



Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Factors impacting bicyclist lateral position and velocity in proximity to commercial vehicle loading zones: Application of a bicycling simulator



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ARTICLE INFO

Keywords:

Bicycle safety
Commercial vehicle loading zone
Bicycling simulator
Bicycle-truck conflicts

ABSTRACT

There is little research on the behavioral interaction between bicycle lanes and commercial vehicle loading zones (CVLZ) in the United States. These interactions are important to understand, to preempt increasing conflicts between truckers and bicyclists. In this study, a bicycling simulator experiment examined bicycle and truck interactions. The experiment was successfully completed by 48 participants. The bicycling simulator collected data regarding a participant's velocity and lateral position. Three independent variables reflecting common engineering approaches were included in this experiment: pavement marking (L1: white lane markings with no supplemental pavement color, termed white lane markings, L2: white lane markings with solid green pavement applied on the conflict area, termed solid green, and L3: white lane markings with dashed green pavement applied on the conflict area, termed dashed green), signage (L1: No sign and L2: a truck warning sign), and truck maneuver (L1: no truck in CVLZ, L2: truck parked in CVLZ, and L3: truck pulling out of CVLZ).

The results showed that truck presence does have an effect on bicyclist's performance, and this effect varies based on the engineering and design treatments employed. Of the three independent variables, truck maneuvering had the greatest impact by decreasing mean bicyclist velocity and increasing mean lateral position. It was also observed that when a truck was present in a CVLZ, bicyclists had a lower velocity and lower divergence from right-edge of bike lane on solid green pavement, and a higher divergence from the right-edge of bike lane was observed when a warning sign was present.

1. Introduction

To mitigate the negative impacts of urban population growth, cities across the United States are reevaluating land use and diversifying transportation modes. Policy makers and urban planners have recognized that an outcome of urban population growth is traffic congestion, which significantly affects the quality of life for residents. Therefore, policy makers and urban planners are supporting and investing in alternative transportation infrastructure, such as bicycle infrastructure, in order to improve traffic flow (Rowangould and Tayarani, 2016).

According to the U.S. Census Bureau, the number of bicyclists commuting to work in the United States grew by 50% between 2000 and 2008–2012 (Mckenzie, 2014). In addition, urban areas experienced an increase in the number of commercial vehicles travelling and

delivering goods alongside bicyclists due to a growth in urban populations and a shift to e-commerce. In fact, the number of registered trucks in the U.S. increased by 35,860,020 between 2010 and 2016 (FHWA, 2011, 2017).

Truck traffic plays a pivotal role on bicyclists' perceptions of safety and comfort in urban environments (Winters et al., 2011). Bicycling alongside both truck traffic, and in proximity to Commercial Vehicle Loading Zones (CVLZ), could decrease bicyclist level of comfort by more than 42% (Abadi and Hurwitz, 2018). One study in Manhattan, New York City, found that about 14% of commercial vehicles (trucks) conflicted with a bicycle in dense urban areas (Conway et al., 2013).

Bicycle-truck conflicts are important to recognize and understand, because they often result in severe consequences. In fact, in recent years, large trucks are the only vehicle classification to be over-represented in bicyclist fatalities. For example, large trucks were

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<https://doi.org/10.1016/j.aap.2019.01.024>

Received 9 May 2018; Received in revised form 25 November 2018; Accepted 18 January 2019

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involved in 10.15% of bicyclist fatalities in the United States in 2013, despite comprising only 3.94% of registered vehicles (NHTSA, 2015, 2017). Notably, one recent study on traffic crashes in Seattle from 2004 to 2014 showed that the rate of fatalities and serious injuries for all roadway bicycle accidents was 0.4% and 7.6%, while these rates for bicycle-truck accidents were 4% and 13%, respectively (Butrina et al., 2016).

Although there are many points of conflict between bicycles and trucks, the space between bicycle lanes and a CVLZ in dense urban areas is examined in this paper, because there is little understanding of this contested space. Even national standards such as Manual on Uniform Traffic Control Devices (MUTCD) do not include recommendations for CVLZ design (FHWA, 2009). Due to the lack of specificity regarding CVLZs, cities across the United States have varied rules and regulations for these zones, though they generally include a paid permit, colored pavement marking, and signage to indicate the constraints within the loading zone (e.g., SDOT, 2016a, 2016b; SFMTA, 2016).

