Using Simulation to Assess Conflicts Between Bicyclists and Right-Turning Vehicles

SAFER SIM

SAFETY RESEARCH USING SIMULATION

UNIVERSITY TRANSPORTATION CENTER

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Abstract

Protected bike lanes, or cycle tracks, are increasing in popularity across the nation. However, despite the documented benefits of protected bike lanes, including safer cycling and increased ridership among differing populations of bicyclists, there remain ongoing concerns about potential conflicts between bicycles and vehicles when they merge back together at an intersection. The fear is that following a period of separation, drivers are less likely to anticipate and scan for the presence of bicycles. This research examines how transitions from fully separated to mixed-traffic environments and vice versa affect driver behavior. The goal is to assess whether certain segment-intersection treatment combinations can alert drivers of the presence of bicyclists and thus encourage them to scan for bicyclists prior to a right turn, reducing potential right-hook conflicts. Driving simulation is utilized in this study, and driver performance for right-turning vehicles is recorded under the presence of various bicycle infrastructure treatments along segments and at intersections. The experimental design includes two types of bike lanes and two intersection configurations, namely conventional and protected bike lanes and intersections with through bike lanes and protected intersections. Results show that the presence of the bicyclist as well as the presence of protected bike lanes reduce average speed on the segment. Additionally, the presence of the bicyclist significantly reduces the intersection speed when non-protected intersection design has been implemented. The presence of the bicyclist was also found to significantly affect participants' glancing behavior at the intersection approach, triggering more of them to place a right glance regardless of the intersection configuration. In addition, participants were found to be less likely to glance for the bicyclist when riding on a segment with protected bike lanes compared to scenarios with conventional bike lanes. This research can be used to guide decisions on bicycle infrastructure implementation for safer multimodal operations.

1 Introduction

Bicycle commuting trips in the United States (U.S.) account for 0.6% of all commuting trips, but at the same time bicyclists' fatal accidents represent 2.2% of the total fatalities [1]. Recent efforts to improve bicycle safety have focused on bicycle infrastructure treatments with an increased interest in protected bike lanes (i.e., cycle tracks). The mayor of New York City has announced the city's plan to implement innovative bicycle infrastructure treatments, emphasizing the need to increase the number of miles of protected bike lanes [2]. Recently, the Massachusetts Department of Transportation (DOT) became the first state DOT to publish guidelines for planning and designing separated bike lanes [3].

Protected bike lanes, also known as separated bike lanes or cycle tracks, provide a physical separation between motorists and bicyclists. As a result, they essentially eliminate the possibility of collision along roadway segments and improve the level of comfort for many bicyclists. However, this separation is not always maintained at intersections, and bicyclists are often forced to interact with motorists in a mixed-traffic environment. Serious concerns have been raised regarding the placement of protected bike lanes since, after a period of separation, drivers might not anticipate interacting with bicyclists and, as a result, might be less likely to scan for bicyclists prior to right turns. In particular, recent research findings suggest that more than 50% of drivers turning right omit scanning right for bicyclists at intersections after traveling next to protected bike lanes [4].

The placement of protected or Dutch intersection features after a protected bike lane is a potential solution for reducing right-hook crashes. This design utilizes a curb extension and islands, which alter the placement of the driver and the bicyclist at the intersection. As a result of this placement, drivers that are turning right, encounter the bicyclist in front of them, not to the right of them which is the case for conventional intersections. Finally, vehicles and bicyclists are physically separated with an island that forces the driver to make the turn at a wider angle.

Extensive research efforts have focused on studying right-hook crashes under various bicycle infrastructure treatments at intersections and roadway segments. However, studies that investigate the impact of combinations of segment-level and intersection-level bicycle infrastructure treatments and their effect on right-hook crashes are missing. There is a need to understand the impact of such treatment combinations on the behavior of drivers that are performing a right turn at intersections.

The objective of this study is to examine whether the placement of a protected intersection after a protected bike lane can increase a driver's situational awareness of bicyclist presence and thus encourage scanning for bicyclists prior to a right turn. We hypothesize that protected intersections, which combine pavement markings and physical barriers, are more effective than conventional intersections in communicating to a driver performing a right turn that a bicyclist might be present. We further hypothesize that this holds both when protected bike lanes and when conventional bike lanes are implemented upstream of those intersections. Another hypothesis tested through this study is that drivers traveling next to a protected bike lane are less likely to scan for bicyclists as they turn right at protected or conventional intersections. Finally, we anticipate that the presence of a bicyclist on the segment prior to the intersection does not have any impact on driver behavior at the segment level or intersection level.

Overall, this study investigates the effectiveness of four segment-intersection bicycle infrastructure treatment combinations in altering driver behavior while performing a right turn as well as while driving along segments. A driving simulator experiment has been designed to test driver behavior during right-turning movements at intersections and along roadway segments that consist of combinations of protected and conventional bike lanes followed by protected and conventional intersections. The advantages of using a simulation environment are that multiple combinations can be tested in a controlled environment where one can also obtain demographic and other driver information in an effort to understand factors that motivate certain behaviors.

2 Background

Research on the impact of protected bike lanes has flourished over the past few years as more and more urban areas have implemented them. However, research on the impact of protected intersections is limited, raising the need to understand their safety benefits and design implementation guidelines. Additionally, existing studies either focus on the segment treatments (e.g., away from the intersection) or only evaluate intersection treatments, ignoring the benefits that could result from combining segment and intersection bicycle infrastructure treatments.

In general, research findings conclude that protected bike lanes have the ability to improve safety [5, 6, 7, 8] as they eliminate the interactions between motorists and bicyclists. Specifically, protected bike lanes have been found to prevent certain types of crashes that occur, for example, when a vehicle overtaking a bicycle and “dooring” crashes [9]. For the bicyclists, riding on protected bike lanes is considered more comfortable and less stressful than conventional bike lanes or shared streets [10]. However, crashes and conflicts have been commonplace at intersections that follow segments with protected bike lanes [11, 12]. Summala et al. [13] investigated driver and bicyclist behavior at T-intersections with cycle tracks (i.e., protected bike lanes). Video recordings of drivers’ head movement and braking behavior revealed that drivers making a right turn after traveling on a roadway segment next to a cycle track scan right less frequently than left.

