross during the drive.

Table 1**:** Independent Variable Combinations for Scenarios

Scenario	Bicycle Marking	Intersection Radius	Bicycle Crossing
1	No Marking	Full	No
2	Min Marking	Full	No
3	Full Marking	Full	No
4	No Marking	Small	No
5	Min Marking	Small	No
6	Full Marking	Small	No
7	No Marking	Full	Yes
8	Min Marking	Full	Yes
9	Full Marking	Full	Yes
10	No Marking	Small	Yes
11	Min Marking	Small	Yes
12	Full Marking	Small	Yes

Each virtual scenario consisted of approximately half a mile of simulated roadway with two turning segments separated by a long straight away. The long sections of straight roadway will be used to give drivers time to recover from making turns at intersections as excessive turns could cause simulator sickness in participants. The drives were in either of two orders: a straightaway followed by a right turn with another straightaway followed by a left, or a straightaway followed by a left turn with another straightaway followed by a right. This was done to change the turning patterns for participants to reduce the potential effect simulator sickness would have on participants. Figure 6 shows the sequence of drives started with a right turn, Figure 7 shows the sequence of drives started with a left turn.

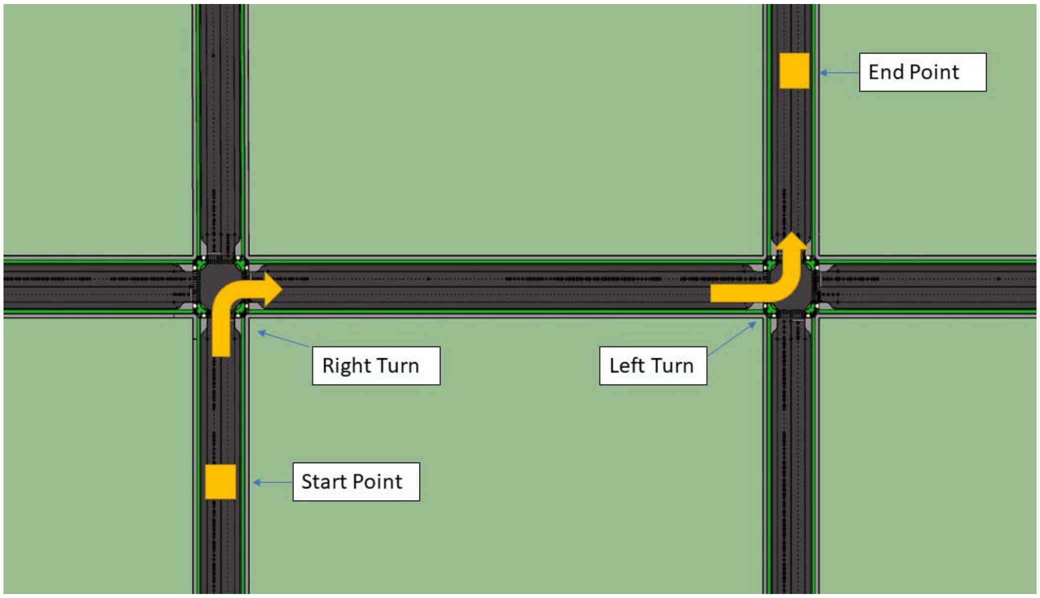


Figure 6: The sequence of events for a right turn start

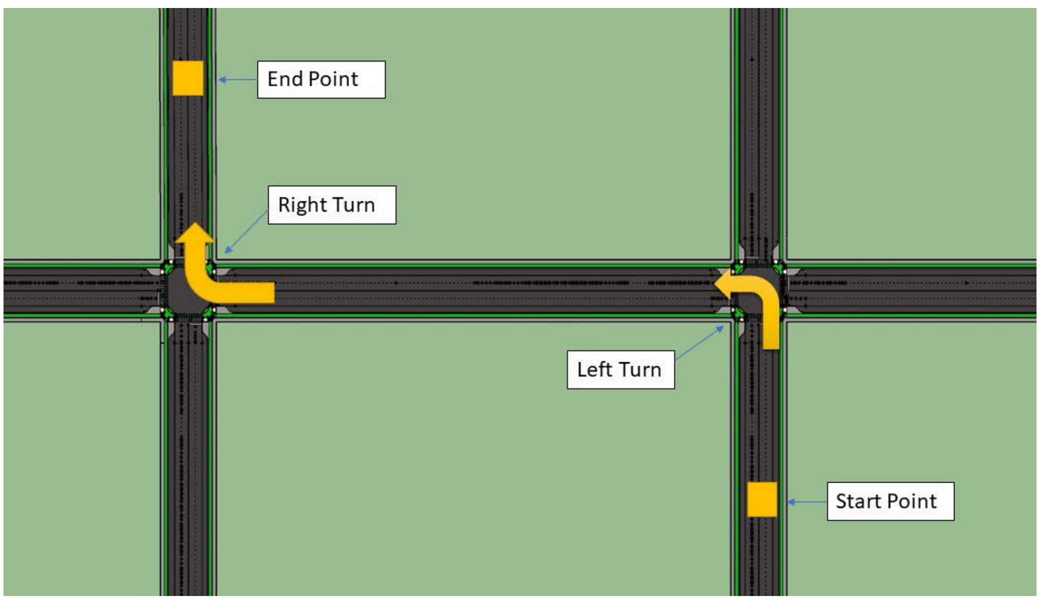


Figure 7: The sequence of events for a left turn start

The roadway leading to each intersection consisted of four 12-foot travel lanes with ten feet of on street parking and a six-foot protected cycle lane on either. Intersection approaches included bulb outs on the intersection approach to reduce the width of the roadway from 68 feet to 48 and prevent vehicle parking and obstructions as the participant interacts with the intersection. The intersection used in each scenario is depicted in TABLE.

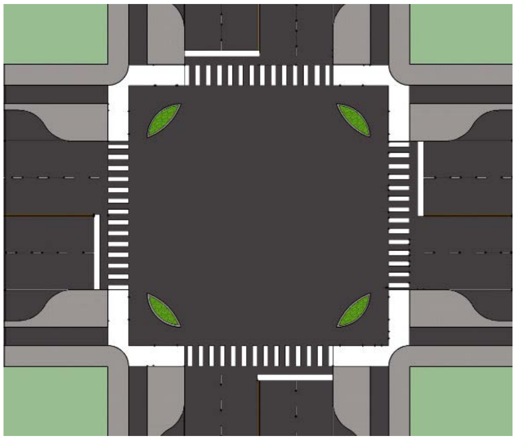
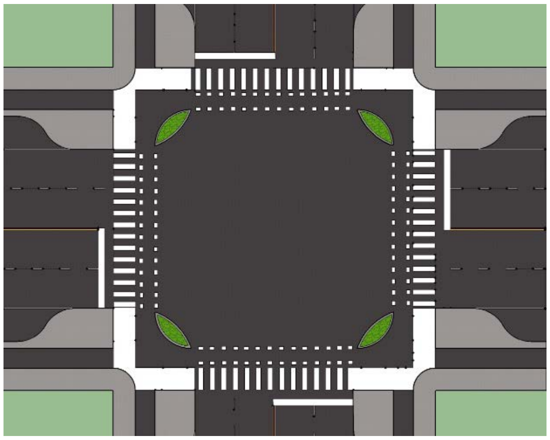
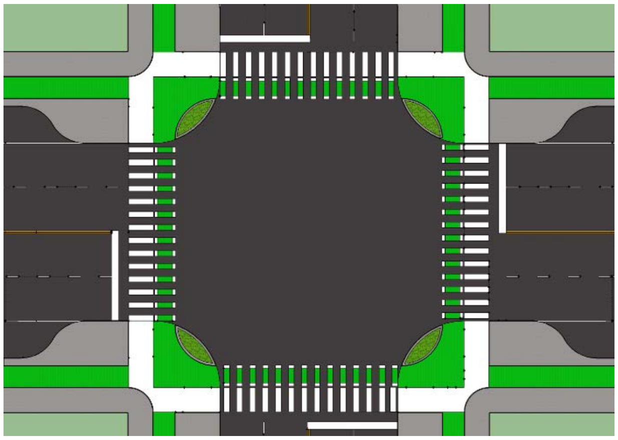
Because of the varying levels of variables, 12 different combinations of bicycle marking, intersection radius, and bicycle crossing are possible from the proposed experimental design in Table 1. Thirty-six participants were recruited for this experiment, providing for three participants for each combination of variables. All participants drove every combination possible, but the sequence varied based on the Latin square configuration. Latin square sequencing ensures that for the given combinations, no combination of scenarios will repeat across each participant group. The Latin square used for this research is displayed in Table 2. Each participant sequence was duplicated three times. After every twelve participants, the sequence of drives repeated (Participants 1, 13, and 25 thus drove the twelve scenarios in the same sequence).

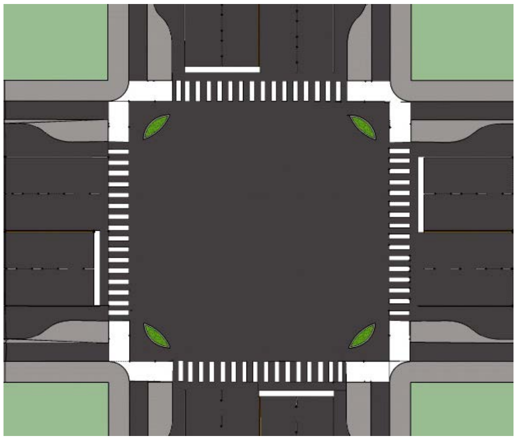
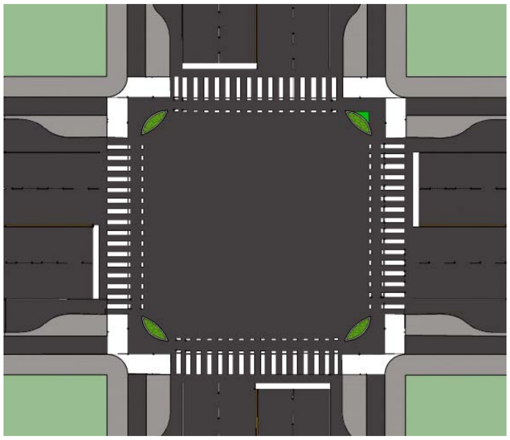
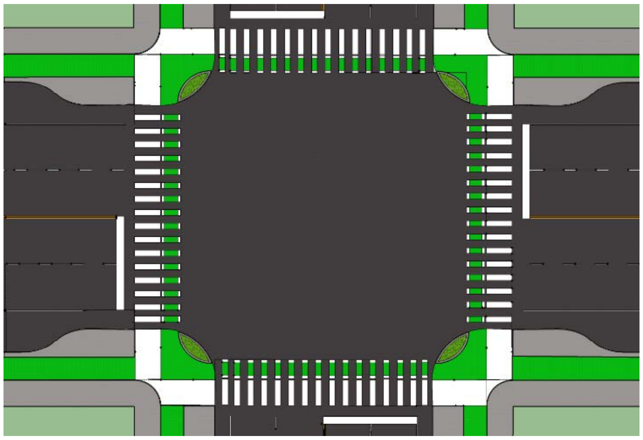
Table 2: Latin square scenario order for participants

	Drive Number											
Participant	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	1	2	12	3	11	4	10	5	9	6	8	7
2	2	3	1	4	12	5	11	6	10	7	9	8
3	3	4	2	5	1	6	12	7	11	8	10	9
4	4	5	3	6	2	7	1	8	12	9	11	10
5	5	6	4	7	3	8	2	9	1	10	12	11
6	6	7	5	8	4	9	3	10	2	11	1	12
7	7	8	6	9	5	10	4	11	3	12	2	1
8	8	9	7	10	6	11	5	12	4	1	3	2
9	9	10	8	11	7	12	6	1	5	2	4	3
10	10	11	9	12	8	1	7	2	6	3	5	4
11	11	12	10	1	9	2	8	3	7	4	6	5
12	12	1	11	2	10	3	9	4	8	5	7	6

Throughout the experiment, six different variations of protected intersections were used to record participant data. Three of the intersections had a larger turning radius of five meters, and the three intersections had a radius of three meters. Each level of cyclist lane marking was repeated in two protected intersections. Using the scenario list from Table 1, the scenario each protected intersection was used is identified in Table 3, along with an image and description of the protected intersection elements that were present for each protected intersection design.

Table 3: Protected Intersections used for each experimental scenario

Scenarios Present	Protected Intersection Image	Variables Present
1,7		No pavement marking, large turn radius
2,8		Minimum pavement marking, large turn radius
3,9		Maximum pavement marking, large turn radius

4,10		No pavement marking, small turn radius
5,11		Minimum pavement marking, small turn radius
6,12		Full pavement marking, small turn radius

Dependent Variables

Several dependent variables will be analyzed to assess the effects of the identified independent variables in Table 1. All dependent variables that will be used for analysis are identified in Table 4.

Table 4: Dependent Variables

Variable	Units	Description
Eye Glances	Glances	What did the participant look at while performing the turning movements
Intersection approach speed	m/s	How fast the participant approached the protected intersection
Turn speed	m/s	How fast the participant turned through the protected intersection
Intersection exit speed	m/s	How fast the participant exited the protected intersection
Yielding behavior	Qualitative	How did the driver yield at the intersections with and without a bike present

Simulator Subjects

In order to work with human subjects through simulation projects, Human Subject Research Training is required by the University of Massachusetts, Amherst. This certification is done through an online web site run by the Collaborating Institutional Training Initiative. The specific course related to simulator subjects is the *Group 2: Social Behavioral and Education Research Investigators and Key Personnel-Basic Course.*

Once this training was been completed, subjects were scheduled during mutually agreeable time slots when the driving simulator was available in the lab. All subjects were instructed to drive as they normally would, obeying all speed limits and traffic laws (Fitzpatrick, 2013). During testing, certain components of the drivers' driving behavior and speed were recorded by the observer. The vehicle speed was analyzed at certain points along the drive. Eye movement and recognition data was used extensively to determine the effectiveness of different intersection treatments on driver reactions and approaches to pedestrian and bicycle interactions. The author was the primary

experimenter and was assisted by other students working in the Human Performance Lab. Table 5 presents an agenda for running subjects in the driving simulator (Fitzpatrick, 2013).

Table 5: Agenda for simulator experiment

#	Task
1	Welcome/Introduction
2	Informed Consent
3	Experiment
4	Wrap-up/Debriefing
5	Compensation

Demographic Data

Thirty-six participants were recruited for this experiment, 19 males and 17 females. The average age of participants in this experiment was 25.1 years old (SD = 9.6), and the average participant received their license at 16 years and 11 months (SD = 1.8). Seventeen of the participants were new to the simulator, and 28 of the participants identified as Caucasian. Participant ages ranged from 18 to 65, with the majority of participants falling within the 18-25 age range.