The growing number of bicycles and trucks sharing road space, and the possible points of conflict between the two modes at a CVLZ have inspired this research project. The present research tested the impacts of three independent variables – pavement marking, signage, and truck maneuvering, on bicyclist safety next to CVLZs. This study is unique in the way that it leveraged the Oregon State University (OSU) high-fidelity bicycling simulator to investigate factors contributing to conflicts between bicycles and trucks. Forty-eight participants completed bicycling simulator experiments. The simulator allowed for the investigation of causal mechanisms for conflicts, including crashes, between trucks and bicycles, and the variables that contribute to them. The end goal was to better understand the relationship between truck movements, engineering treatments, and bicyclist behavior, in and around CVLZ, and ultimately, to improve road safety.

2. Background

2.1. Bicycle-truck crashes

Only a handful of studies have investigated issues associated with bicycle and truck crashes. Early studies employed descriptive statistics to provide a basic description of bicycle-truck crashes. For example, Riley and Bates (1980) showed that trucks commonly caused bicyclist deaths in side impact crashes, and that the majority of bicyclists died from multiple injuries associated with being run over by the wheels of a truck. Gilbert and McCarthy (1994) found that trucks were more frequently involved in bicyclist fatalities than expected, both in relation to the proportion of traffic in London and compared to national data on vehicle types involved in bicyclist fatalities. In addition, McCarthy and Gilbert (1996) concluded that trucks were involved in a higher proportion of fatal crashes involving female bicyclists (66%) than male (28%).

A few studies looked into bicycle-truck conflicts within a larger scope of research on bicyclist safety. These studies often used police reports and crash datasets to highlight the severity of bicycle-truck conflicts among all other types of bicycle-related crashes. For example, Kim et al. (2007) developed a probabilistic model of bicyclist injury severity in bicycle–motor vehicle crashes and found that if a truck was involved in a crash with a bicycle, the likelihood of fatal injury for the bicyclist increased by 380.9%, and the likelihood of incapacitating injury increased by 101.8%. Similarly, Moore et al. (2011) investigated the level of injury severity sustained by crashes involving bicyclists at intersections and non-intersections and found that in the case of bicycle-truck crashes, the likelihood of serious bicyclist injury increases by 99.9% at intersection locations and 122.4% at non-intersection locations.

Studies specifically focused on bicycle-truck conflicts in urban areas are rare. Conway et al. (2013) investigated vehicle and surrounding

area characteristics that influence the conflicts between commercial vehicles and bicycles in dense commercial centers in New York City. Conway et al. investigated the influence of specific variables such as vehicle type, parking regulations, and bicycle lane configuration on the likelihood of conflicts between bicycles and trucks and confirmed that conflict frequencies vary considerably for different bicycle lane configurations.

A multi-method approach was used to understand risk factors in bike-truck encounters in Norway's urban areas (Pokorny, 2018). This extensive study included analyzing bicycle-truck crash data and minor encounters, reviewing fatal accident reports, surveying bicyclists, interviewing truck company employees, reviewing street video footage, examining conflict and behavior between modes, and associating elements of bicyclist risk with urban road infrastructure. Pokorny (2018) reported that Norway has a high rate of fatal crashes between trucks and bicyclists and categorized encounters between right-turning trucks and straight riding bicyclists as most risky. It was suggested that separated green phases or specific layouts for advanced bicycle boxes at signalized intersections could limit high-risk bicycle-truck encounters.

As reviewed, previous research on bicycle-truck conflicts have employed crash reports, field observations, and stated preference surveys. While these datasets can be a helpful starting point, they cannot consider near-miss events and lack the detail necessary to determine what factors contributed to a crash, such as travel direction and relative position of the parties involved. Therefore, in this research project, a bicycling simulator experiment was implemented to identify how conflicts between trucks and bicycles occur, and to better evaluate the influence of engineering treatments.