Recent studies suggest the need for interventions at intersections when protected bike lanes are placed upstream of those intersections to reduce the risk of right-hook crashes [14]. Examples of intersection treatments that have been studied include the evaluation of traffic signal phases dedicated to bicyclists [15] and various intersection-designs such as mixing zones, i.e., configurations that mix the traffic upstream of the intersection [16, 17] and protected intersections [18]. In particular, Madsen and

Lahrmann [16] studied conflicts between drivers and bicyclists extracted from video recordings for protected intersections and four other mixing zone designs that varied with respect to the cycle track's length and the infrastructure treatments for bicyclists and right-turning vehicles at the intersection. Overall, protected intersections were the safest in terms of conflicts. However, because very few conflicts were observed during this observational study, the results were not statistically significant. Schepers [19] noted that mixing cars and bicyclists is recommended only in cases where the speed limit is no more than 18.6 mph (30 km/hour). Warner et al. [18] assessed the effectiveness of various intersection design elements, including protected intersections and intersections with painted through bike lanes, through a driving simulator experiment. Their study found no significant differences among the different intersection treatments for scanning right for bicyclists while approaching the intersection.

In a nutshell, existing research on right-hook crashes focuses on intersection designs without considering the effect of bicycle treatment in the segment prior to the intersection. For example, a protected bike lane followed by a protected intersection may affect drivers' ability to scan for and detect bicyclists differently than a conventional bike lane leading to a protected intersection. Overall, there is a need to investigate the effect of transitioning from separated or protected (i.e., treatments that physically separate bicyclists from vehicular traffic) to mixed-traffic environments (i.e., no physical separation between bicyclists and drivers) and vice versa.

3 Methodology

Driver behavior at four segment-intersection combinations was examined using a driving simulator. The four combinations were: (1) a protected bike lane (PBL) followed by a protected intersection (PI), (2) a PBL followed by a non-protected intersection (NPI), (3) a conventional bike lane (CBL) followed by a PI, and (4) a CBL followed by an NPI. Figure 3.1 illustrates the experimental design. The focus was on right-turn movements at intersections, but behavior along segments prior to the right turns was also captured.

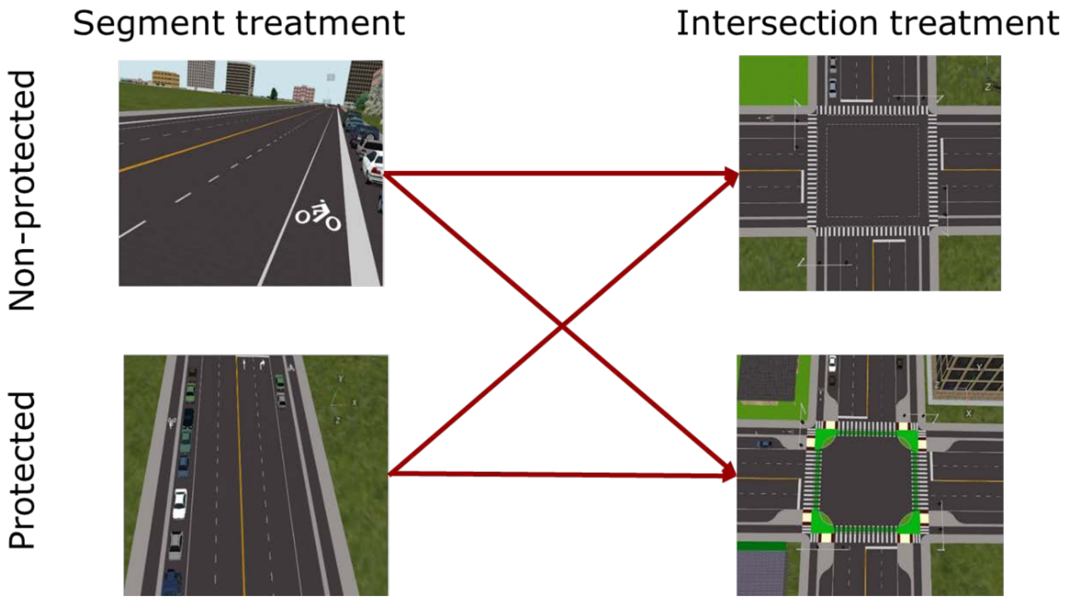


Figure 3.1 - Bicycle infrastructure treatments used in the experimental design

The main benefit of driving simulation is the ability to design and test various scenarios that cannot be easily found in the field. For example, there is currently a limited number of protected intersections in the U.S. The driving simulator records kinematic data, i.e., X and Y coordinates, velocity, acceleration, and lateral position of the vehicle over time. In order to capture the visual behavior of the driver, the study utilized an eye-tracking device that tracks and records participants' gaze. The combination of driving simulation and eye tracking allows for an in-depth understanding of drivers' response to various elements of the environment.

3.1 Experimental Design

3.1.1 Scenario Description

The experiment consisted of eight drives, each representing one of the four segment-intersection combinations (Figure 3.1) with or without a bicyclist on the segment prior to the intersection. Table 3.1 presents all the drives that were tested. To eliminate the order effect, the Latin square matrix method was chosen to generate a different order for the eight drives for each participant.

Table 3.1 - Scenarios

Segment	Intersection	Bicyclist Present	
		Yes	No
PBL	PI	1	5
PPL	NPI	2	6
CPL	NPI	3	7
CPL	PI	4	8

The participants drove 310 m on a straight, four-lane roadway segment that led to an intersection; see Figure 3.2. The speed limit on that segment was 35 mph. While approaching the intersection, drivers received an indication to make a right turn. The drive terminated a few meters after the intersection. Points A and B on the segment indicate the start and end point of the section where one could see the coded bicyclist (when one existed); see Figure 3.2. The bicyclist traveled these 80 m at a speed of 10 mph. Therefore, the participant encountered the bicyclist upstream of the intersection and drove at least the last 50 m prior to the right turn without interacting with the bike. Points C and D on the segment define the intersection area.