Data and Analysis

This research generated results for right turning movements and left turning movements through a protected intersection. In total, 432 right and left turns (n=864 total turns) were driven by thirty-six participants. For each turn, six different sets of data markers were placed in the scenarios to capture the approach, curve, and exit speed of participants during the simulator drives. Data markers were placed symmetrically for both right and left turns in all scenarios. For the approach speeds, the data markers captured the driver's speed for 70 meters before the intersection. During the curve, data markers were placed on the entrance and exit crosswalks of the curve, approximately 15-20 meters apart. On exit from the protected intersection, driver speed was captured for 70 meters after the intersection. A full layout of the data markers used on the right

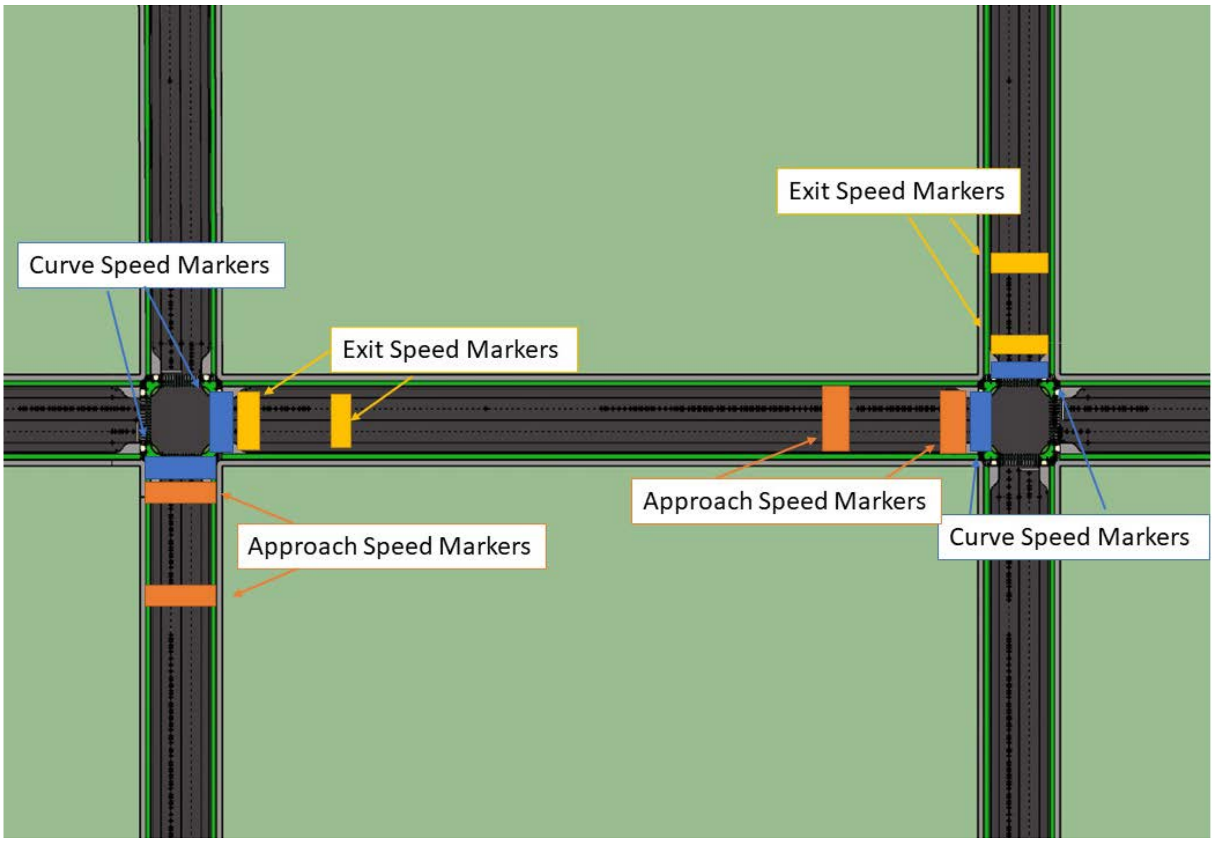


Figure 8: Data marker layout for all scenarios

starting position is shown in Figure 8, for left starting positions an identical layout was used.

Because of the data marker layout used for this research, analysis was possible at six different locations throughout each drive. To conduct the analysis, extensive use of Python code was utilized

to process the large volume of data. The driving simulator generates sixty data points a second for the duration of each drive. This data was consolidated and converted into a CSV format, and then processed for every participant individual drives, resulting in 432 different sets available for analysis. The data was then aggregated based on the data marker classification in Figure 8, and then displayed using box plots generated in Python.

The number drives with each variable included is shown in Table 6. This table will be referenced repeatedly as the speed analysis results had varying levels of turns included in each of the respective analyses that was conducted.

Table 6: Breakdown of Turns and Variables for all Participants

	Right Turn	Left Turn	Total Turns
Turns	432	432	864
Cyclist Present			
Cyclist	216	216	432
No Cyclist	216	216	432
Intersection Radius			
Small	216	216	432
Large	216	216	432
Bicycle Lane Marking Level			
No Markings	144	144	288
Minimum Markings	144	144	288
Maximum Markings	144	144	288

Box plots were used to display the data due to their ability to summarize data in a succinct manner and provide five different data points for analysis. Each of the box plots has several different values associated the plot, with an example box plot provided for reference in Figure 9. The graphs generated in python also added a dot to indicate the average of the aggregated speeds, providing for a further level of analysis. It is important to remember that a large interquartile range indicates a large spread in values and thus there was more variation related to that data marker.

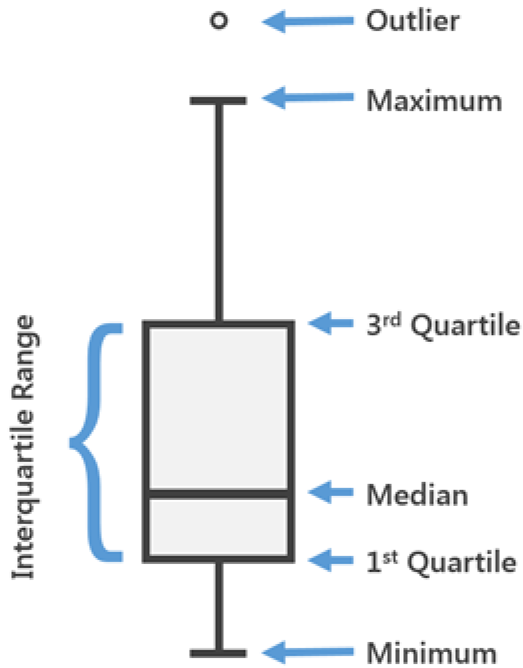


Figure 9: The important points of a box plot
(ESRI, 2018)

A trajectory analysis was conducted for all combinations of variables, including both right and left turn movements through the protected intersections. This analysis is included in each section, with a separate section detailing the combination analysis of variables that was conducted as well In addition to the box plots, a linear regression was performed for each segment of the curve to identify which variables had the most significant influence of the participant's speed in that section. A linear regression was conducted to determine the effect and significance level of each variable of the protected intersection. The regression analysis, and the box plots associated with the speed analysis, are presented in the following sections.

Right Turn Results

For the data analysis, each participant's drives through a protected intersection were aggregated together and then divided into three categories, based upon the location of the data markers that were flagged in the intersection. This section analyzes and describes the results of the aggregated speed data for each participant, focusing on the right turning movement through the protected

intersection. In total, 432 different observations of right turning movements were analyzed for the different levels of variables for each protected intersection scenario.

These observations are displayed in Figure 10, where the speeds of all participants are plotted as the intersection was navigated. As shown in, participants entering speeds ranged substantially across all drives and participants. However, the entering speeds of participants are decreased as the driver navigates the intersection, and then the speeds typically increase as the participants exit the intersection, though not at the same sharp rate as their entering speeds.

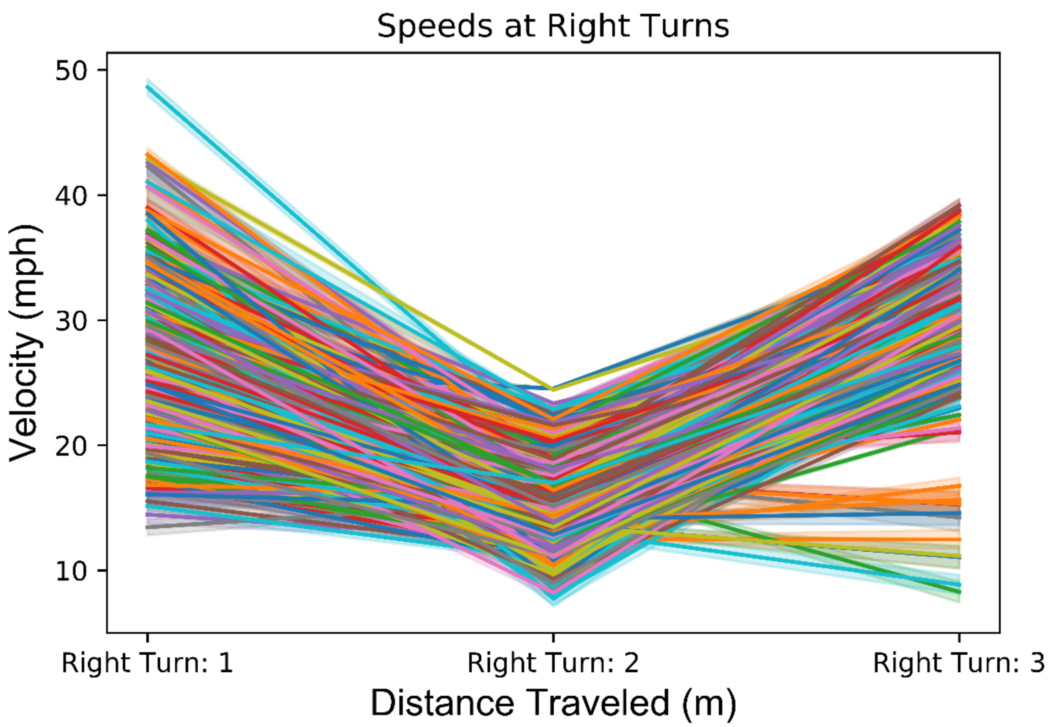


Figure 10: Speeds for participants while turning right

Bike vs No Bike Scenario

The first section of the drive that was analyzed was the entering speed, or the approach speed, that all participants had when entering the protected intersection. As tabulated in Table 6, 216 right turns were used for the analysis of driver speed with and without a cyclist present, for a total of

432 different observations for each segment of the curve analyzed. Because of the multiple variables involved, the box plot in Figure 11 shows the average speed of participants over the 70 meters leading to the approach of the intersection when a cyclist was or was not present for the right turn. As shown in the graphs, the approach speed for drivers when a cyclist was present or preparing to cross the intersection was slightly higher compared to when no cyclist was present, as indicated by difference in interquartile range and median for both plots.

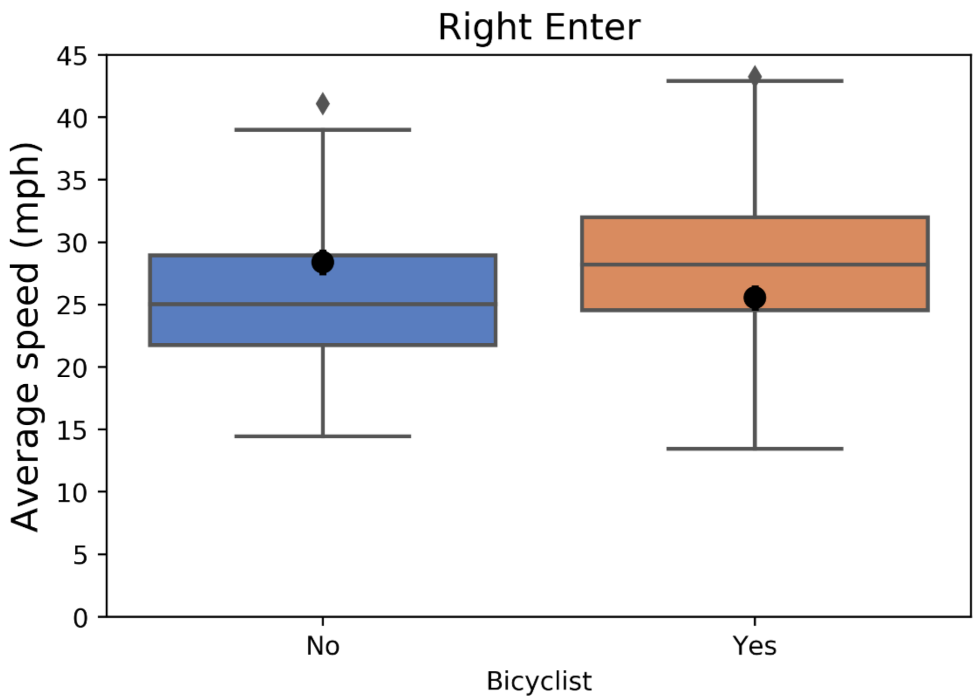


Figure 11: Box plots for driver speed with and without a bicycle present

As the participants proceeded through the turn, the overall range of speeds decreases from when the participants were first entering, Figure 12. This is likely due to drivers braking in order to turn right through the intersection, as instructed. The median speeds are approximately 10mph lower than the median speeds of the entering vehicle, and the range is not as large. The average speeds of the participants, represented by the black dot in within the interquartile range, was lower on turns with a cyclist present, indicating that the average driver braked or reduced their speed to avoid conflicts with the cyclist.

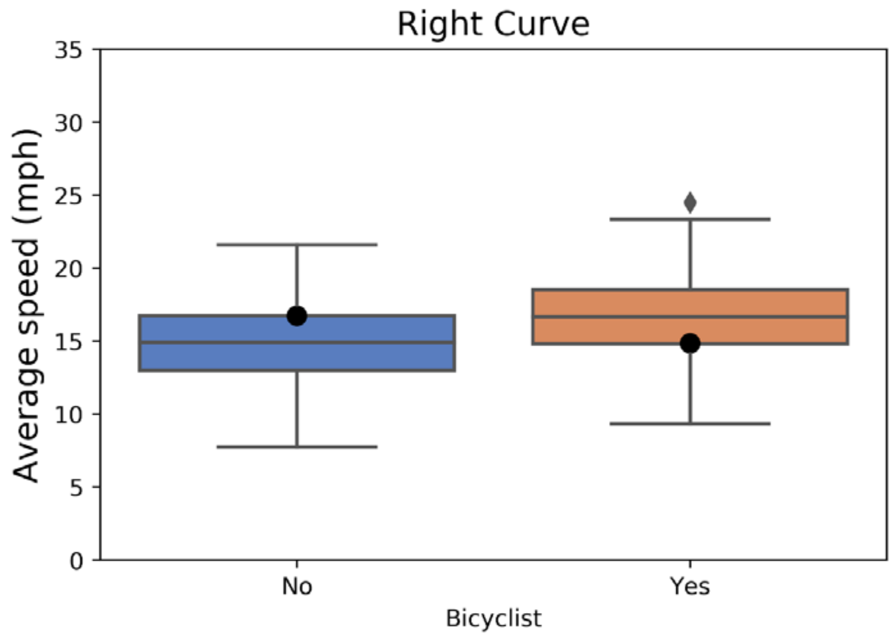


Figure 12: The average speed for all drivers through the right turn

As participants completed their turning movements and proceeded to exit the intersection, most participants accelerated quickly and increased their average speed significantly in comparison to the average speed during the turning movement. The median and average speed for each scenario was nearly identical across all participants, with a slightly larger range of speeds for the no cyclist scenario.