2.2. Bicycling simulator

The bicycling simulator has been one of the more challenging simulators to develop due to the inherently unstable dynamics of the bicycle coupled with the dynamics of the human rider, and because of the difficulties associated with the real-time simulation of human-controlled and human-powered vehicles moving in a virtual environment (Kwon et al., 2001). The major elements of a typical bicycling simulator include: cueing systems (visual, auditory, proprioceptive, and motion), bicycle dynamics, computers and electronics, bicycle frame and control, measurement algorithms, and data processing and storage (Fisher et al., 2011). Different forms of bicycling simulators have been utilized in medical science (Deutsch et al., 2012; Ranky et al., 2010; Vogt et al., 2015), sport science (Watson and Swensen, 2006), video games (ElectronicSports, 2008), and mechanical engineering (He et al., 2005; Jeong et al., 2006). However, very few studies have employed full-scale bicycling simulators in the context of transportation safety.

In the U.S., bicycling simulators have been used at the University of Iowa (Hank Lab, 2018) and the University of Missouri (ZouSim, 2018) to conduct studies in transportation safety. Researchers at the Hank lab in the University of Iowa have extensively employed a bicycling simulator to investigate different aspects of the road-crossing behavior of child and adult bicyclists (Babu et al., 2009; Chihak et al., 2010; Grechkin et al., 2013; Plumert et al., 2004, 2007; Stevens et al., 2013). For instance, Plumert et al. (2011) examined how child and adult bicyclists' gap choices and movement timing changed over a single experimental session in response to general and specific experience with crossing traffic-filled intersections in a virtual environment and found that gap acceptance shifted in response to traffic density. A fully instrumented bicycling simulator has been also used by researchers at the University of Missouri to study bicyclist behavior. Brown et al. (2017) investigated the use of alternative pavement markings for bicycle wayfinding and proper bicycle placement at intersections in the fully instrumented bicycling simulator at the University of Missouri and found that wayfinding markings with a green background performed better than other alternatives.

Internationally, full-scale bicycling simulators have been developed

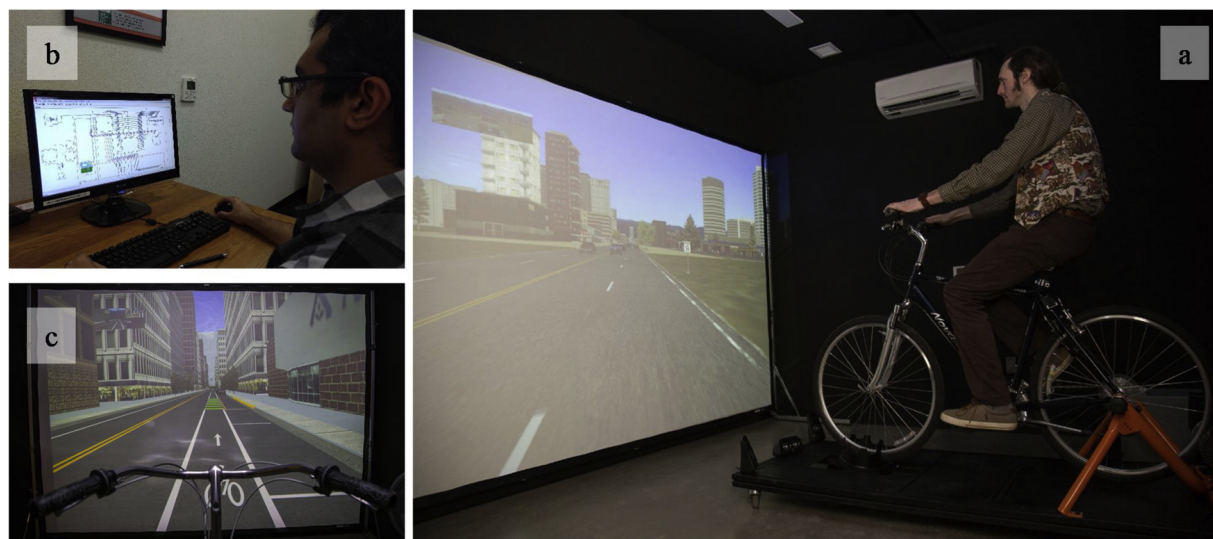


Fig. 1. Views from (a) OSU bicycle simulator, (b) Operator workstation, and (c) Simulated environment.