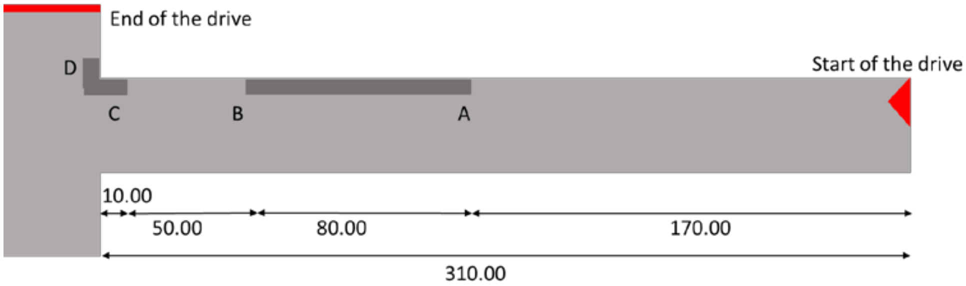


Figure 3.2 - Drive geometric configuration

Given that it wasn't the intention of this research to study driver behavior when there are car-bicyclist interactions at the intersection, the drives were designed so that drivers bypassed the bicyclist before approaching the intersection. The inclusion of bicyclists in the drives was intended to test whether scanning patterns and driver behavior at the segment and intersection levels while performing the right turn were affected by the presence of bicyclists in the upstream segment. Ideally, the driver would scan for bicycles even without having detected one during their drive; the existence of bicycle infrastructure alone should have informed them that bicyclists might be present, and as a result, drivers should have anticipated potential interactions with bicyclists.

3.1.2 Dependent and Independent Variables

Table 3.1 displays the independent variables used in the experiment: PBL or CBL, PI or NPI, and the binary variable indicating the presence of a bicyclist. Participant demographics (i.e., gender and age) and cycling frequency were also considered in the analysis. The dependent variables were the average speed and glances during specific parts of the drive.

While the driver was on the segment, the analysis focused on the AB part of the drive (Figure 3.2), where the driver encountered the bicyclist (if one existed). For the intersection, the segment defined by points C and D was included in the analysis. The intersection was further split into two zones (see Figure 3.3). Zone 1 was defined as the intersection approach section and captured the area that corresponded to 3 s before the driver reached the stop bar. Zone 2 started when the driver passed the stop bar and terminated at the point where the bike lane ended and a potential bicyclist would enter the intersection.

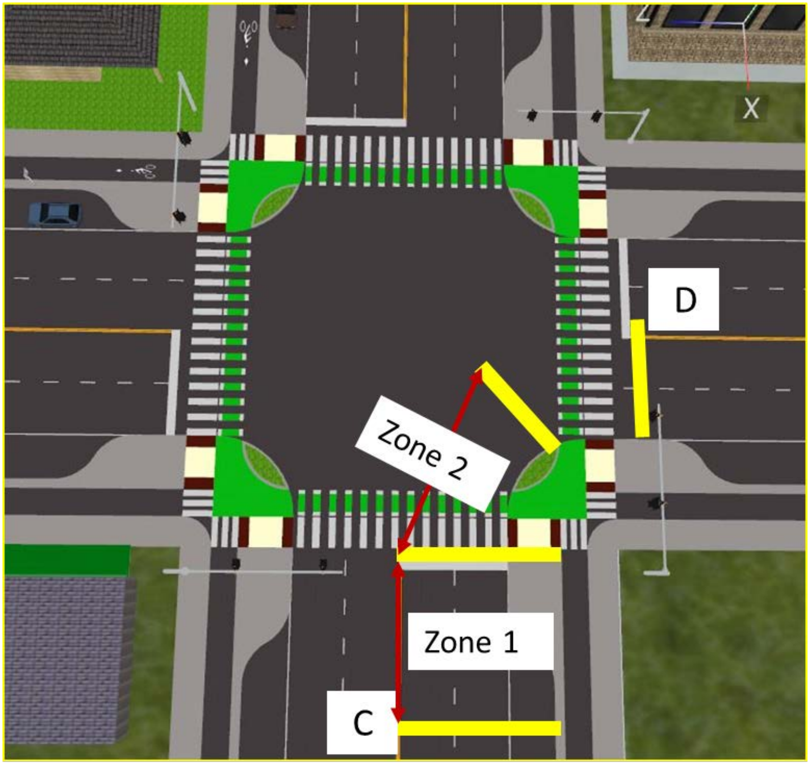


Figure 3.3 - Intersection zones

To assess changes in glances, we focused on four aspects: (1) whether the driver glanced at the bicyclist in the presence of protected and conventional bike lanes while traveling in section AB, (2) whether the driver glanced at the intersection infrastructure under all eight segment-intersection bicycle-presence drives while in Zone 1, (3) whether the driver glanced to the right for a bicyclist while in Zone 1 under all eight segment-intersection bicycle-presence drives, and (4) whether the driver glanced right for a bicyclist while in Zone 2 under all eight segment-intersection bicycle-presence drives. Glances were treated as binary variables.

Since protected bike lanes keep the driver and the bicyclist away from each other and eliminate interactions between them while traveling on the segment, it was expected that drivers would not glance at the bicyclist on the segment and would fail to scan for bicyclists as they performed a right turn at the intersection. At the intersection, a design that incorporates colored pavement markings, curb extension, and raised elements is more likely to capture the driver’s attention. As a result, we expected drivers to glance at the intersection treatment and scan for bicyclists as they turned right when in a protected intersection regardless of the segment infrastructure treatment upstream of the intersection. Finally, it was expected that glance behavior at the intersection approach and while the right turn was performed would not be affected by the presence of a bicyclist upstream of the intersection segment.

Speed data was analyzed for the following parts of each drive: (1) while the driver was traveling in section AB, and (2) while the driver was traveling in section CD. Speed may be impacted by segment-level bicycle-infrastructure treatments and the presence of a bicyclist. In PBLs, one would expect higher speeds than in a CBL due to the greater distance between bicyclists and drivers. Higher speeds would also be expected in the drives without bicyclists than in those where a bicyclist was present in the bike lane while a driver was traversing the segment. The combination of segment-intersection infrastructure was expected to alter driver speed as follows: in a protected intersection, the driver was expected to view the design from a greater distance and thus reduce speed earlier than in unprotected intersections.