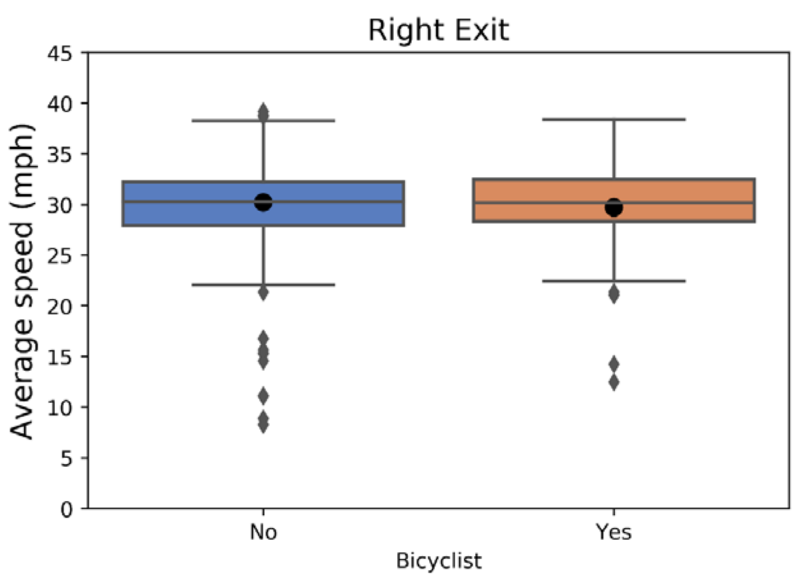


Figure 13: Average speed for participants exiting the intersection with and without a cyclist

Large Radius vs Small Radius

The next variable that was examined was the effect of the protected intersection radius on driver speed on approach, turning, and exiting the intersection. The first section of the drive that was analyzed for this analysis was the entering speed, or the approach speed, that all participants had when entering the protected intersection. As tabulated in Table 6, 216 right turns were used for the analysis of driver speed for each intersection radius size (large or small), for a total of 432 different observations for each segment of the curve analyzed. For this section of analysis, the large radius is displayed under the abbreviation "F", and the smaller radius is identified with an "S".

Separating the participants speed by approach yields a similar distribution of participants across both sizes of protected intersection. There was no significant change in participant behavior when approaching either a large or small protected intersection, as displayed in Figure 14, where the median, mean, and minimum and maximum ranges are almost identical in value.

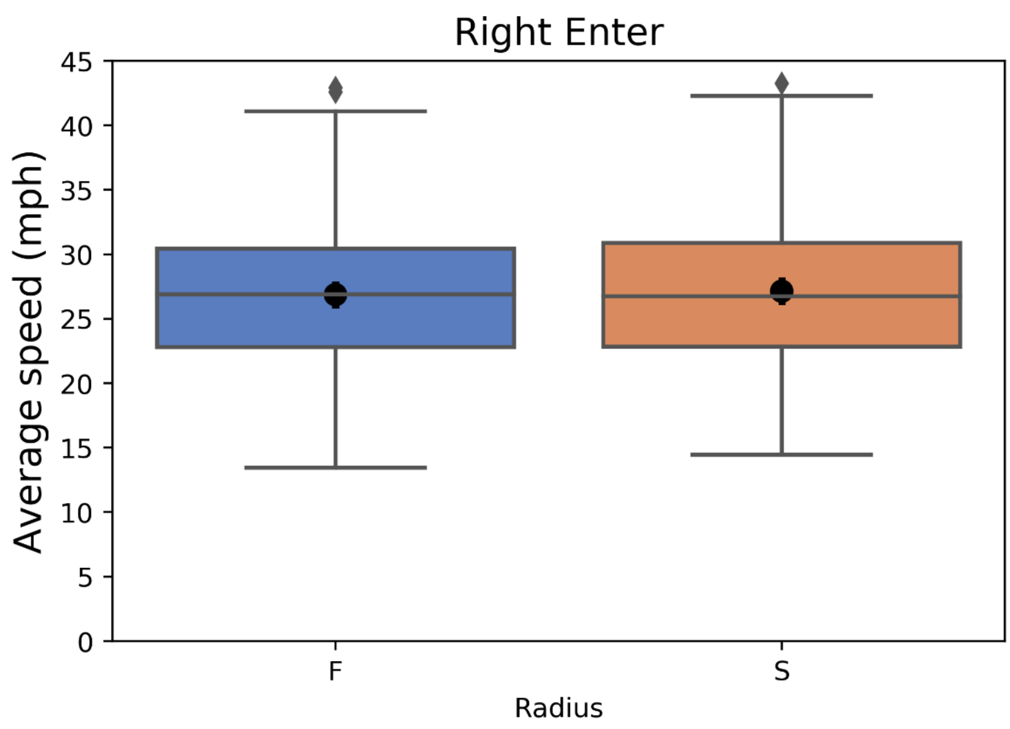


Figure 14: Protected intersection size and average speed for all participants on approach

As participants entered and began to perform the turning motion through the intersection, the average speed of participants decreased in comparison to their approach speed by approximately 10mph for each participant. The smaller radius protected intersection had a slightly higher range, median, and mean, in comparison to the larger protected intersection, which indicates that participants could accelerate and travel at a higher speed when the protected intersection was larger. This data is displayed in Figure 15.

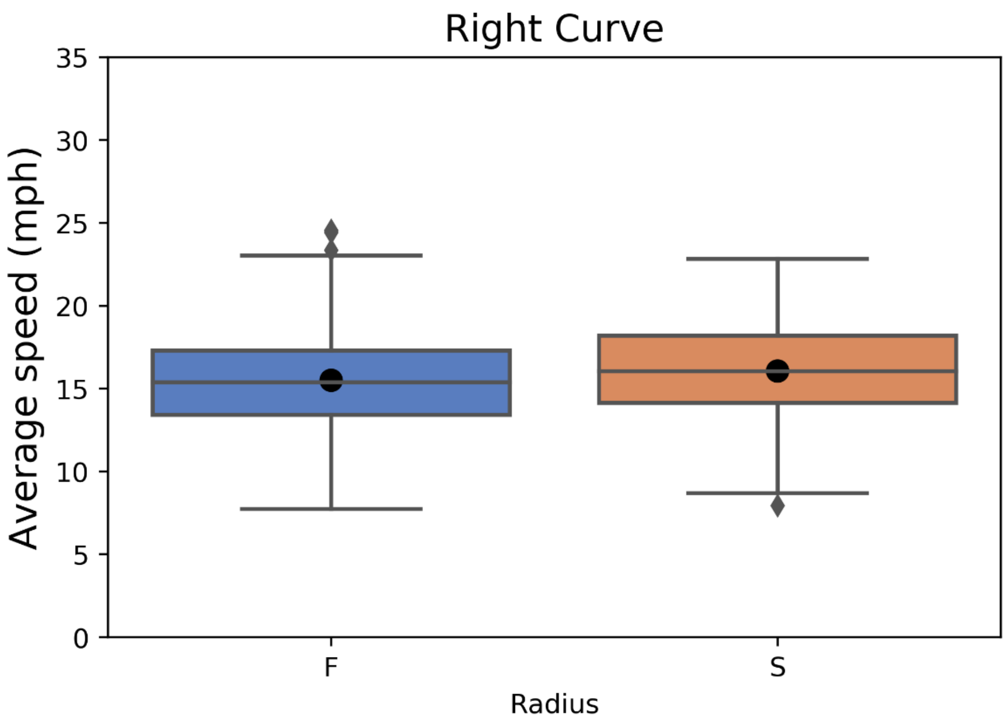


Figure 15: Protected intersection size and average speed for all participants on turning through the intersection

Average speed of the participants upon exiting the different sizes of protected intersections is displayed in Figure 16. The first and third quartile range of these exit speeds is quite smaller in comparison to the entering and turning speeds presented above. Additionally, both the small and the large protected intersection resulted in a high number of outlier speeds. The large number of outlier data points can be attributed to participant behavior upon completing the turn and braking slowly to end that particular drive.

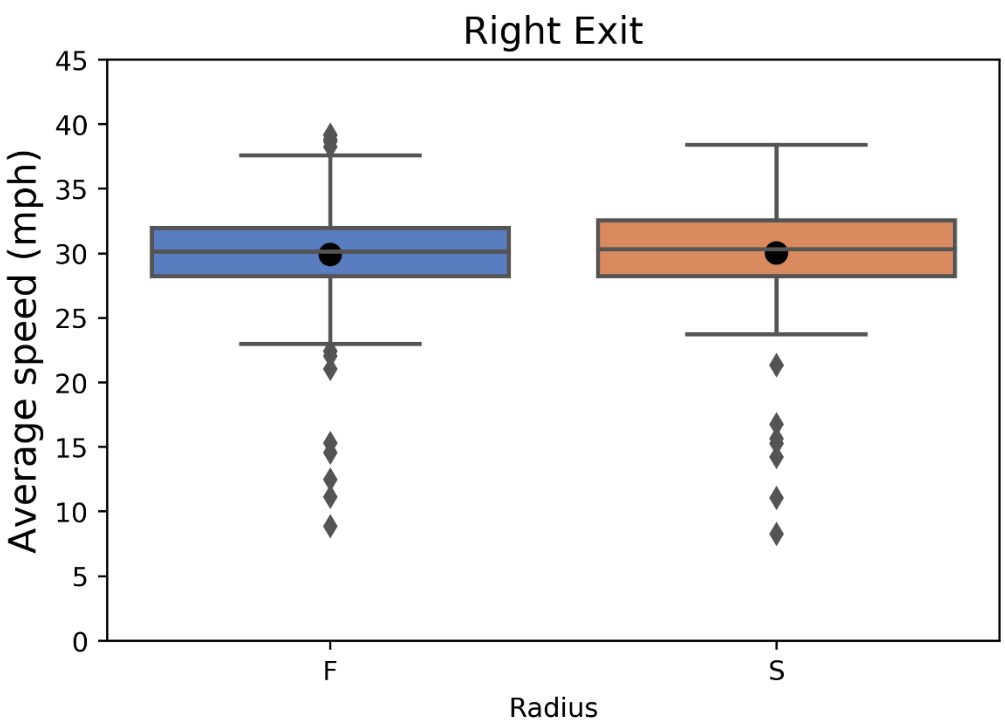


Figure 16: Protected intersection size and average speed for all participants on exiting protected intersection

Bicycle Lane Marking

The final variable that was analyzed was the bicycle lane marking present in the protected intersection. Three different levels of pavement marking were used throughout the experiment, no marking, represented as black pavement, minimum marking, represented as dashed white lines, and maximum marking, represented by a dashed white line on the outside of a solid green strip of pavement. Because there were three levels of markings used throughout the experiment, as

tabulated in Table 6, 432 right turns were used for the analysis of driver speed in relation to the different levels of pavement marking present, with 144 observations per level.

Participant's approach speed to the protected intersections with different levels of bicycle marking is displayed in Figure 17. The ranges of speeds varied from one marking level to the next, with the largest range present on minimum level of pavement marking. The average of the approach speeds for all levels of marking is close to the median speeds for all participants.

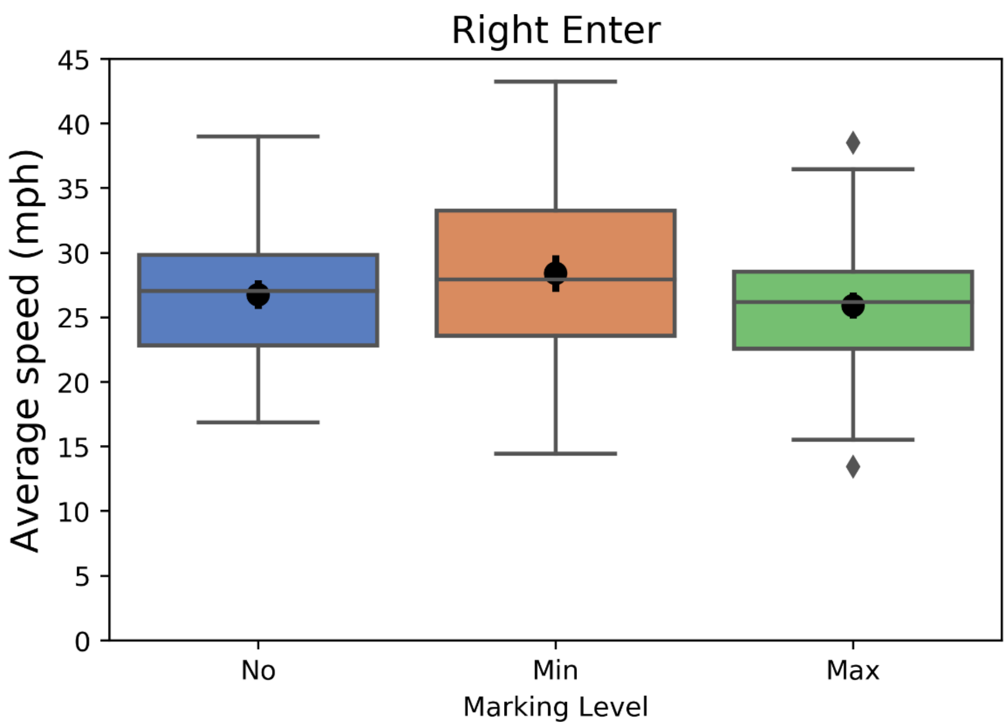


Figure 17: Average approach speed of participants in protected intersection by level of bicycle pavement marking

The variation of speeds decreased as participants began turning through the turn, as illustrated in Figure 18. This trend mirrors similar trends identified with the radius and cyclist variables, suggesting that there is a combination of factors at that influences a participant's chosen speed through the protected intersections. The range in speeds is lower when compared to the approach speed when participant's average speed is separated by pavement marking level, and the average and median speeds of participants completing a right turn are not substantially different from one another.