Table 1

Treatment options.

| Variable Name | Level | Levels Description |
|------------------|-------|------------------------------|
| Pavement Marking | 0 | White Lane Marking (Fig. 2a) |
| | 1 | Solid Green (Fig. 2b) |
| | 2 | Dashed Green (Fig. 2c) |
| Signage | 0 | None |
| | 1 | Warning Sign (Fig. 3) |
| Truck Maneuver | 0 | None |
| | 1 | Parked |
| | 2 | Exiting |

in a few countries including: Germany (e.g., PanoLab at Max-Planck Institute (PanoLab, 2018), and FIVIS Bicycle Simulator at the Bonn-Rhein-Sieg University of Applied Science (Schulzyk et al., 2009)), France (LEPSIS Lab Bicycling Simulator at the IFSTTAR (IFSTTAR, 2018)), and Taiwan (Bicycling Simulator at Lunghwa University of Science and Technology (Liu et al., 2012)). However, they have been seldom employed with the purpose of transportation safety research. In one of these rare efforts, Liu et al. (2012) investigated the response patterns of bicyclists to a right-turning motorcycle, considering two factors of speed difference and cut-in time gap. They found that less experienced, young bicyclists may not associate speed differences with danger and that they may judge the situation of a higher speed differential as safer than it is and not respond in a timely manner.

3. Method

3.1. OSU bicycling simulator

OSU features a bicycling simulator consisting of an instrumented urban bicycle placed on top of an adjustable stationary platform (Fig. 1a). A 3.20 m × 2.54 m screen provides the forward view with a visual angle of 109° (horizontally) × 89° (vertically) and image resolution of 1024 × 768 pixels. In addition, a small window on the top left corner of the screen acts as a rear view mirror (Hurwitz and Abadi, 2018). Researchers build the environment and monitor subject bicyclists from the operator workstation (Fig. 1b) which is in a separate room from participants in the bicycle simulator experiment.

The update rate for the projected graphics is 60 Hz. Ambient sounds around the bicycle are modeled with a 5.1 Logitech surround sound system. The computer system consists of a quad core host running Realtime Technologies SimCreator Software with an update rate for the

graphics of 60 Hz. Real-world scenarios could include certain difficulties to capture performance measurements (Tahami et al., 2017; Tahami et al., 2018). However, the simulator software is capable of capturing and outputting highly accurate values for performance measures such as speed, position, brake, and acceleration. Fig. 1c shows views of the simulated environment created for this experiment from the participant's view.

The virtual environment was developed using simulator software packages, including Internet Scene Assembler (ISA), Simcreator, AutoCAD, and Google Sketchup. The simulated test track was developed in ISA using Java Script-based sensors on the test tracks to display dynamic objects, such as a truck cutting in front of a bicyclist or a pedestrian walking on side-walk.

3.2. Treatment options

Three independent variables are included in the experiment: colored pavement marking, signage, and truck maneuver (Table 1).

The National Association of City Transportation Officials Urban Bikeway Design Guide (NACTO, 2011) identified three different pavement markings for conflict areas or areas where different modes cross or merge. Pavement color or the negative space between two sections of pavement color increases visibility of bicyclists and bike infrastructure, and the dashed white lines indicate that merging is permitted. NACTO's three recommendations for pavement marking in conflict zones are the three levels of bike lane colored pavement markings used in this research 1) white lane markings with no supplemental pavement color on conflict area, termed white lane markings hereafter (Fig. 2a), 2) white lane markings with solid green pavement applied on the conflict area, termed solid green hereafter (Fig. 2b), and 3) white lane markings with dashed green pavement applied on the conflict area, called dashed green hereafter (Fig. 2c). Two levels of traffic signs were considered: 1) no sign and 2) a sign warning bicyclists of a potential truck conflict on the road. No specific sign is endorsed by MUTCD to address bicycle and truck conflicts. As a result, W11-10, a generic warning sign was employed in this study (Fig. 3) (FHWA, 2009). The warning sign was mounted on a sign pole and was placed 1 m upstream of the CVLZ. Three levels of truck maneuver were considered: 1) no truck, 2) truck parked in a CVLZ, and 3) a truck exiting the CVLZ 2.5 s before the bicyclist arrived. This cut-in time gap of 2.5 s is based on the accepted reaction times for motorists and bicyclists.