3.1.3 Participants and Experimental Procedure

Thirty-two drivers completed the study: 16 females between 18 and 31 years old, and 16 males between 18 and 36 years old. The average age was 23.7 years, and the median age was 24 years with a standard deviation of 4.5 years. The participants were recruited from the University of Massachusetts Amherst area via emails, and all had a valid driver's license. Of the 32 participants, 15 reported that they did not cycle. Among the remaining 17, 5 cycled more than 4 times per week, 3 cycled more than one time per week, and 9 cycled 1-2 times per month. The participants cycled for commuting-only purposes, recreational-only purposes, and both. The majority of the participants (19 out of 32) drove fewer than 50 miles during the week prior to participating in the experiment, which could be attributed to the fact that all subjects were students or staff at the University and tended to live close by.

The study procedure consisted of four steps:

1. The participant completed the consent form and a pre-study questionnaire that obtained demographics as well as driving history and frequency (see Appendix A).
2. The second step consisted of a test drive, which aimed to familiarize the participant with the car and the simulator environment through a short drive. The participant was seated in the driver's seat and fitted with the eye tracker. Besides allowing the participant to get used to the car (e.g., braking, turning etc.), this step informed the researcher if the participant was susceptible to simulator sickness, which would result in exclusion.
3. The participant drove the eight scenarios.
4. The participant completed the post-study questionnaire regarding cycling purpose and frequency (see Appendix B).

3.2 Apparatus

3.2.1 Driving Simulator

This study was conducted at the University of Massachusetts (UMass) Amherst Human Performance Laboratory's (HPL) high-fidelity driving simulator. The simulator is a stationary, real-size 2013 Ford Fusion model; see Figure 3.4. The vehicle is surrounded by screens that offer a viewing angle of 330 degrees and upon which the simulated world is projected. The car is equipped with an electric motion pitch that can create vibration when the driver accelerates or brakes, adding to the realism of the experiment. The simulator records position, speed, acceleration, and driver control actuation at a frequency of 60 Hz. All the displayed simulated scenarios were created with the SimCreator software developed by Realtime Technologies, Inc. (RTI).

Figure 3.4 - Driving simulator at the University of Massachusetts Amherst Human Performance Lab

3.2.2 Eye Tracker

Participants' eye movement during the drives was recorded using the ASL MobileEye tracker for the RTI Simulator; see Figure 3.5. A binary scoring method (0-1), namely glance scoring, was employed in this study to assess: (1) whether the drivers glanced at the bicyclist while traveling in segment AB, (2) whether they glanced at the intersection infrastructure while traveling in Zone 1, (3) whether they glanced right for the bicyclist in the proximity of the intersection while traveling in Zone 1, and (4) whether they scanned right for bicycles while making a right turn while traveling in Zone 2.

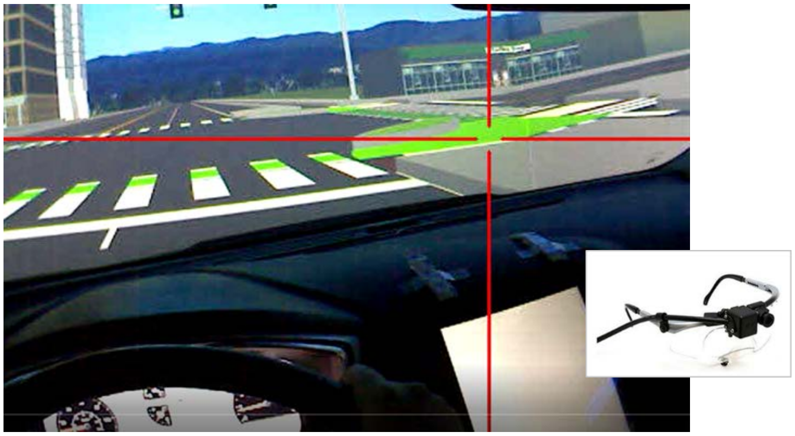


Figure 3.5 – Eye-tracking device and video output capturing eye movements

3.2.3 Questionnaires

Participants were asked to answer pre-study and post-study questionnaires. The pre-study questionnaire collected demographic information such as gender, age, and race. Additionally, participants were asked to provide information regarding their driving history and experience. Specifically, they were asked to provide the age at which they obtained their driving license, an approximation of the miles they had driven during the previous week, and an approximation of the miles they had driven during the previous year. Appendix A presents the pre-study questionnaire.

Cycling history and frequency were collected in the post-study questionnaire because answering those questions before the drives could have biased the participants towards the study. The post-study questionnaire asked participants to state whether they cycle. If they answered yes, the participants had to further indicate their cycling frequency and purpose for bicycling. Appendix B presents the post-study questionnaire.

4 Results

To assess whether demographic characteristics or cycling frequency affect driver behavior, we included age, gender, and cycling frequency as independent variables. Since gender could be controlled during the recruiting period, female-male populations were equal.

Participants were split into two age groups, 18-25 (62.50%) and 26-36 (37.50%), considered novice and young drivers, respectively. This separation was based on research findings that differentiate between the risk perceived by age groups of 25 years and younger and 25-65 years [20,21,22]. Therefore, age was treated as a binary variable.

Three groups were created based on cycling frequency. People who reported that they did not bike at all were considered “no bicyclists” and represented 46.88% of participants. Participants who reported biking 1-2 times per week or more than 4 times per week were grouped together and formed the category of “weekly” bicyclists (18.75%). Finally, participants who cycled 1-2 times per month formed the category of “monthly” bicyclists (34.38%).

4.1 Eye Glances

Driver behavior was investigated in terms of eye glances at both the segment and intersection levels, and the results are presented in the following sections.