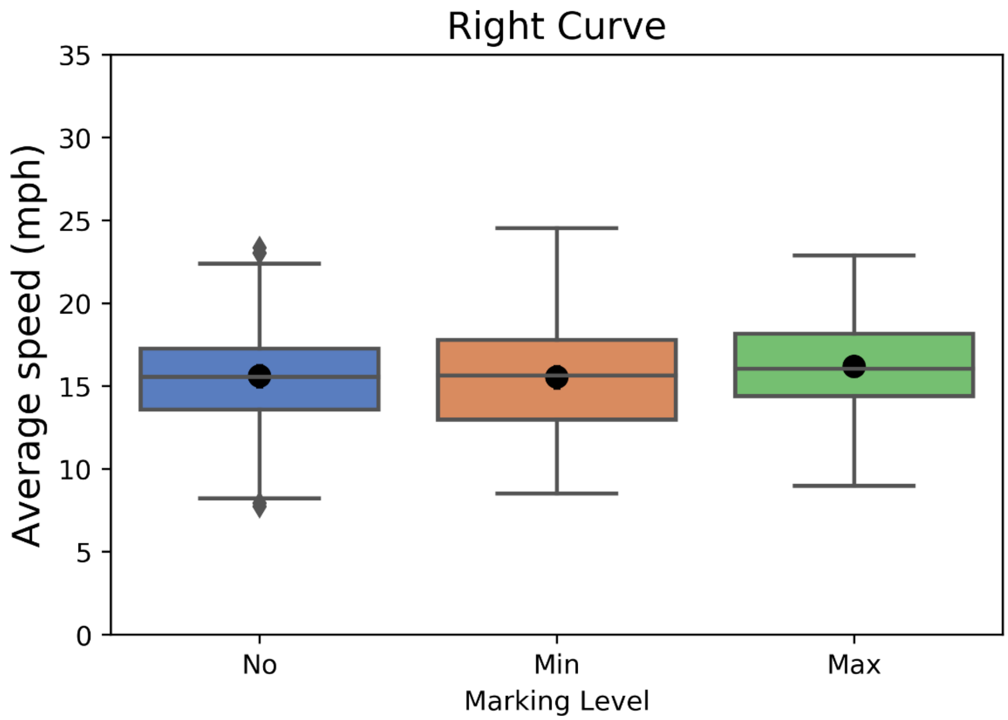


Figure 18: Average turning speed of participants in protected intersection by level of bicycle pavement marking

Upon exiting the protected intersection, participant's average speed increases in a similar magnitude when compared to the cyclists and radius box plots from prior sections. Figure 19 indicates that there was no real difference in observed mean and median speeds across all levels of marking for each participant. The interquartile range and maximum and minimum values do change slightly, the difference is not large enough to indicate a preference based on speed alone for one marking level or another.

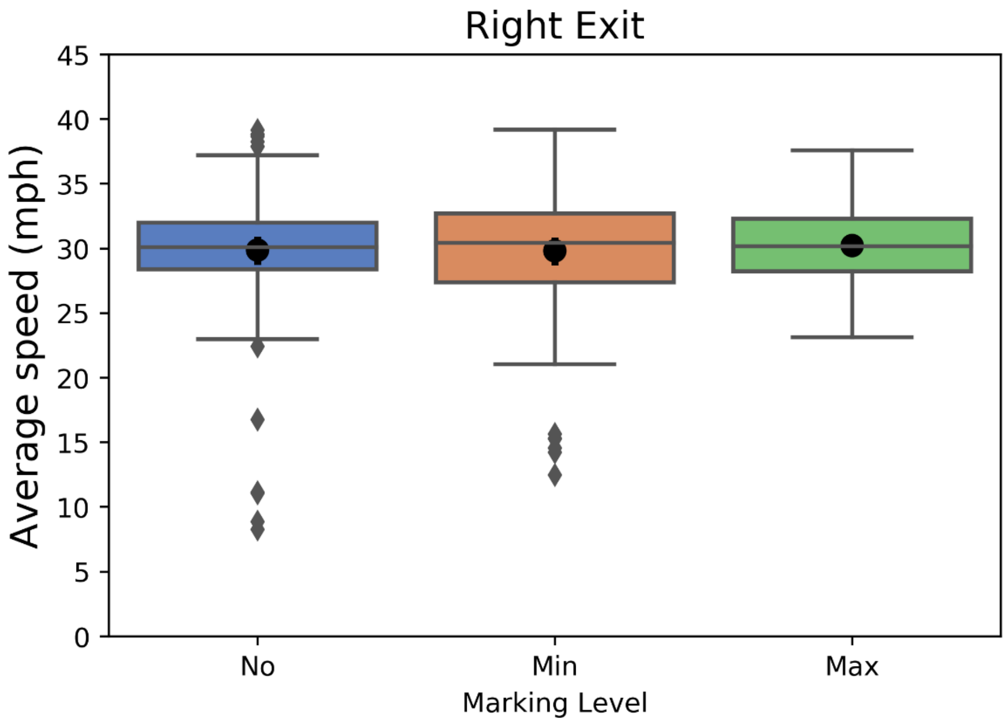


Figure 19: Average exit speed of participants in protected intersection by level of bicycle pavement marking

Left Turn Results

For this data analysis, each participant's drives through a protected intersection were aggregated together and then divided into three categories, based upon the location of the data markers that were flagged in the intersection. This section analyzes and describes the results of the aggregated speed data for each participant, focusing on the left turning movement through the protected intersection. In total, 432 different observations were recorded for participants making left turns through the protected intersections. The trajectory of each participant is displayed in Figure 20, for all combinations of variables. Their speeds have a wide range upon entering and exiting the intersection and are more dispersed and varied in comparison to the right turn analysis presented in Figure 10. The resulting sections analyze the participants speed related to each level of variable possible.

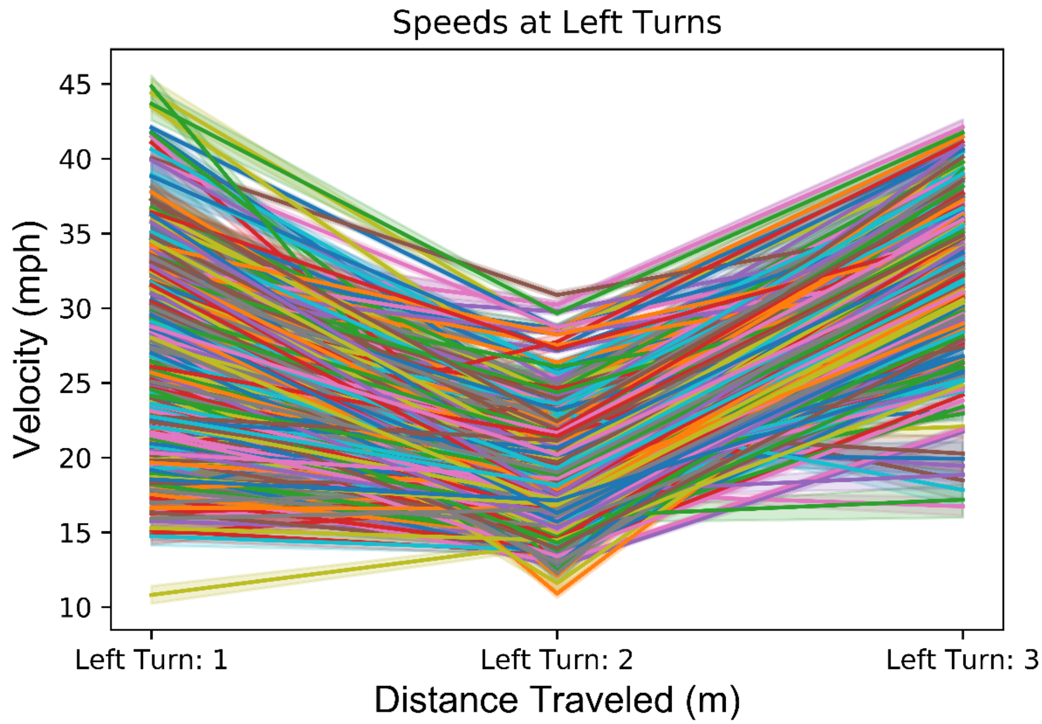


Figure 20: Trajectories for all participants turning left

Bike vs No Bike Scenario

The analysis of the left turning movement for each participant was the same as for the right-hand turns. As shown in Figure 21, the average speeds of the participant's approach to the intersections was slightly lower in comparison to the right turn approach speeds presented in Figure 11, and the range of the speeds was larger. This may be because of the identification of the cyclist crossing from the left may not have been as obvious as the right crossing cyclist, leading to a larger variation in driver speeds on approach to the intersection.

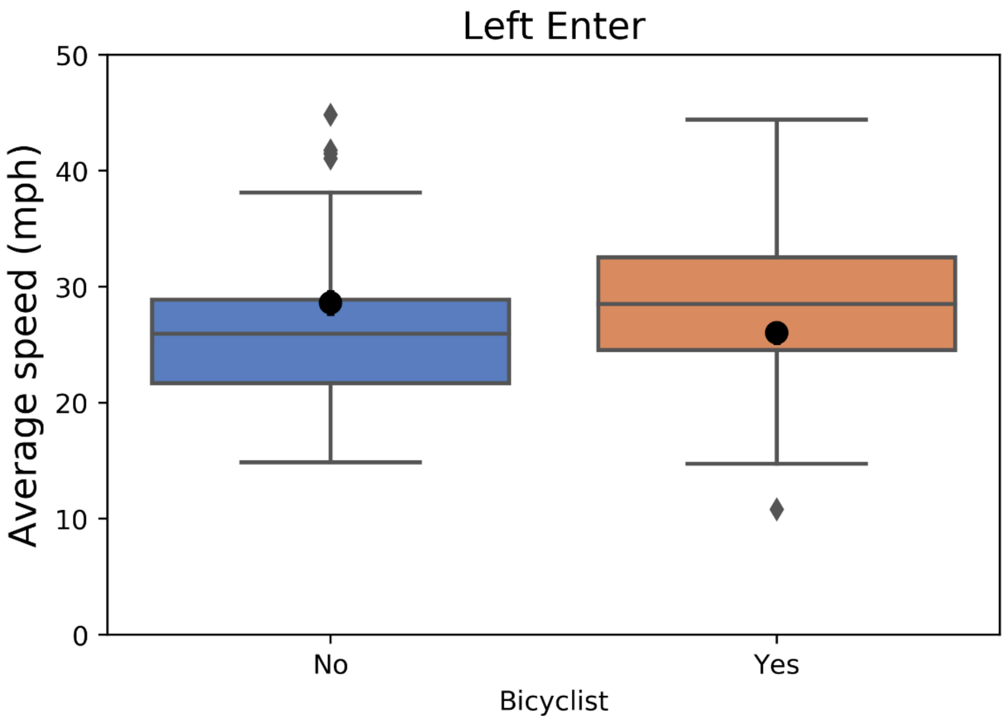


Figure 21: Average participant speeds for left turn approaches with a cyclist

For the participant's speed through the curve, participants reduced their speed by approximately 10-15mph in comparison to their approach speed, and this was generally true for both scenarios with and without a cyclist present. The median speeds were lower, however the averages for scenarios with and without a cyclist were outside of the interquartile range, suggesting that the median speed is not a good indicator of the speed distribution of the participants. This analysis is displayed in Figure 22.

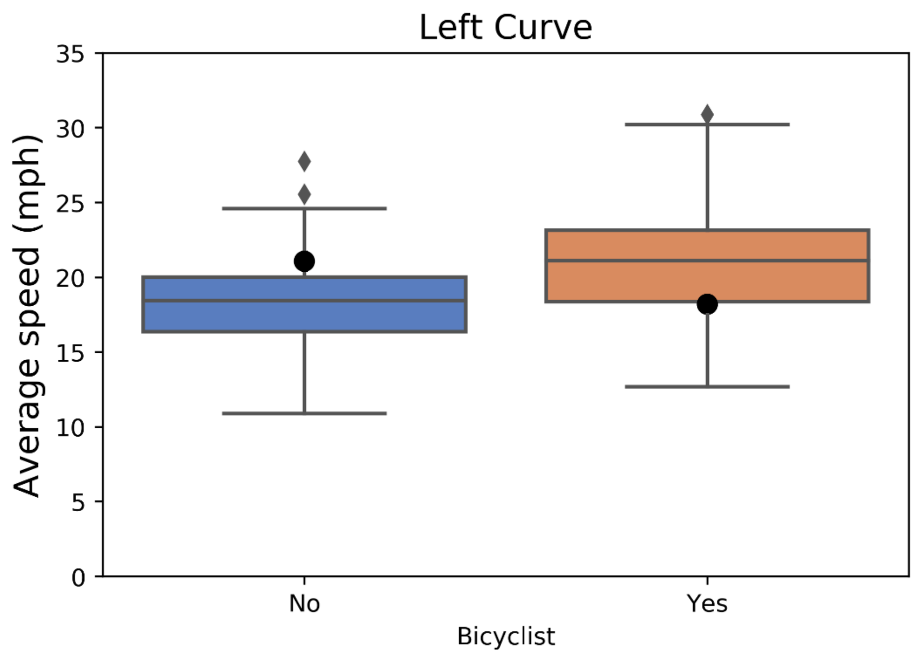


Figure 22: Average speed through the left turn for participants in scenarios with and without a cyclist

As participants completed the turn and exited the protected intersection, the average speed of each participant increased by approximately 10mph. The median and average speed of participants was greater than 30mph for all participants, for both the no cyclist and cyclist scenario, Figure 23. This distribution of speeds had a range greater than 25mph, and multiple participants were recorded at speeds that laid outside of the distribution bounds. The average speeds for the left turns are comparable to the right turn exit speed presented in Figure 19.

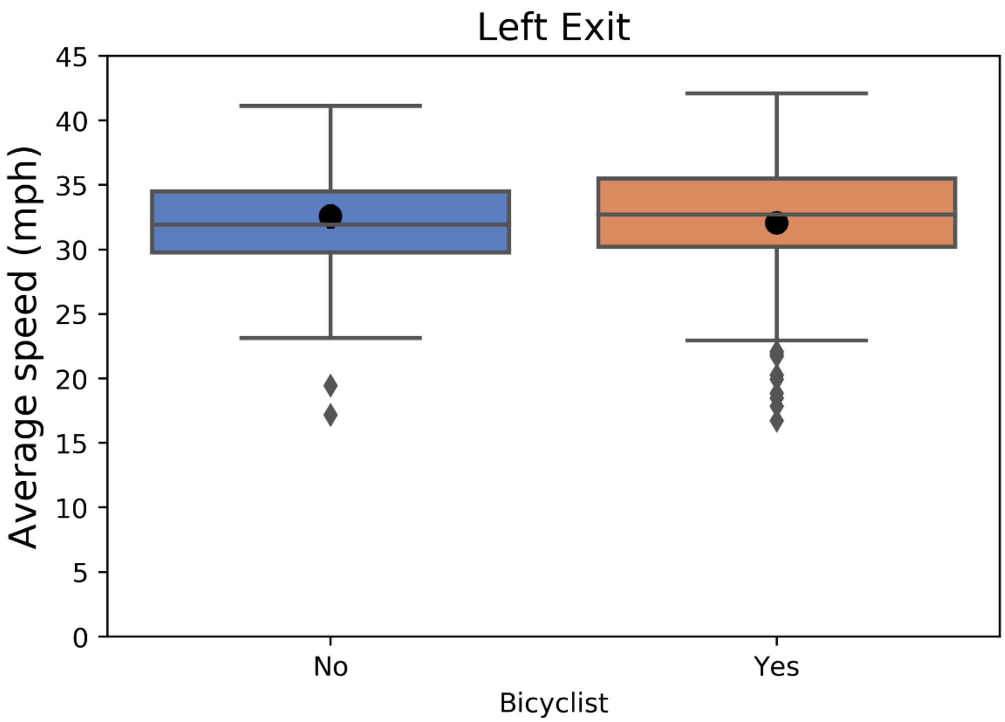


Figure 23: Average participant speed on exiting a left turn from a protected intersection