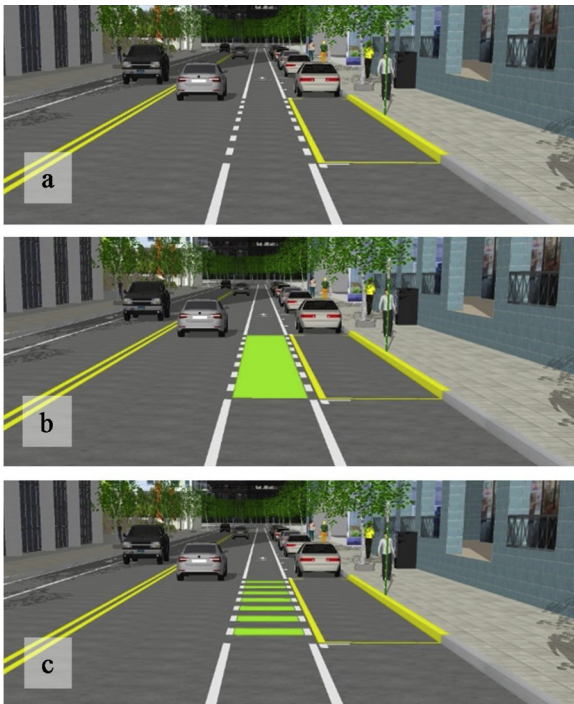


Fig. 2. Three levels of pavement marking (a) White lane markings, (b) Solid green, and (c) Dashed green (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).



Fig. 3. MUTCD W11-10 warning sign.

3.3. Research question

The bicyclist performance was measured in terms of velocity (m/s) and lateral position (m). The potential influence of the experimental factors (Table 1) on each of the response variables formed the basis of the following research question regarding the bicyclists’ performance: Do engineering treatments and truck maneuver have any effect on the bicyclists’ velocity and lateral position in the bicycling environment?

3.4. Experimental design

The independent variables (factors) and levels (Table 1) resulted in a study with a 3 × 3 × 2 factorial design. The roadway cross-section included two 12-ft travel lanes with 6-ft bicycle lanes in each direction. An 8-ft parking lane interrupted by an on-street CVLZ was created in one direction to account for bicycle-truck interactions. Eighteen scenarios were presented to participants across six grids (Table 2). Fig. 4 shows an example grid layout. Participants began at the start line and rode through three loading zones. The bicyclist was prompted to stop pedaling at the finish line at which point the researcher terminated the simulation. Participants were then asked if they need a break to catch their breath and were offered drinking water. Unless participants

Table 2
Cut-in scenarios.

| Scenario # | Cut-in # | Pavement Marking | Signage | Truck Maneuver |
|---------------|----------|--------------------|---------|----------------|
| <i>Grid 1</i> | | | | |
| 6 | 1 | White Lane Marking | Warning | Exiting |
| 2 | 2 | | None | Parked |
| 5 | 3 | | Warning | Parked |
| <i>Grid 2</i> | | | | |
| 4 | 1 | White Lane Marking | Warning | None |
| 1 | 2 | | None | None |
| 3 | 3 | | None | Exiting |
| <i>Grid 3</i> | | | | |
| 8 | 1 | Solid Green | None | Parked |
| 12 | 2 | | Warning | Exiting |
| 10 | 3 | | Warning | None |
| <i>Grid 4</i> | | | | |
| 7 | 1 | Solid Green | None | None |
| 9 | 2 | | None | Exiting |
| 11 | 3 | | Warning | Parked |
| <i>Grid 5</i> | | | | |
| 17 | 1 | Dashed Green | Warning | Parked |
| 15 | 2 | | None | Exiting |
| 13 | 3 | | None | None |
| <i>Grid 6</i> | | | | |
| 16 | 1 | Dashed Green | Warning | None |
| 14 | 2 | | None | Parked |
| 18 | 3 | | Warning | Exiting |

needed a break, next trial was immediately initiated.