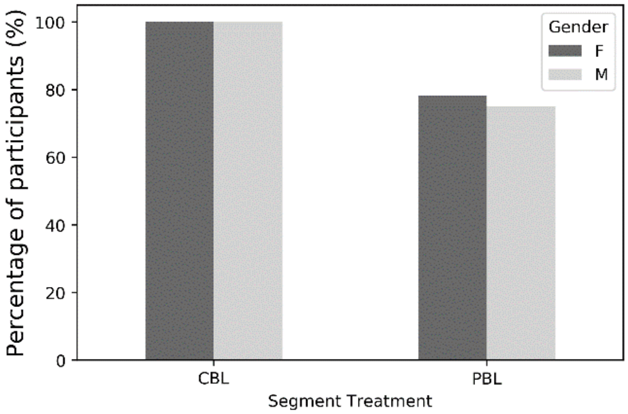
4.1.1 Segment Analysis

For the AB segment, only scenarios that included the bicyclist were considered for the analysis. Glances were scored only when the red cross (see Figure 3.5) was placed on the bicyclist. In the case of CBLs, all participants viewed the bicyclist. However, in the case of PBLs, only 76% of participants glanced at the bicyclist. Glances were further analyzed with respect to gender, age, and cycling frequency to investigate whether any of these factors could be associated with the participants’ visual search. While gender did not seem to have any impact on glances on the AB segment, age and cycling frequency appeared to be stronger determinants of drivers' visual search in the case of a PBL (see Figure 4.1). In particular, participants in the 26-36 age group and the ones that were even occasional cyclists were more likely to glance at the bicyclist.

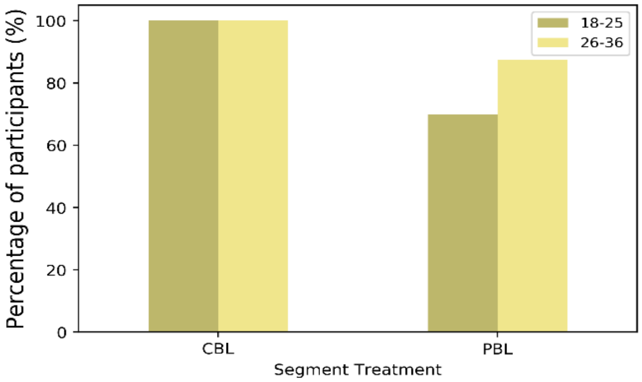
After passing the bicyclist, several drivers glanced at the right mirror or outside the window while turning their head to the right. These glances took place either within the AB area or downstream of it but not within the CD area. If the latter was the case, then the glances would count towards intersection right scanning (either Zone 1 or 2). In the scenarios where a bicyclist was present, these glances were possibly an additional check that the driver had passed the bicyclist. For the remainder of this report, this glance is denoted as "bicyclist back."

In total, 14.6% and 31.5% of the participants made this glance in the presence of PBL and CBL, respectively, when a bicyclist was present. In the drives with PBL, the glance was made by looking out the window and glancing at the area where the bicyclist could potentially be. In the case of CBL, the participants glanced at the right mirror in addition to looking out the window. Results were inconclusive on the impact of gender, age, and cycling frequency on the behavior of glancing at the bicyclist after passing him/her.

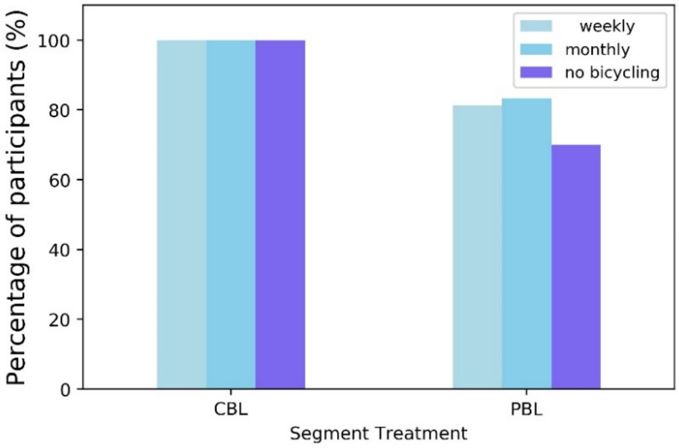
A binary logistic regression model was developed to study the factors impacting driver glancing behavior at the segment when a bicyclist was present. The following factors were considered: segment treatment, gender, age, and cycling frequency (see Table 4.1). The variables were modeled as binary: gender = 1 for female participants, 0 otherwise; age = 1 for the 18-25 age group, 0 otherwise; cycling = 1 if participants reported cycling on a monthly or weekly basis, 0 otherwise; and segment treatment = 1 for PBL, 0 otherwise.



(a) By gender



(b) By age



(c) By cycling frequency

Figure 4.1 - Glances at the bicyclist (AB segment level)

Table 4.1 - Logistic regression for glances at the bicyclist

	Estimate	St. Error	Wald X^2 test	p-value
Intercept	6.51	2.79	5.45	0.020
Gender	0.32	0.62	0.26	0.609
Age	-1.20	0.72	2.74	0.098
Cycling Freq.	0.83	0.63	1.75	0.186
Segment Treatment	-5.06	2.72	3.44	0.064

HL Test (Confidence Level=90%): p-value 0.97 > 0.1, AUC=0.89

Regarding the model's parameters, no significance was found at the 95% confidence level; however, age and segment treatment were found to be significant at the 90% confidence level. Age was negatively correlated with glances, meaning that belonging to the younger age group (i.e., 18-25 years old) meant lower likelihood of glancing. In addition, the presence of a protected bike lane also resulted in a lower probability of glancing at the bicyclist.

Two criteria were implemented to evaluate the model's performance. The first one was the Hosmer-Lemeshow (HL) test, which reports a model's goodness of fit (GOF). For GOF, the objective is to accept the null hypothesis; higher p-values (e.g., greater than 0.05 for the 0.05 significance level or 0.1 for the 0.10 significance level) indicate good models. The second metric is the area under the curve (AUC), which is the receiver operating characteristic (ROC) curve. Higher AUC values are associated with higher model accuracy and, according to Hosmer et al. [23], AUC > 0.7 allows us to accept the model. For this model, AUC was found to equal 0.89, and the HL p-value was 0.97 (see Table 4.1). Therefore, the model is accurate and fits the data.

The same method was followed to test the significance of the same factors for the "bicyclist back" check. However, none of the variables were found significant at the 90% confidence level.

In a nutshell, segment infrastructure affects drivers' likelihood to glance at the bicyclist on the segment, i.e., they are more likely to glance when the bicyclist is traveling on a CBL adjacent to the traffic lane. This finding is in agreement with the literature on drivers' attention allocation, which claims that drivers tend to be more focused on objects and stimuli that appear in front of them [24].