Normal Radius vs Small Radius

The next variable that was examined was the effect of the protected intersection radius on driver speed on approach, turning, and exiting the intersection. The first section of the drive that was analyzed for this analysis was the entering speed, or the approach speed, that all participants had when entering the protected intersection. As tabulated in Table 6, 216 left turns were used for the analysis of driver speed for each intersection radius size (large or small), for a total of 432 different observations for each segment of the curve analyzed. For this section of analysis, the large radius is displayed under the abbreviation “F”, and the smaller radius is identified with an “S”. The average and median speeds for all participants were 27mph for both the large and small radius of the protected intersection. This data is presented in

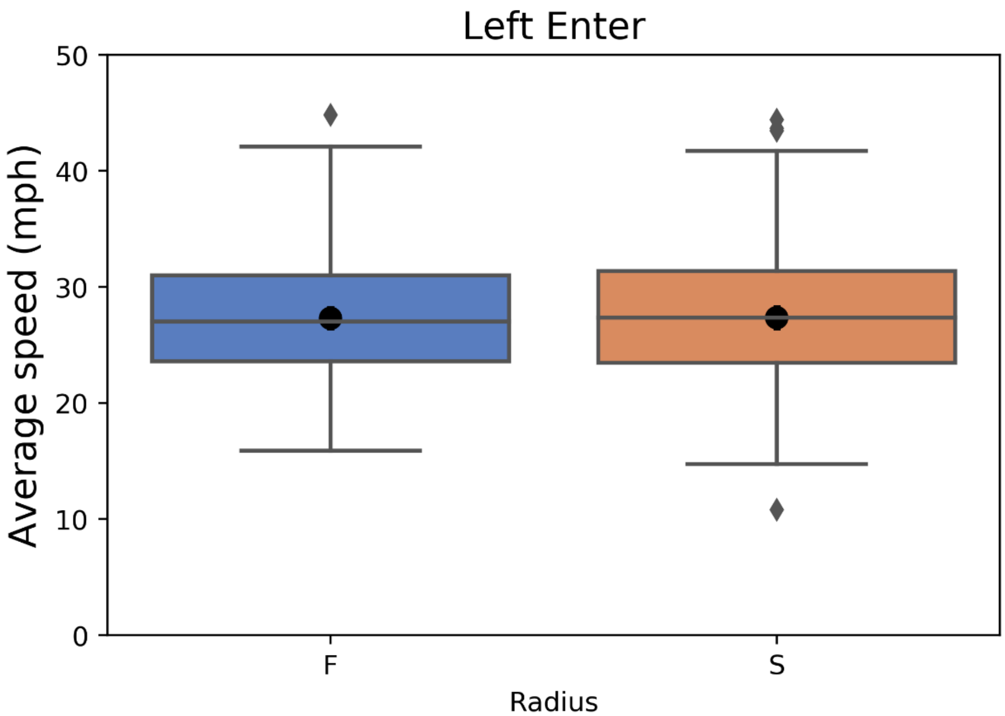


Figure 24: Average participant speed entering the protected intersection and making a left turn

Similarly, to the right turns participants performed, the left turn through the curve of the protected intersection resulted in a significantly lower average and median speed for the majority of participants, Figure 25. The average and median speeds were 20 mph in comparison to the 27 mph for the average entering speed, suggesting that the turning movement influenced driver's speed. This data mirrors the average speed for the bike no bike scenarios, suggesting that there are multiple variables influencing participant's speed throughout the protected intersection.

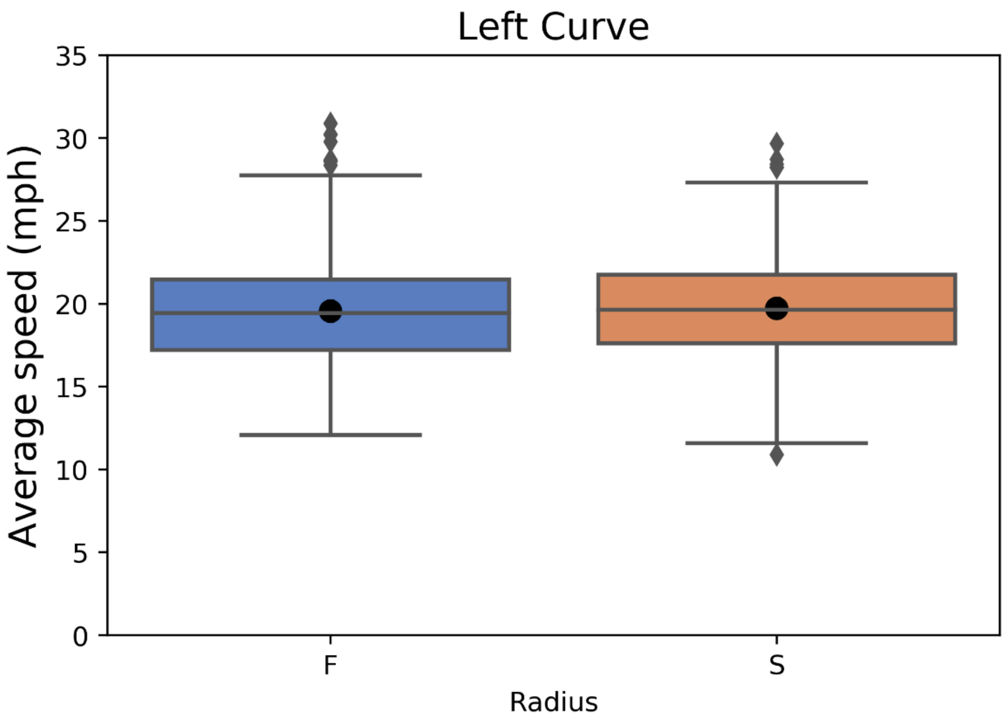


Figure 25: Average participant speed while turning left through the protected intersection

The average exit speeds of participants after completing a left turn are displayed in Figure 26. The average speed for the large and small radius was nearly identical at 32.36 for the small radius, and 32.26 for the larger radius. The range in speeds was closer than the range for average speed through right turns, Figure 16. The higher exit speeds can be attributed to participant’s rapid acceleration after completing the end of scenario straightaway as participants tended to accelerate as the end of the scenario approached. This behavior was witnessed a majority of time, with very few participants opting to come to a gradual stop after completing both turns. This does not explain participant’s higher speeds on the straightaway connecting the two protected intersections.

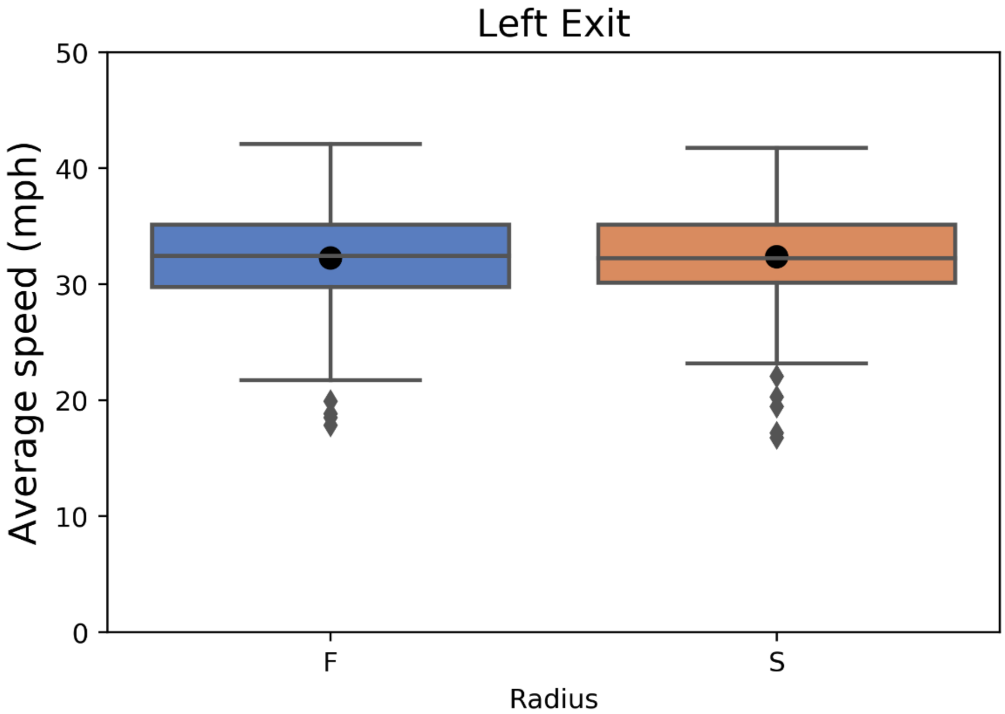


Figure 26: Average participant speed while exiting the protected intersection after a left turn

Bicycle Lane Marking

This section analyzes the effect that different levels of pavement marking had on average driver speed. Like the previous sections, the analysis of pavement markings begins with the average approach speed of all participants across all levels of pavement marking. As shown in Figure 27, the average speeds were slightly higher for the maximum level of pavement marking, in comparison to the none and minimum level. However, the median speed of each level was differed by +/- 1 mph, indicating that the distribution was relatively the same, albeit skewed slightly faster for the maximum pavement marking level.

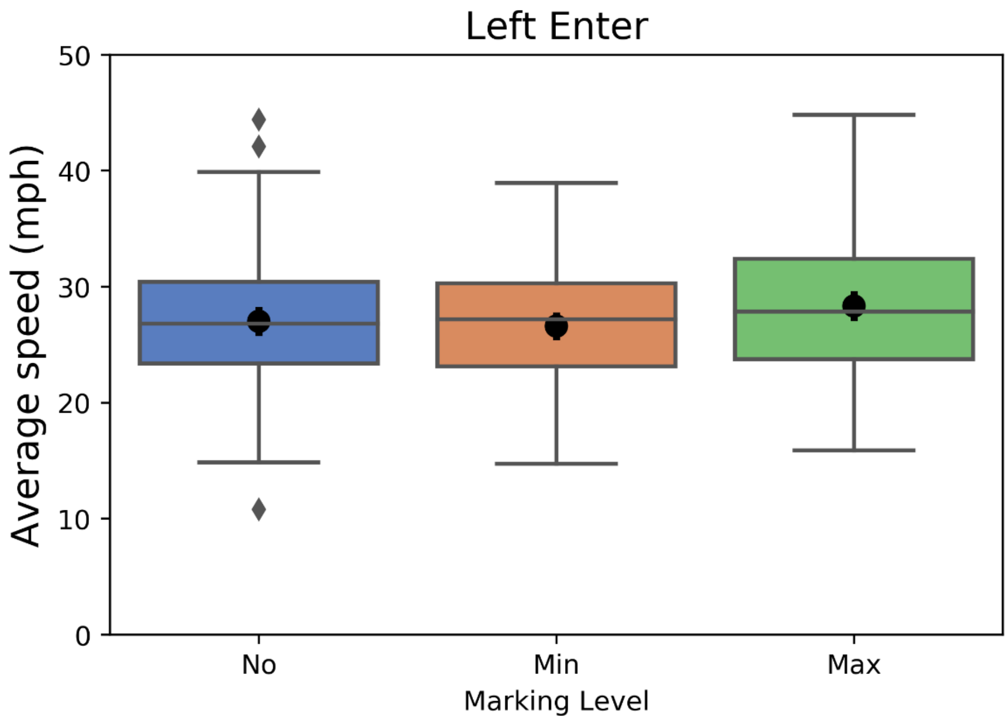


Figure 27: The average speed distribution of participants for different levels of pavement markings

Like the previous analyses conducted of other variables, there was a distinct reduction in average participant speed as participants performed the left turn through the protected intersections. This data is presented in Figure 28. This aligns with previous analysis, suggesting that drivers moderated their speed while turning in order to perform a safer turning motion through the protected intersection. Again, the averages and median speeds of participants were approximately the same across all level of pavement marking analyzed.

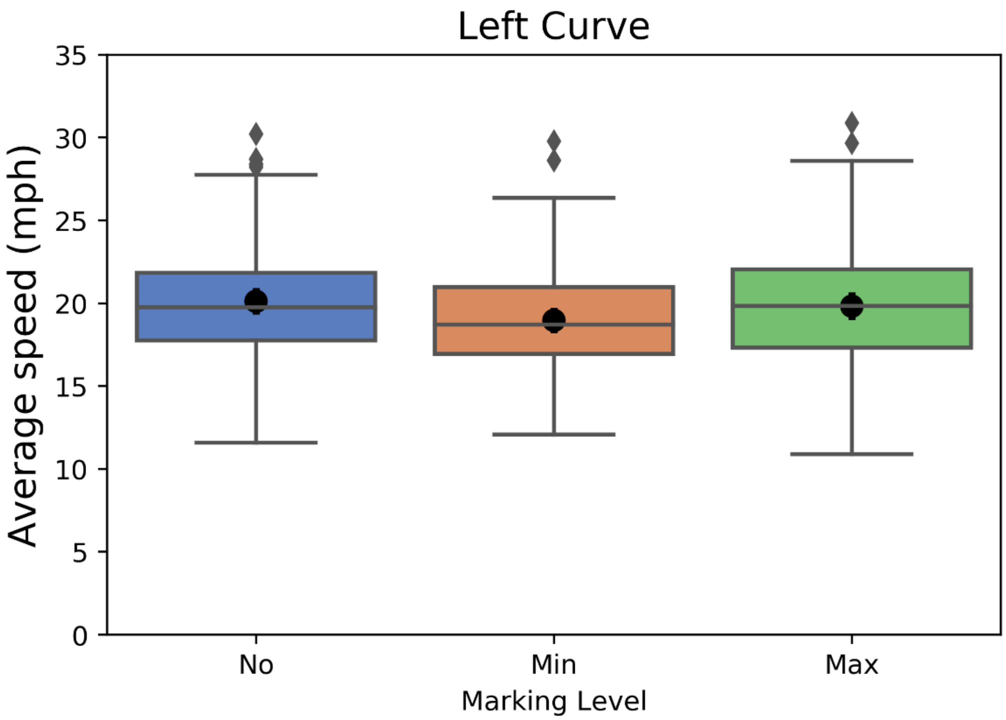


Figure 28: Average participant speed through the left curve of the protected intersection

Average participant speed upon exiting the left curve was higher than both the driver's entering and curve speed, Figure 29. This can potentially be attributed to the straight segment of roadway the participants were provided with upon completing the left turn, as the length of the straightway allowed participants to rapidly accelerate. The large range and high average and median speeds across all levels of pavement marking suggest that after exiting the protected intersection, the markings did not influence participant speed.