A basic limitation of within-subject design is practice and carryover effects, which can cause a participant’s performance to degrade over the course of the experiment as they become tired, bored, or familiar with experimental design. To control for carryover effects, the order of intersection grids were counterbalanced using a randomized partial counterbalancing procedure and the duration of the test rides were manipulated to be relatively brief. The grids were presented to participants in the following sequences: 3-6-1-4-2-5, 5-1-6-2-4-3, 2-4-6-5-1-3, 4-5-1-2-3-6, 3-5-4-2-6-1, and 6-1-3-4-5-2. Before starting the main experiment, bicyclists were required to perform a calibration ride to acclimate to the operational characteristics of the bicycling simulator such as seat height, braking, turning, and pedaling in an environment similar to the one the experiment would take place in. Participants were allowed to ride for as long as they chose until they felt comfortable with these operational characteristics. When they self-identified as comfortable, typically from three- to five-minute after starting, the calibration ride was terminated. The calibration ride also helped to confirm if participants were prone to simulator sickness. None of the participants in the present study experienced simulator sickness symptoms and therefore no data were excluded from the final analysis.

3.5. Participants

Study participants were recruited from the community in and around Corvallis, Oregon and every effort was made to recruit a representative sample of Oregon bicyclists. The simulator experiment was successfully completed by 48 participants, including 24 women ($M_{age} = 29.71$, $SD_{age} = 10.03$) and 24 men ($M_{age} = 28.42$, $SD_{age} = 11.90$). Participants most frequently bicycled on a daily basis (52.1%), to commute to work/school (72.9%), and bicycled for 10–20 minutes on an average trip (50.0%). Additionally, over 83% of participants had experience bicycle riding in a busy downtown.

4. Results

Because each participant was exposed to all possible combinations of independent variables, repeated-measures analysis of variance (ANOVA) tests were performed with pavement marking, signage, and truck maneuver as within-subject factors. Bicyclist velocity and lateral

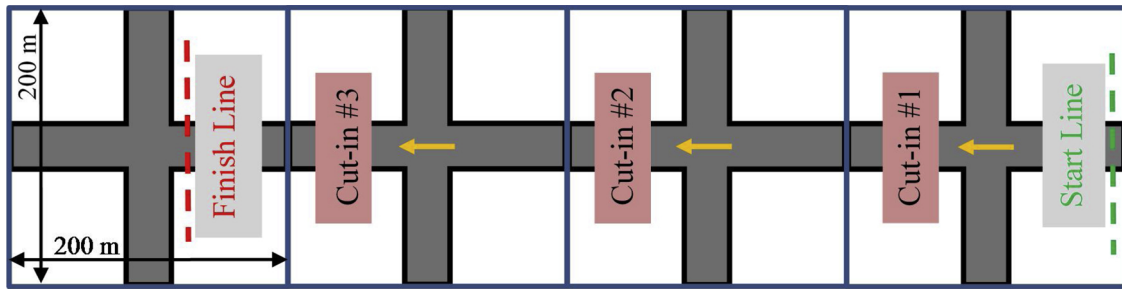


Fig. 4. Example Grid Layout.

position were analyzed separately as the dependent variables. Velocity and lateral position were measured along a fixed 40-m segment of the road including a 20-m section prior to loading zone as well as the entirety of the 20-m loading zone. Mauchly’s sphericity test was used to confirm sphericity assumptions. A significance level of 0.05 was adopted. Pairwise comparisons of estimated marginal means were conducted whenever a significant effect was observed. Effect size was reported by using partial eta squared. IBM SPSS Statistics software version 24 was used for data analysis.

4.1. Velocity

Mean (M) and standard deviation (SD) values for velocity at each level of each independent variable are reported in Table 3. Bicyclists had the highest mean velocity when no truck was present in the CVLZ and no engineering treatment was applied around the conflict area (white lane markings without any warning sign) ($M_{Velocity} = 5.66$ m/s, $SD_{Velocity} = 0.83$ m/s). Participants encountering an exiting truck while bicycling on a solid green bike lane without a warning sign had the lowest mean velocity ($M_{Velocity} = 3.94$ m/s, $SD_{Velocity} = 0.92$ m/s).