4.1.2 Intersection Analysis

The intersection analysis focused on two zones, as shown in Figure 3.3. For Zone 1 the analysis concentrated on (1) whether the drivers glanced at the intersection infrastructure, and (2) whether they glanced to the right through the window or using the right mirror. For Zone 2 the focus was on glances at the bike lane (protected or conventional) in the area of the intersection because it could be seen from the right window while the participant was making the right turn.

While in Zone 1, approximately 94% and 62% of the participants glanced at the intersection infrastructure treatment in protected and conventional intersections, respectively. As protected intersection design elements often display bright colors (e.g., green pavement markings) and include physical barriers, it is expected that they will capture drivers' attention.

In both Zones 1 and 2, drivers were more likely to glance to their right at the intersection when a protected intersection was implemented (i.e., Scenarios 1, 4, 5, and 8) and in scenarios with bicyclist presence (i.e., Scenarios 1-4) (see Figure 4.2 and Figure 4.3). Gender, age, and cycling frequency did not appear to have an impact on this glancing behavior in either zone.

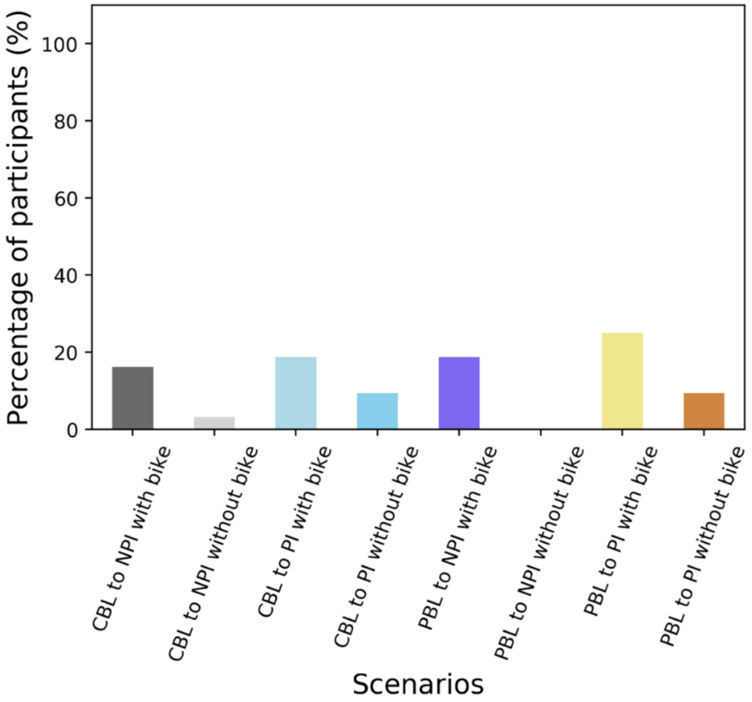


Figure 4.2 - Intersection right glances (Zone 1)

It can be seen that glancing to the right while in Zone 2 was rather rare; a glance took place in this area during only 8 of the 256 drives (see Figure 4.3).

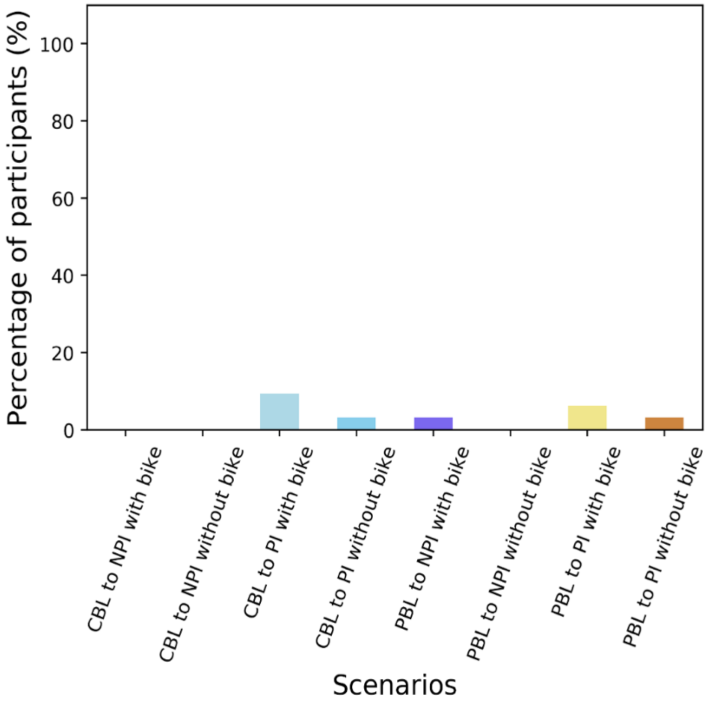


Figure 4.3 - Intersection right glances (Zone 2)

A logistic regression model was conducted to study which factors impact the glancing behavior of drivers at the intersection approach (Zone 1). The considered factors were gender, age, cycling frequency, bicyclist presence, segment treatment, and intersection treatment. All variables were treated as binary, as described in Section 4.1.1. For bicyclist presence, we set the variable as 1 if the bicyclist was present and 0 otherwise; for intersection treatment, we set the variable as 1 for protected intersection and 0 otherwise; for segment treatment, we set the decision variable as 1 for protected bike lanes and 0 otherwise. The results are reported in Table 4-2.

Table 4.2 - Logistic regression for glances at the bicyclist in Zone 1 (Confidence Level=95%)

	Estimate	St. Error	Wald X^2 test	p-value
Intercept	-3.36	0.64	27.38	<0.001
Bicyclist	1.45	0.45	10.35	0.0012
Gender	0.01	0.39	0.001	0.981
Age	-0.01	0.40	<0.001	0.985
Cycling frequency	0.15	0.39	0.15	0.696
Segment treatment	0.15	0.39	0.15	0.697
Intersection treatment	0.61	0.39	2.35	0.125

HL Test (Confidence Level=95%): p-value 0.77 > 0.05, AUC=0.71

At the 95% confidence level, only bicyclist presence significantly affected glances. This finding is a strong indication that the drivers are affected by the presence of bicyclists on the roadway and adjust their behavior accordingly. The p-value of the HL test is high, indicating a good fit. The model also has an acceptable AUC.

Due to the very low number of glances in Zone 2, it was not possible to construct a regression model to evaluate which factors affect right-glancing behavior in that zone.