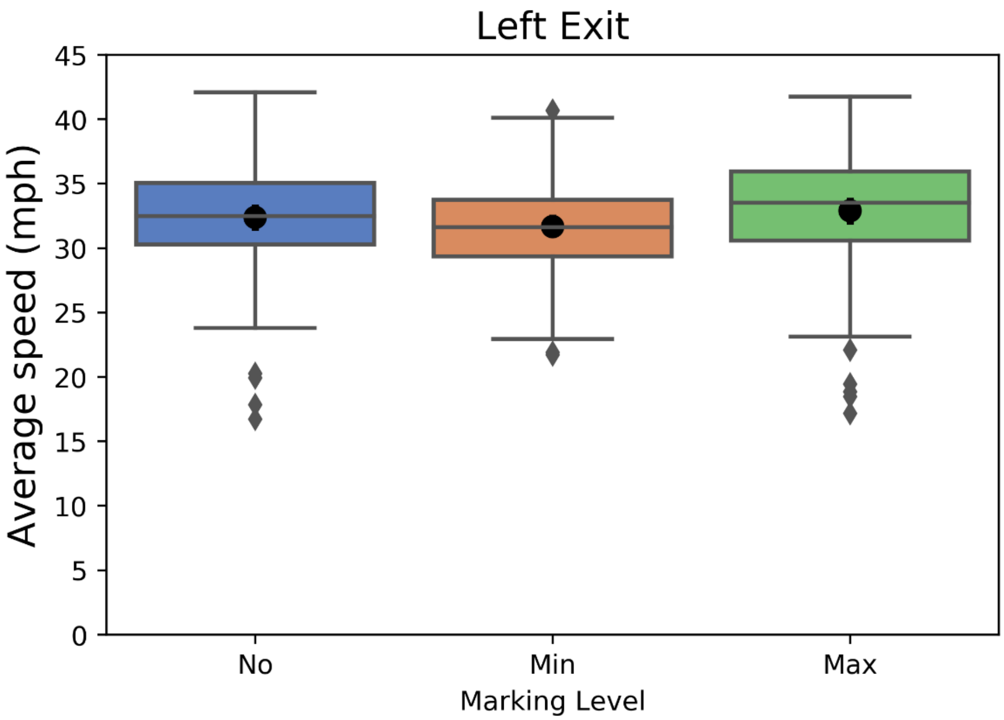


Figure 29: Average participant speed exiting the protected intersection for left turns

Trajectory Analysis

To complement the speed analysis conducted in the prior sections, a trajectory analysis of all participants and drives was created to visualize the participant's speeds while navigating the scenario. For this analysis, the distance of the left and right starting drives was normalized in order to display all drives on one chart. Two charts are presented comparing the participant's speed to whether a bicycle was present during the drive. When a driver came to a complete stop or braked, their speed decreased over the distance driven. This is represented by the speeds touching zero in the two valleys of the following charts. As shown in Figure 30, drivers were much more likely do stop at the intersection if a cyclist was present, and depending on when the cyclist was identified, their speeds decreased quicker than when a cyclist was not present, Figure 31.

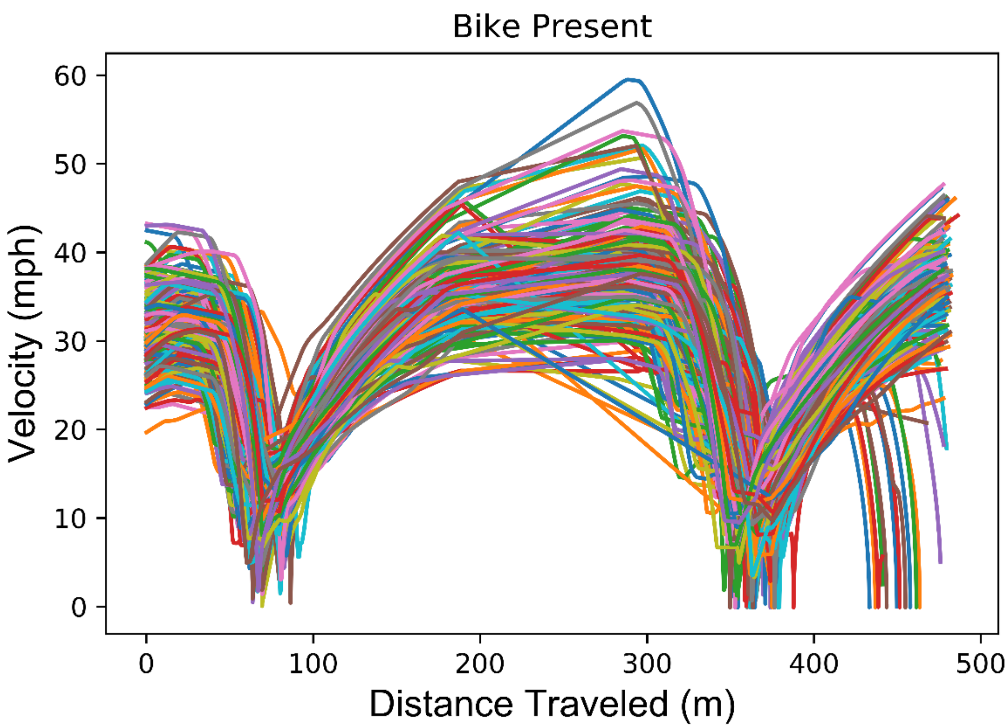


Figure 30: Driver speed through drive when bike was present

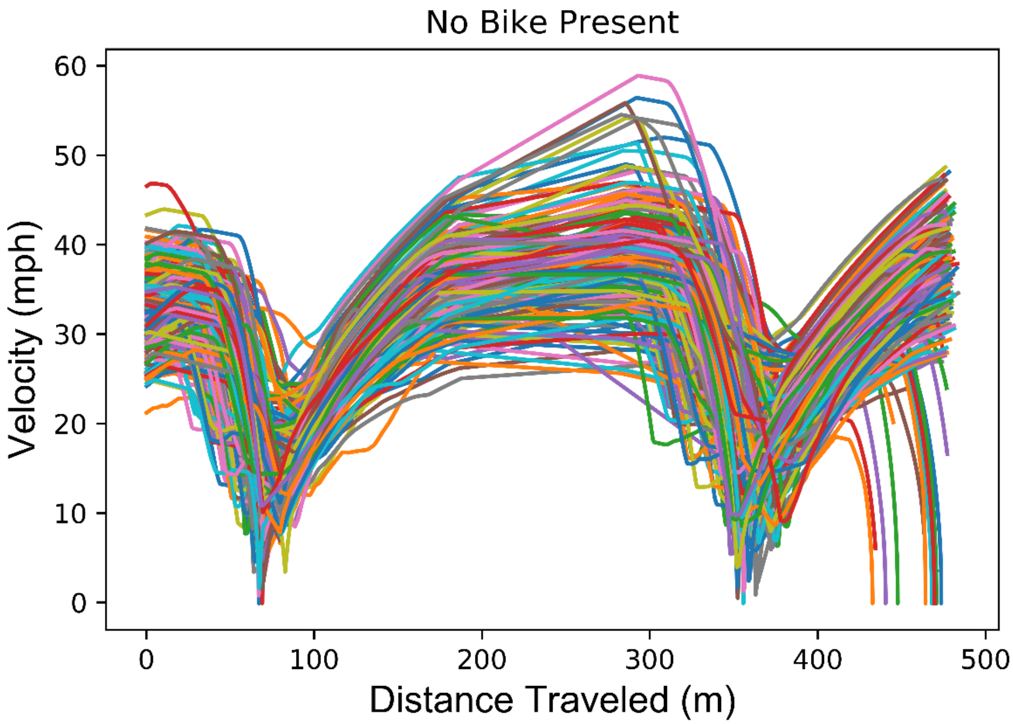


Figure 31: Driver speed through drive when no bike was present

Comparing the participant's speeds for all combinations of radius and cycle lane markings yields interesting results. The similar shapes of Figure 32 and Figure 33 suggests that radius did not significantly alter the speeds of participants through the drive, as the peaks and valleys are close in size and magnitude. This could indicate that drivers treated all intersections the same, regardless of the radius of the protected portion that participants had to navigate. To further discern if the radius influenced participant speed, Figure 32 and Figure 33were divided into their component pieces to see if differences arose when the individual marking levels were compared to the radius of the intersection.

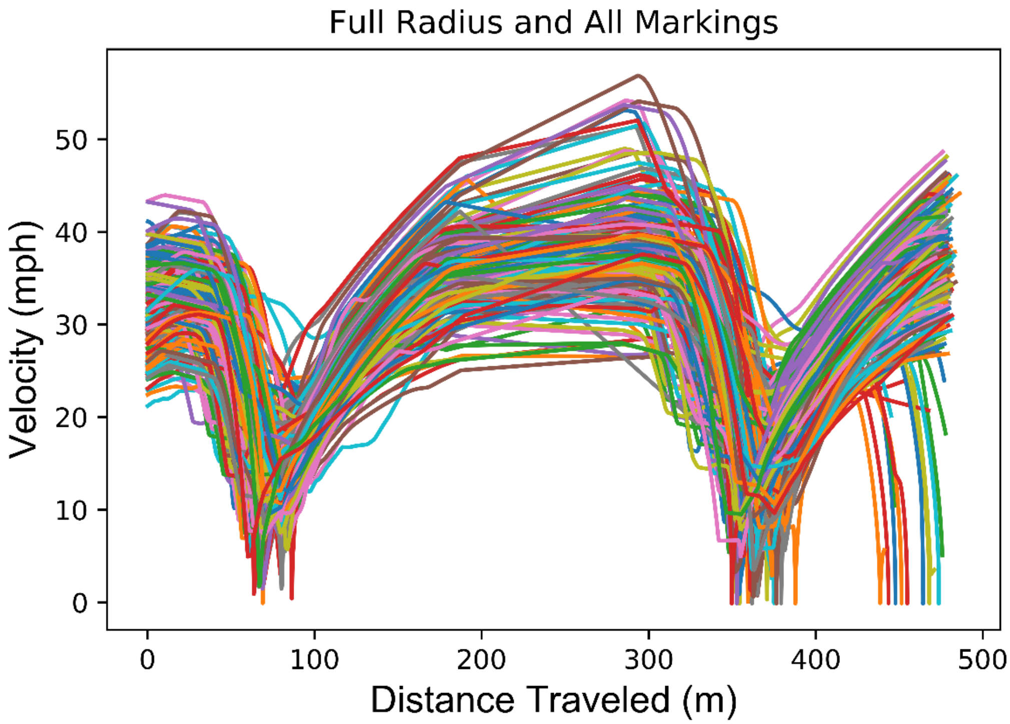


Figure 32: Trajectory data for all marking levels with a large radius

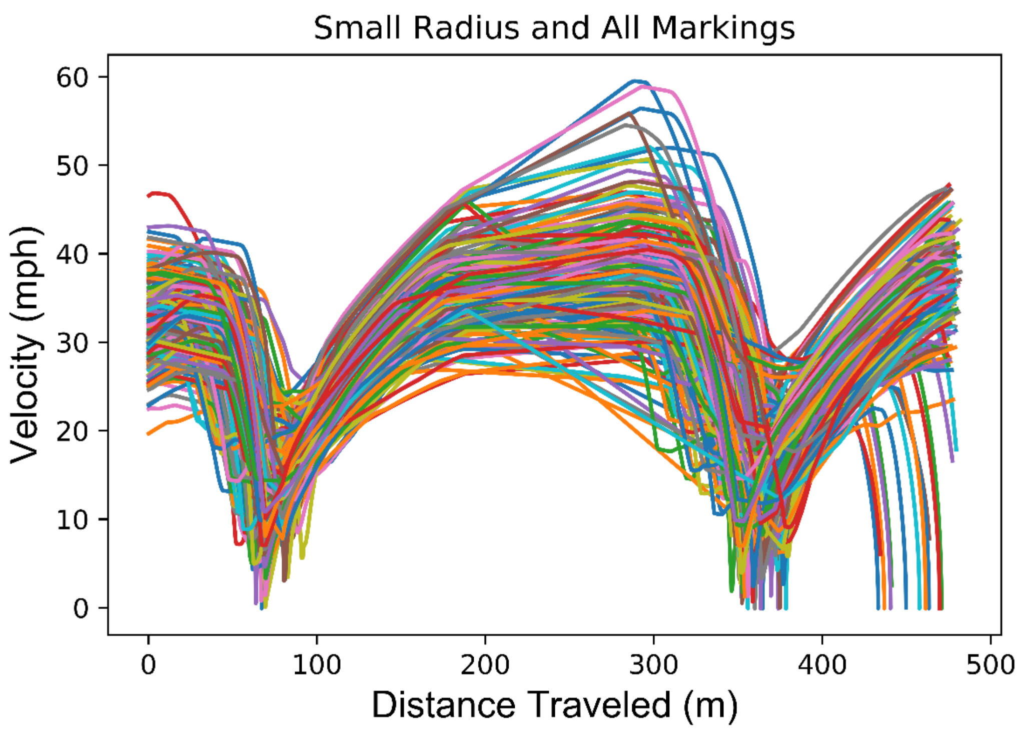


Figure 33: Trajectory data for all marking levels with a small radius

As shown in Figure 36, the greatest consistency of participant speed was seen when the full radius was utilized in conjunction with the maximum level of pavement marking in an intersection, the solid green cycle lane with dashed white lines. While the ranges of speeds are the same, the valleys of Figure 35 and Figure 36, indicating the location of the turning movement, are wider, which suggests that the participants speed was reduced for a longer period of time than in instances where there was no pavement marking present, as in Figure 34. This indicates that some level of pavement marking, combined with a larger turning radius, may be effective in reducing driver speeds in a protected interseciton, yielding higher levels of safety for all users.

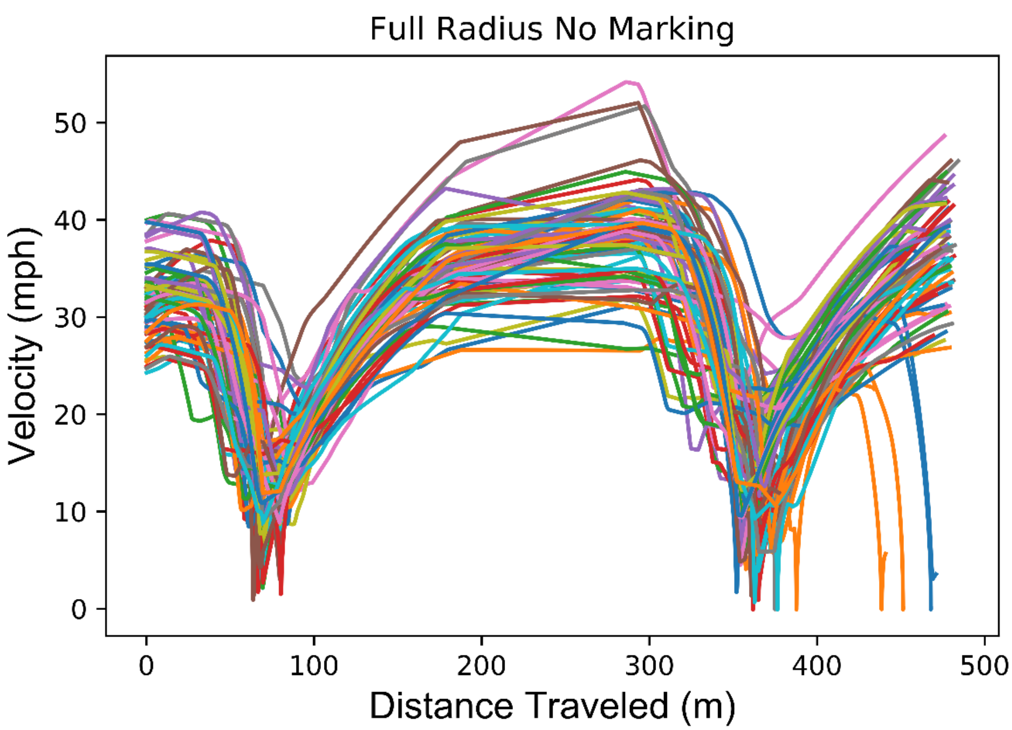


Figure 34: Trajectory of participants with a full radius and no marking

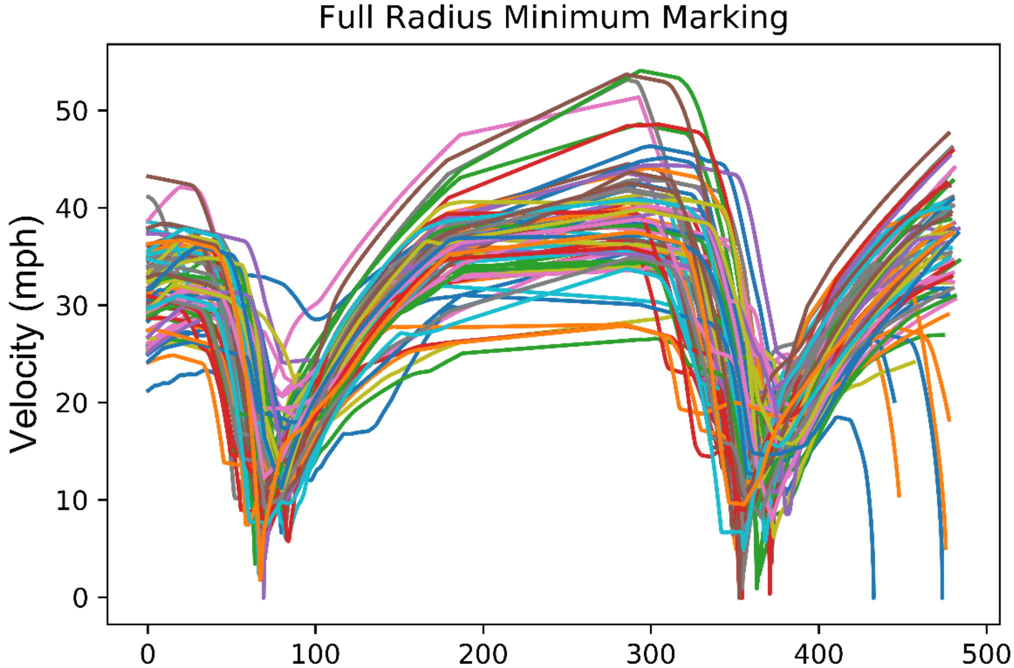


Figure 35: Trajectory of participants with a full radius and minimum marking

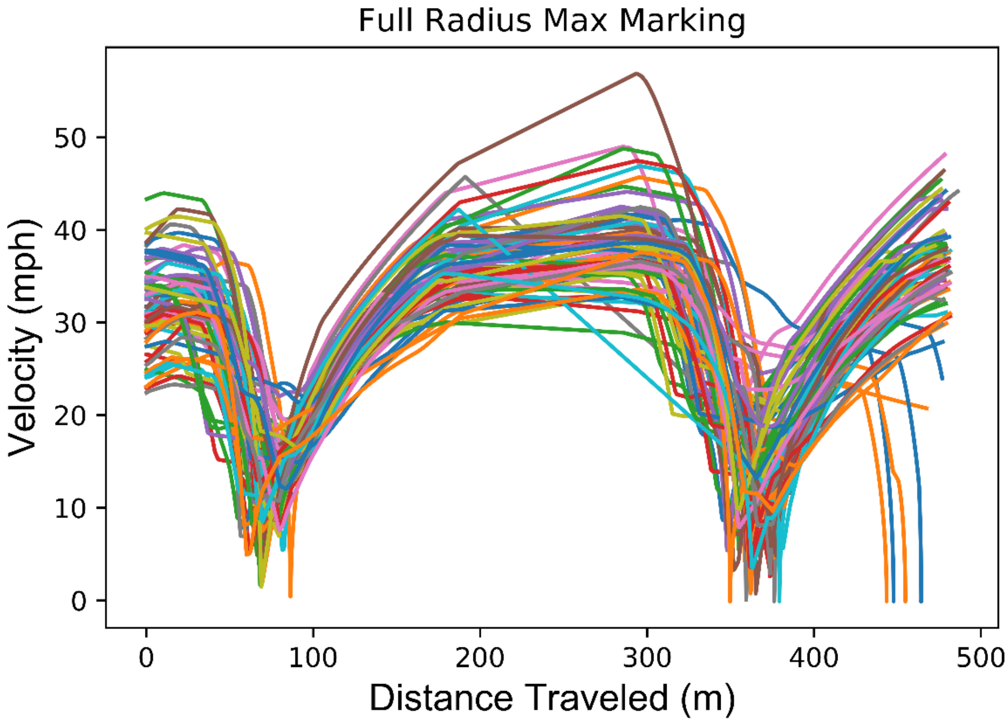


Figure 36: Trajectory of participants with a full radius and maximum marking

When the trajectories are compared for turning movements with a smaller radius and any level of pavement marking, the greatest consistency in driver speed is seen with a maxium pavement marking and the small radius of the protected intersection, Figure 39. As noted, the charactertistcs of the valleys for Figure 39 show the same wide spread at the point of the curve as in Figure 35 and Figure 36. While these trajectories do not definitively represent a difference in speed reduction between the size of the radius and the pavement marking used, the overall consistency in terms of trajectory data suggests that having a smaller radius coupled with a maximum llevel of pavement marking may have some postive benefits on reducing driver speed through a protected intersection.

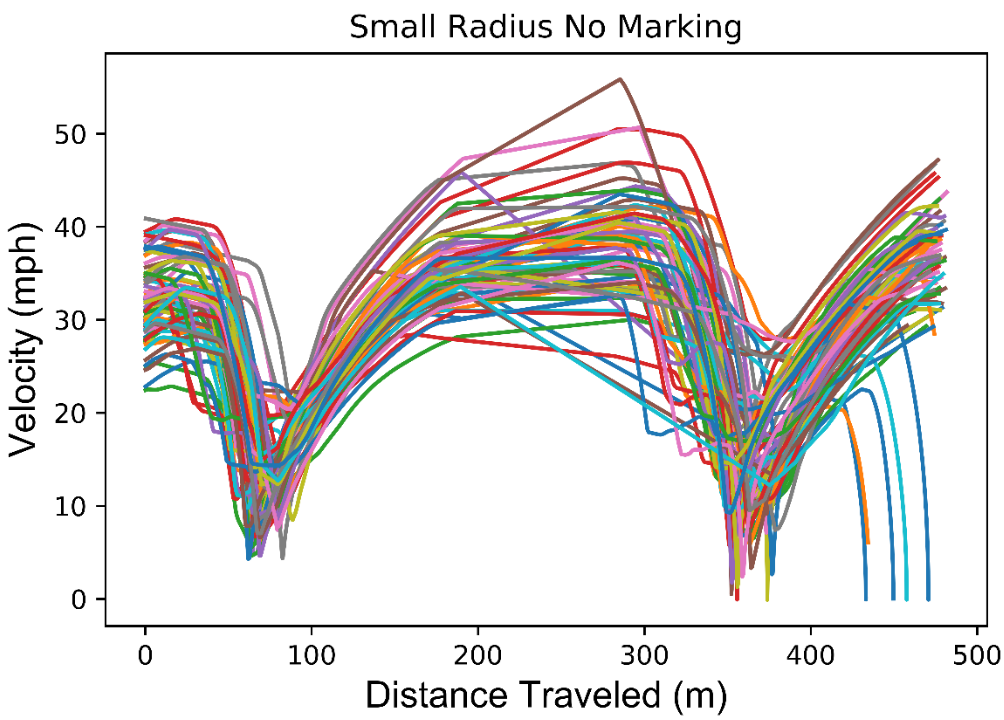


Figure 37: Trajectory of participants with a small radius and no marking

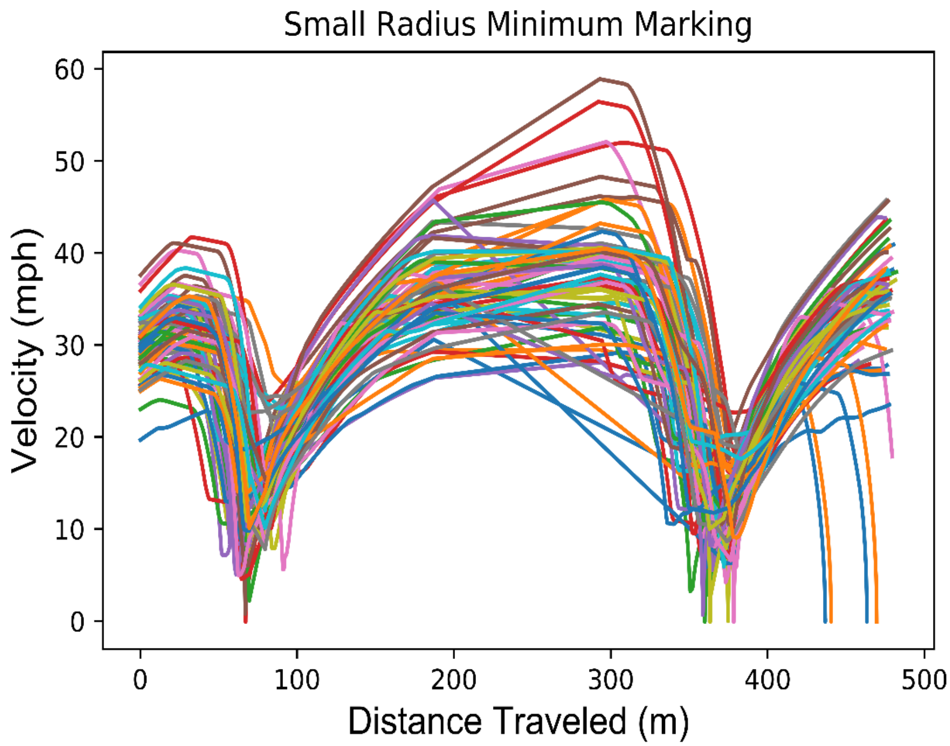


Figure 38: Trajectory of participants with a small radius and minimum marking

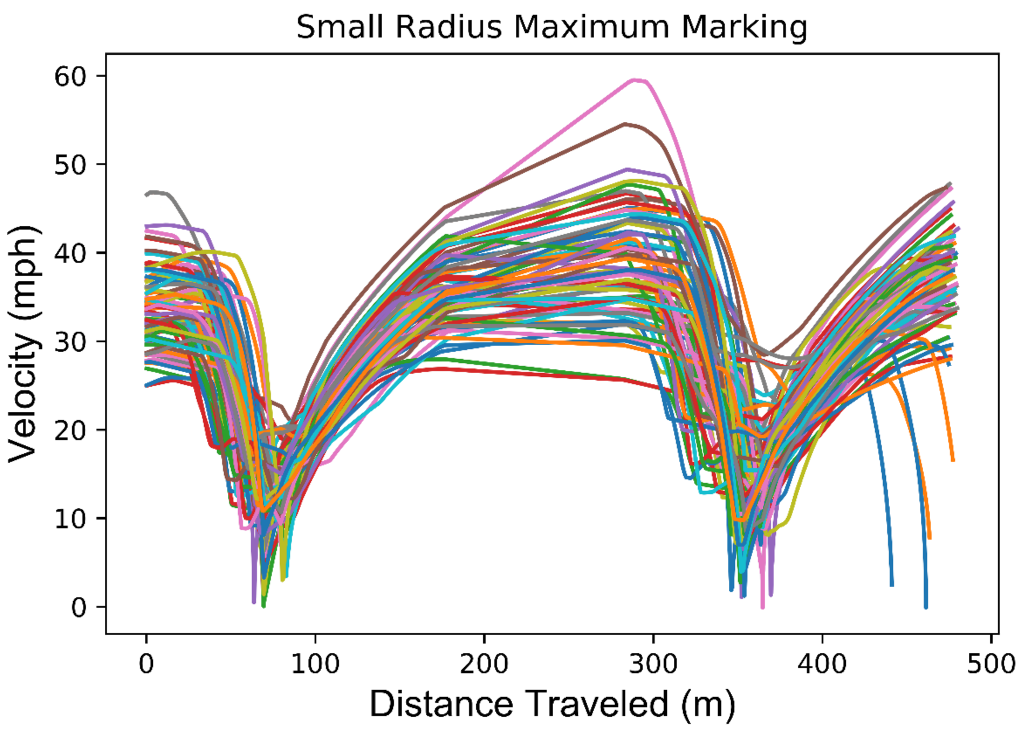


Figure 39: Trajectory of participants with a small radius and maximum marking

Linear Regression Analysis

Plotting the average speed data for all participants across all drives and for each variable level only explains a portion of the results of this experiment. To fully understand the effect each variable had, a linear regression analysis was conducted using the average speeds for all participants, broken up by variable type. All levels of variables were considered, as well as each separate section of the protected intersection that data was collected for, resulting in the need for multiple regression analyses to be made due to the three levels of pavement marking used to delineate the cyclist path in the protected intersection. Because of the binary nature of variables in regression analysis, multiple regressions were necessary to effectively capture the effect each level of pavement marking had on average participant speed through the protected intersection. This resulted in five different combinations of regression analysis being performed for both the right and left turn intersections across all drives. The combination of pavement marking that provided the strongest results was the comparison of no pavement marking to any level of pavement marking, thereby combining the minimum and maximum level of pavement marking into one category, allowing for the creation of a binary variable. Two separate regression analyses provided the most significant results for two variables in two separate portions of the protected intersection. In addition, all regression analysis conducted indicated that the bicyclist influence on driver speed was significant across all entering speed data and curve data analyzed.

Interpreting the results of the linear regression required an understanding of the different variables and values the regression analysis would produce. The first result that was analyzed was the Adjusted R Square value, which adjusts the R Square based on the number of variables used in the regression analysis. The R Square value represents the coefficient of determination, indicating how many data points fall on the regression line. It is calculated by taking the square root of the multiple R value. The multiple R value indicates the fit of the linear regression, with the value of one being a perfect fit, and a value of zero being no fit or relationship for the data. These values were obtained through the analysis process but were not used in determining the significance of the regression. Instead, the Adjusted R Square was the primary measure of fit for the regression analysis, based on the ability of the value to handle multiple variables and a large volume of observations.

The second value used in the determination of significance for the regression analysis was the P value generated for each variable used in the analysis. A 95 percent confidence interval was used, meaning that a variable was considered significant, or influential on the average speed, if the value of P was less than 0.05. Due to these constraints, out of all the regression models produced, one model for the right turn curve speed, and another model for the left turn curve speed, generated the most significant variables. The significance for each of these analyses is presented in Table 7.