The main takeaway from this analysis is that the presence of a bicyclist does affect glancing behavior when at the stop line as the driver is getting ready to perform a right turn. This contradicts our original hypothesis that the presence of a bicyclist would not affect driver behavior at the intersection. Additionally, while it is not statistically significant, there seems to be a trend indicating that the intersection treatment affects glances at the intersection (i.e., Zone 1). In particular, more drivers were observed glancing right when a protected intersection was implemented.

4.2 Speed

4.2.1 Segment

Speed distribution on segment AB across all four segment environments, i.e., combinations of segment treatment and bicyclist presence, is presented by box plots in Figure 4.4. These box plots show the median, percentiles, and upper and lower observations for each scenario. Standard error is also displayed. The figure shows that there was a small variation in speeds among the four combinations. An analysis of variance (ANOVA) test was conducted on the four mean speed groups using 256 observations from 32 participants driving 8 different scenarios. The ANOVA can determine whether there were significant differences in the mean speeds in the four segment environments. The test resulted in a p-value of 0.243 at the with a 95% confidence level; therefore, we failed to reject the null hypothesis, which was that the speed among the four segment environments would be the same.

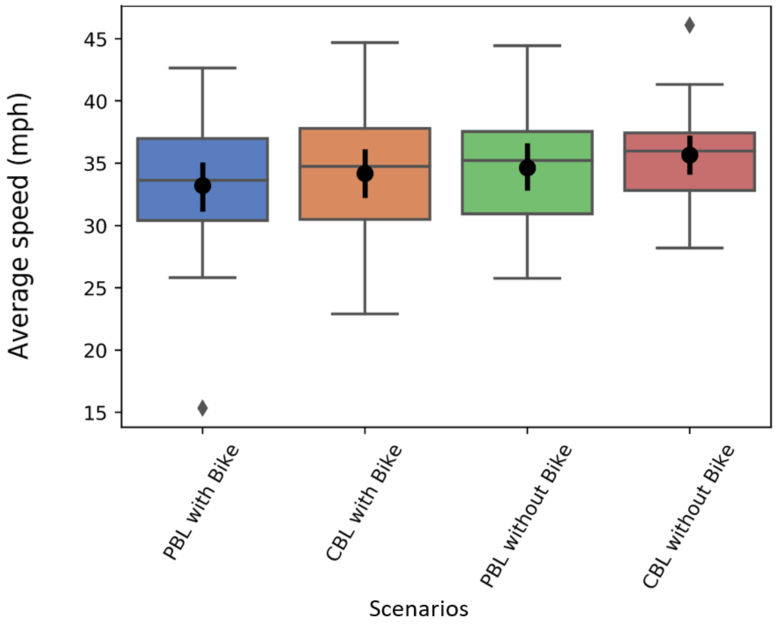


Figure 4.4 - Box plot of speed on segment AB across all four segment environments

However, further grouping of the infrastructure treatments resulted in significant differences in speed. A paired t-test was conducted to compare the average speed with PBLs versus CBLs. This test showed that participants developed significantly lower average speeds with PBLs (33.9 mph) than with CBLs (34.9 mph). While this is not a big difference, one would have expected the opposite outcome, i.e., lower speeds with CBLs due to the potential interaction with bicyclists. It seems that other factors affect the speed in the case of PBLs, e.g., the existence of a parking lane next to the traffic lane of interest.

Moreover, the presence of a bicyclist was found to significantly affect participant speed regardless of the segment treatment (see Table 4.4). The average speed for scenarios that had a bicyclist present was 33.69 mph versus 35.12 mph for those that did not have a bicyclist.

Focusing only on the scenarios that had bicyclist presence, a t-test was performed to compare speeds with the presence of CBLs and PBLs (see Table 4.4). The differences are rather small (~1 mph), which could be attributed to the fact that drivers did not interact with the bicyclist for a big part of the segment.

Table 4.3 - t-test results for the impact of bicyclist presence and segment treatment on average speed (mph) while traveling on segment AB

Segment Treatment	Bicyclist		p-value (Confidence Level=95%)
	With	Without	
CBL and PBL	33.69	35.12	0.01
CBL	34.17	35.65	0.04
PBL	33.19	34.61	0.034

4.2.2 Speed analysis at the intersection

Intersection-speed box plots observed while traveling within segment CD across all eight scenarios are shown in Figure 4.5. An ANOVA test was performed using 256 observations from 32 participants driving 8 scenarios each. The ANOVA test resulted in a p-value of 0.87 with a 95% confidence level, failing to reject the null hypothesis, i.e., intersection speeds among the eight scenarios were the same (see Figure 4.5).

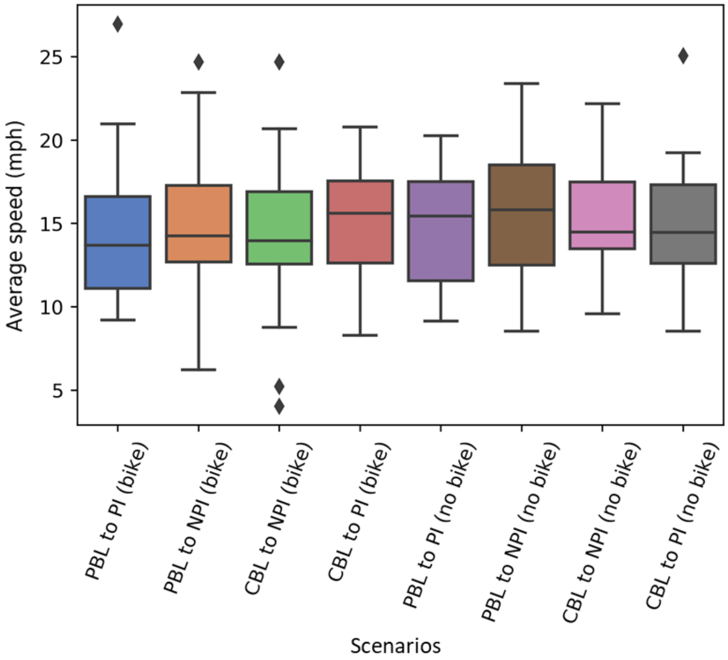


Figure 4.5 - Box plot of speed at intersection (segment CD) across all eight scenarios

The following statistical tests were performed to investigate whether the segment treatment, intersection treatment, or bicyclist presence affected driver speeding behavior. An ANOVA was conducted after grouping the speeds based on intersection treatment and bicycle presence (PI with bike, PI without bike, NPI with bike, NPI without bike). A total of 256 observations were used, and the ANOVA test resulted in a p-value equal to 0.71. Therefore, speeds do not vary significantly between scenarios that include different intersection treatments and/or the presence of bicyclist.

Focusing only on the intersection treatment, we conducted a t-test between the speeds collected from the PI versus the NPI scenarios regardless of the presence of a bicyclist. However, this analysis revealed no statistically significant differences, as the p-value was equal to 0.57 at the 0.05 significance level.

The presence of a bicyclist was found to have an impact on the speeding behavior at the intersection, but only for the cases where an NPI was implemented. The t-test between intersection speeds for the NPI with bicyclist presence and without bicyclist presence showed that when drivers encountered a bicyclist upstream of the intersection, average speed at the intersection was reduced by approximately 1 mph. This result is significant at the 0.10 significance level with a p-value = 0.073. However, speeds were not statistically different in the case of the PI between scenarios with a bicyclist present and those without a bicyclist.

In conclusion, we can infer that neither the intersection treatment nor the combination of segment-intersection treatment impacts speeding behavior at the intersection.

5 Conclusions

This study conducted an in-depth analysis of the effect that the combination of segment and intersection bicycle treatments may have on driver behavior while making right turns. For segment, two infrastructure treatments were considered, namely, protected bike lanes and conventional bike lanes. For intersection, the two treatments were the protected, or Dutch, intersection and the non-protected intersection consisting of intersection through bike lanes. Driver behavior was assessed through eye movement and speed data at both the segment and the intersection under the presence or absence of bicyclists.

The results of the study show that age and segment treatment significantly affect glance behavior at the segment level when a bicyclist is present. This means that younger drivers (i.e., 18-25 years old) and the presence of protected bike lanes result in a lower probability of glances at the bicyclist. As a result, protected bike lanes could be contributing to lower situational awareness regarding the potential presence of bicyclists at the intersection. Bicyclist presence was found to affect both glances at the intersection approach (Zone 1) and speed at the segment level regardless of the segment treatment; this suggests that drivers tend to anticipate interaction with bicyclists if they have seen one earlier in the drive. The presence of bicyclists on a bike lane results in higher situational awareness in drivers; this leads to greater safety for bicyclists, a phenomenon often referred to as safety in numbers. Regardless of bicyclist presence, speeds were significantly lower while traveling next to protected bike lanes than conventional bike lanes.

Overall, neither the intersection infrastructure treatment nor the combination of segment-intersection treatments was found to affect driver speed while approaching the intersection and completing a right turn. A limitation of this study is that, due to the placement of the data markers, it was not possible to distinguish between intersection approach speed and the speed while performing a right turn. Only the presence of a bicyclist was found to be a statistically significant factor affecting speeds at the intersection, and then only in the absence of protected-intersection elements.

While this study lacked scenarios with driver-bicycle interactions, it still contributes to the understanding of driver behavior in complex roadway environments such as when bicycle infrastructure treatments are present. Because the presence of a bicyclist along the segment appeared to impact driver behavior, future studies should examine this impact for a variety of bicycle demand scenarios (both in terms of volume and location where bicyclist is present). It is also important to study how drivers interact with bicyclists in the presence of such treatments and how they would react if bicyclists were present at the intersection prior to the right turn. Different geometric configurations of protected intersection design elements and a more diverse population in terms of age should also be tested. Finally, given that bicycle infrastructure treatments are mostly placed in busy urban environments, future studies should increase driver workload (e.g., increase motorized traffic) to examine whether the combination of segment-intersection treatments can be associated with bicyclist safety.

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Appendix A: Pre-Study Questionnaire

Date: _______
Participant ID: ________
(HPL Admin use only)

HUMAN PERFORMANCE LABORATORY
PRE-STUDY QUESTIONNAIRE

This is a ***strictly confidential*** questionnaire. Only a randomly generated participant ID number, assigned by the research administrator, will be on this questionnaire. No information reported by you here will be traced back to you personally in any way. **You can skip any questions you do not feel comfortable answering.**

Section 1: Demographics

Gender: ☐ Male ☐ Female

Age: ______

Race / Ethnicity: ☐ Black / African American ☐ Asian
(check all that apply) ☐ Caucasian ☐ American Indian / Native Alaskan
(question asked for reporting purposes) ☐ Hispanic / Latino ☐ Other

Have you participated in a study at this laboratory in the past? ☐ Yes ☐ No

Section 2: Driving History

Approximately how old were you when you got your driver's license? _____ **Years** _____ **Months**

About how many miles did you drive in the past week?
☐ Less than 50 ☐ Less than 100 ☐ 100-200 ☐ 200-300 ☐ 300-500 ☐ 500 or more

About how many miles did you drive in the past 12 months?
☐ Less than 5,000 ☐ 5,000 to 10,000 ☐ 10,001 to 15,000 ☐15,001-20,000 ☐ More than 20,000

Do you usually wear glasses or contacts while driving? ☐ No
☐ Yes, glasses
☐ Yes, contacts

Do you ever get motion sickness symptoms while driving or riding in a car? ☐ Yes ☐ No
(If you respond Yes to this question, please bring it to the immediate attention of the experimenter.)

Do you have any other restrictions on your driver’s license? ☐ Yes ☐ No

If yes, please describe: ____

Is there anything related to your background or health, including any medications, that might cause to you drive much better or worse than other drivers?

☐ Yes ☐ No

If yes, please describe: ____

Appendix B: Post-Study Questionnaire

Date: _______
Participant ID: ________
(HPL Admin use only)

HUMAN PERFORMANCE LABORATORY
POST-STUDY QUESTIONNAIRE

Cycling History

Do you cycle for commuting purposes or for recreational purposes?
☐ Yes, for commuting only ☐ Yes, for recreation only ☐ Yes, both for commuting & recreation ☐ No
If you answered **No** please skip the rest of this questionnaire.

How often do you cycle?
☐ > 4 times a week ☐ 1-2 times a week ☐ 1-2 times a month

If a cyclist, approximately how old were you when you started cycling? _____ **Years** _____ **Months**