Table 7: Variables and P levels of the regression analysis

Drive	Variables	P-value
Right Curve	Marking	0.403239
	Radius	0.047512
	Bicyclist	7.45E-11
	Adjusted R Squared	0.09714
Left Curve	Marking	0.032062
	Radius	0.587094
	Bicyclist	8.25E-18
	Adjusted R Squared	0.161037

The regression analysis presented in Table 7 was further refined by eliminating the insignificant variables for each curve. For the right curve analysis, pavement marking level was removed as a variable due to the high P-value associated with the marking level (p = 0.403239). For the left curve analysis, the radius was removed as a variable for analysis, again due to the high P-value associated with the variable (p=0.587094). Removing both variables resulted in slightly adjusted values for each variable, shown in Table 8.

Table 8: Updated Variables and P levels for the regression analysis

Drive	Variables	P-value
Right Curve	Radius	0.047127
	Bicyclist	7.2E-11
	Adjusted R Squared	0.097773
Left Curve	Marking	0.032062
	Bicyclist	7.81E-18
	Adjusted R Squared	0.162418

The same linear regression analysis was conducted but with gender added into the list of potential variables affecting participant speed for both left and right turns. As displayed in Table 9, a participant's gender had a significant effect on their speed through the right and left curves presented in this research. Comparing the Adjusted R Squared values in Table 7, Table 8, and Table 9 shows an increase in values with the inclusion of gender. These values increase further when the insignificant variables are removed as was done previously from Table 7 to Table 8. The results of this removal are portrayed in Table 10.

Based on the Adjusted R Squared values, the inclusion of gender as a variable and the removal of the insignificant variables increased the fit of the regression analysis, indicating that these variables were influential in determining a participant's speed in a given intersection. However, including gender as variable indicates that there may be other factors at play given that gender was not controlled for in this experiment, aside from the desire to maintain a relatively even balance of male to female participants. While the variables included in Table 10 are all significant ($p<0.05$), the Adjusted R Squared value is low, which suggests that the combination of variables and values associated with the regression analysis may only accurately predict a participant's speed approximately fifteen to twenty percent of the time. Although this is not a high level of confidence in determining the speed, the level of significance shows that there is some level of influence for each variable included in the final table, therefore it can be reasonably assumed that the changes in level of variable did play a role to some degree on influencing the participants' speed.

Table 9: Variables and Adjusted R values for Regression Analysis, Gender Included

Drive	Variables	P-value
Right Curve	Marking	0.381635
	Radius	0.042784
	Bicyclist	2.5E-11
	Gender	7.53E-07
	Adjusted R Squared	0.145607
Left Curve	Marking	0.029538
	Radius	0.585737
	Bicyclist	1.99E-18
	Gender	1.1E-05
	Adjusted R Squared	0.196411

Table 10: Linear Regression Analysis with Insignificant Variables Removed

Drive	Variables	P-value
Right Curve	Radius	0.042431
	Bicyclist	2.41E-11
	Gender	7.57E-07
	Adjusted R Squared	0.146073
Left Curve	Marking	0.029537
	Bicyclist	1.88E-18
	Gender	1.08E-05
	Adjusted R Squared	0.197733

DISCUSSION

This section will discuss the data presented in the data and analysis section and explore potential explanations and implications that the data has. Like the analysis section, this section will be divided based on the variables analyzed, the regression analysis performed, and the potential application that this research has from a planning and transportation perspective.

Bike vs No Bike Scenario

A total of 432 turns containing a cyclist were observed in this research, 216, or fifty percent of the observed turns were for a participant turning right through a protected intersection, and the other fifty percent were for a participant turning left through a protected intersection. The average speed of the participants across the different drive portions varied on whether the participant was entering, turning, or exiting the protected intersection. Average speed of participants was typically lower when a cyclist was present by 2-5mph, depending on the location of the participant and their proximity to the cyclist.

Participants noticeably had an average speed of 14mph for scenarios with a cyclist, and 17 mph for right turns without a cyclist; an average speed of 18 mph for left turn scenarios with a cyclist, compared to an average speed of 21 mph for left turns without a cyclist present. This difference in average speeds while turning may be explained by the observed typical participant behavior, which could be described as a sudden braking by the participant upon identification of a cyclist crossing the driver's path, coming to a complete or slow, rolling stop, and then proceeding to accelerate through the intersection once the cyclist was clear of the desired travel lanes. The lower speeds for scenarios with a cyclist indicate that the participants were adept at identifying the crossing pattern of the cyclist and were deferential in their behavior towards the cyclist.

The higher overall speeds for left turns may be attributed to the greater distance drivers had to travel to perform the turning movement. A left turn is typically wider and covers a larger distance than a right turn, thus the participants would have more time to accelerate while turning, thereby increasing their average speed throughout the curve. This is further shown in the higher average speeds for left turns across all scenarios, though the difference in average speeds is never greater than 5 mph.

Large Radius vs Small Radius

A total of 864 turns were compared using the protected intersection radius, 432 left and right turns. Within each turn direction, 216 left and right turns had a large radius (5 meters), and 216 had a small radius (3 meters). The average speed of participants sorted by radius type indicated that participants traveled at a lower speed while traversing the protected intersection from the right compared to the left. This may be due to the proximity of vehicle to the protected intersection, as the left turn was wider and had more room to maneuver in comparison to the right turn participants were asked to perform.

Across all data collection categories, speeds for participants were within +/-1mph of each other when sorted based on small or large radius, indicating that the direction of the turn, rather than the physical size of the intersection, may have a larger influence on a driver's average speed through a protected intersection.

Bicycle Lane Marking

The differences in speed for the types of marking examined in this experiment showed the greatest decrease in speeds when the full cycle lane was painted green. As a planner or engineer on a local level, specifically in New England, pavement markings can be an expensive component of a maintenance budget due to the frequency of plows and the different weather the pavement is exposed to. There is a potential to realize the same benefits of pavement markings by changing or dyeing the pavement on application a different, one that would align with the marking guidelines established in the MUTCD for designated cycle lanes. In doing so, the yearly maintenance may be reduce, so long as the pavement is designed and constructed to the same guidelines as a regular roadway, this would alleviate some of the burden on the maintenance side but result in a slightly higher capital cost due to the pavement dye required.

Aside from delineating where a cyclist may be to motorists, enhanced levels of marking on cycle lanes provide an added level of comfort to cyclists. One of the largest theories about cycling infrastructure is that of induced demand, that there exists a latent quantity of people who would rather cycle for transit, but do not feel safe on the current road network and therefore choose not to. But, if the infrastructure was in place, through the addition of painted lines and protected

elements, perhaps the rate of cycling would increase. This induced demand, which could occur if enough protected elements are connected, is perhaps the strongest reason to consider advanced levels of lane markings for cyclists.

Planning and Transportation Perspective

This research has the ability to influence guidance documents for transportation agencies, consultants, and municipalities. By identifying relatively minor changes that can be made to existing intersections based on their geometry, each of the stakeholders listed above can have an immediate effect on the nature of cycling in their communities. Modifying existing intersections by adding bump outs or new pavement marking can have a measurable effect on driver's speed and increase the visibility of cyclists to a driver. Informing a driver that a cyclist pay be present in a specifically delineated area with a solid green pavement or dashed white lines, or some combination thereof, can additionally increase driver awareness of cyclists on approach to an intersection.

From a network perspective, improving the connectivity and ability of different users to utilize existing intersections can enhance the feeling of safety for cyclists, leading to increases in recreational and commuter cyclists, as well as reductions in motor vehicle conflicts between cyclists and motorists. Various studies and citizen feedback to municipalities indicates that the lack of connectivity between protected bicycle elements in a community is a deterrent to a greater frequency of cycling. If transportation planners and engineers can effectively and efficiently increase the level of comfort for cyclists by making modest improvements to already existing infrastructure, then those options should be explored in order to accelerate the vision of safer streets for all users. This research highlights the small changes that can be made to existing intersections to further the network goals for cyclists and communities.

Complete street projects and guidance have done a lot to push the fields of transportation and planning to consider all road users when designing a corridor. However, the guidance included in these documents typically calls for a large, and costly, redesign of an existing corridor to increase the space for buses, cyclists, and pedestrians. While this may be feasible for some large municipalities, and some smaller ones with enough state or federal funding, most municipalities

do not have the budget space available to perform such an undertaken. However, if the municipality or agency is seeking a modest reduction in driver speed through an intersection, then the variables examined in this research are suitable, and affordable options for the municipality to explore. Adding protective islands to an existing intersection would make the most sense, as it would provide a greater level of visibility and safety to cyclists and pedestrians seeking to cross an intersection. Ideally, these islands would be installed at intersections with the capacity and space to handle separated cycle lanes, however, there still may be a speed reduction potential by installing these in an intersection without existing protective elements.

Improving or painting different levels of pavement markings through an intersection may look aesthetically pleasing, but without the cycle lanes or dedicated cycle areas, the benefits may not be as great. While the bright green marking may improve the path visibility of the cyclist, if there is no existing connection to the green marking outside of a standard sidewalk, the effects of the marking will most likely be less. Upgrading the marking level at existing intersections or adding marking to intersections with protected bike lanes but no marking, could increase the visibility of cyclists to drivers, while also in turn increasing the level of comfort experienced by cyclists while traversing the intersection.

The limiting factor to the level of pavement marking and intersection radius would be the up front and maintenance costs associated with each. While the island would ideally not require substantial maintenance due to its shape and composition, the pavement markings would most likely need to be repainted on a bi-annual or annual basis depending on use, weather, and throughput. This could potentially add up if a municipality decided to upgrade the pavement markings of all their intersections to accommodate cyclists and designate their space with paint. A more permanent solution, such as different pavement colors or compositions could be explored to achieve the same benefits as paint, but at a greater upfront cost due to the construction costs associated with different pavement as well as procurement of the necessary materials.

Additional benefits may be realized for communities that have adopted electronic bike (e-bike) and scooter (e-scooter) rideshare systems. Presently, as e-bikes and e-scooters are motorized forms of transit, their use should only be conducted in the roadway and not on the sidewalk, for the same

reason that mopeds use the street. While this separation is beneficial and safer for pedestrians, the e-bike and e-scooter users typically do not have their own helmets, and the bikes and scooters are speed restricted and thus impede traffic if utilizing a full lane. These users, however, can benefit from the adoption and implementation of protected intersection elements, as they travel at the same relative speed as cyclists, and would alternatively have to travel next to automobiles if such elements were not present.

Accommodating e-bikes and e-scooters in the same lanes as regular cyclists could help facilitate modal shifts within a large metropolitan area. Providing more choices for commuters and residents to consider when planning their trips can reduce the number of automobiles on the road network, increase transit ridership, and reduce the number of interactions between automobiles and other users, thereby lowering the crash rate of automobiles. These ancillary benefits are not necessarily guaranteed because a municipality successfully implements protected intersections along one corridor or another, but their existence may facilitate and the lay the groundwork for such a change to even occur. Many times, change starts with one small step taken by an individual or municipality, and by changing a protected intersection element, the corresponding increase in the perceived safety of cyclists may jump start a trend in local transportation that may ultimately benefit the community.

CONCLUSION

The presence of a cyclist had a larger, more persistent effect on a participant's speed than any other variable examined in this experiment. This was expected and anticipated, as the participants routinely yielded and stopped well in advance of the cyclist, likely due to participants familiarity with cyclists in the Amherst area. As the regression analysis showed, each variable was significant in some combination of right or left curves on their own ($p<.05$), with the radius exhibiting a larger influence on participant's speed for right turns, and the marking level influencing driver speeds to a larger degree on the left turns.

Additionally, the inclusion of gender as a variable of interest in the regression analysis ultimately improved the fit of the regression line for both left and right curves with all significant variables included. This suggests that there were factors outside of the experimental design that were influencing the participants' speed throughout out both right and left turns in the protected intersections. Identifying the combinations of variables and the gender associated with lower speeds may lead to different in vehicle treatments to positively influence a decrease in driver speed based on the geometry of the roadway, the level of pavement marking, and who is behind the wheel of the automobile.

The effect of pavement markings was not as significant as first hypothesized. Although the speeds of participants did not change drastically between variable configurations, the effect on driver and cyclist comfort may be greater and more important than the speed data presented. If cyclists feel more confident while navigating an intersection due to the existence of protected elements, than the intersection is operating as designed by providing space for more modes of transportation. While the treatments tested in this experiment would suffer in the Northeast or Midwest due to the necessity of snowplows, localities that do not encounter frequent snowstorms may see further benefits and cost reductions from implementing a higher level of pavement marking or intersection radius.

Limitations

This research was limited by the number of potential variables that could be explored at once, as each additional variable would have necessitated a greater level of participants in order to maintain a statistically viable sample. There are opportunities to expand the sample size in the future using the existing worlds, however, as modifications can be made to the intersections to test different intersection radii, further levels of pavement marking, and different signage of the intersection all together. The eye tracker data collected during this experiment was not especially useful to the data processing, as there was no clear standard of what participants should be glancing at while turning through an intersection. The braking and turning maneuver each participant performed were different and occurred at different points in the turn that there was no objective data point to be discerned if a participant had indeed glanced or not at that location. If the participants did glance at a location repeatedly, it did not influence their behavior while turning.

The static nature of the cyclist and the repetitive nature of the cyclist's movement made portions of the experiment predictable to certain participants. A superior script could be developed to make the cyclists movement dynamic and erratic, causing the driver to encounter the cyclist unexpectedly in different locations. While this would naturally upset the balance of the experiment and require further experimental controls to be put in place, it could perhaps more accurately model interactions between cyclists and motorists in a simulated environment.

Future Work

There are multiple design elements of protected intersections that could be explored to measure the effectiveness of different treatment levels on the safety of protected intersections. In addition to intersection radius and pavement marking, types of signage, position of crosswalks, and different levels of signalization could all be experimented with to determine potential enhancements in the level of safety at protected intersections. These variables could be explored on their own, or in conjunction with previously tested variables to formulate a better understanding of what the ideal protected intersection should look like.

A cost analysis of the different variables identified in this experiment could be undertaken, in order to ascertain the investment level required by transportation agencies and municipalities to improve the safety benefits of already protected intersections. Converting existing intersections into protected intersections is potentially cheaper than a clean scrape of existing infrastructure and could yield tangible benefits at a fraction of the cost.

In addition, comparisons to existing intersections could be made based off existing simulation data, and field studies could be conducted with temporary structures to visualize what a protected intersection would look like. By utilizing temporary structures, researchers would be able to compare the simulated data with real world recordings to determine if the results predicted by the simulator are like those experienced in the real world. Converting existing infrastructure to different uses through temporary structures has already been done for pedestrian plazas and changing an already existing intersection into a protected intersection may be a straightforward process and would benefit an area that already has some level of separated bicycle lanes to record interactions between cyclists and motorists. By making the protected islands movable, in the event of a snowstorm or other emergency, the protected islands could be removed from the intersection thereby making the job of the plows easier as they do not have to navigate a non-contiguous curb.

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