Repeated-measures ANOVA tests were used to determine effects of factors on mean bicyclist velocity. Pairwise comparisons were also conducted to find the origin of difference whenever a significant effect was observed. As shown in Table 4, factors of pavement marking ($F(2, 94) = 3.333$, $P = 0.050$) and truck maneuver ($F(2, 94) = 163.810$, $P < 0.001$) had significant effects on bicyclist velocity. No significant effect was observed for signage or either of the two- and three-way interactions. In terms of independent variables, truck maneuver had the highest effect on bicyclist velocity, with about 78% of within-subject variance being accounted for by the truck maneuver.

Pairwise comparison analysis showed that when a truck is exiting, a bicyclist on a solid green pavement marking had a significantly lower velocity compared to that of white lane markings ($P = 0.050$). Additionally, when white lane markings are applied on conflict areas, with and without a warning sign, all levels of truck maneuver have a significant effect on mean velocity ($P < 0.001$ for all pairwise comparisons). When solid green is applied, the statistically significant difference is observed for all levels of truck maneuver when a warning sign is present in the conflict area ($P < 0.001$ for all pairwise comparisons) and between an exiting truck and parked truck ($P < 0.001$) and no

Table 3 Mean and Standard Deviation of Velocity (m/s) at Independent Variable Levels.

| Truck Maneuver | Descriptive Statistics | White Lane Markings | | Solid Green | | Dashed Green | |
|----------------|------------------------|---------------------|--------------|-------------|--------------|--------------|--------------|
| | | No Sign | Warning Sign | No Sign | Warning Sign | No Sign | Warning Sign |
| No Truck | M | 5.66 | 5.62 | 5.30 | 5.57 | 5.58 | 5.55 |
| | (SD) | (0.83) | (0.98) | (1.19) | (0.80) | (0.89) | (0.88) |
| Truck Parked | M | 5.24 | 5.38 | 5.17 | 5.05 | 5.40 | 5.21 |
| | (SD) | (1.12) | (1.07) | (1.01) | (1.22) | (0.87) | (0.99) |
| Truck Exiting | M | 4.28 | 3.98 | 3.94 | 4.04 | 4.05 | 4.10 |
| | (SD) | (1.35) | (0.75) | (0.92) | (0.73) | (0.74) | (1.09) |

Table 4 Repeated-Measures ANOVA Results on Velocity (m/s).

| Source | $F(v_1, v_2)$ | P | η_p^2 |
|---|------------------|---------|------------|
| Within-Subject Factors | | | |
| Pavement Marking | 3.330 (2, 94)* | 0.050 | 0.066 |
| Signage | 0.216 (1, 47) | 0.644 | 0.005 |
| Truck Maneuver | 163.810 (2, 94)* | < 0.001 | 0.777 |
| Pavement Marking × Signage | 1.854 (2, 94) | 0.162 | 0.038 |
| Pavement Marking × Truck Maneuver | 0.513 (4, 188) | 0.698 | 0.011 |
| Signage × Truck Maneuver | 0.699 (2, 94) | 0.470 | 0.015 |
| Pavement Marking × Signage × Truck Maneuver | 2.467 (4, 188) | 0.069 | 0.050 |

Note: F denotes F statistic; v_1 and v_2 denote degrees of freedom; η_p^2 denotes partial eta squared.

* Statistically significant at 95% confidence interval.

truck ($P < 0.001$) conditions without a warning sign.

4.2. Lateral position

Mean (M) and standard deviation (SD) values for lateral position for each independent variable level are reported in Table 5. The bike lane’s right edge was defined as 0 m making the left edge 1.83 m. Bicyclists had the least divergence from the bike lane’s right edge when no truck was present in the CVLZ, no colored pavement marking was used (only white lane marking) and a warning sign was placed near the conflict area ($M_{Lateral} = 0.59$ m, $SD_{Lateral} = 0.15$ m). However, participants encountering a parked truck while in a bike lane with white edge markings and a warning sign had the most divergence from right edge of bike lane ($M_{Lateral} = 1.20$ m, $SD_{Lateral} = 0.73$ m).

Repeated-measures ANOVA tests were used to determine effects of factors on mean bicyclist lateral position. Pairwise comparisons were also conducted to find the origin of difference whenever a significant effect was observed. As shown in Table 6, pavement marking ($F(2, 94) = 5.678$, $P = 0.005$), signage ($F(1, 47) = 4.805$, $P = 0.033$) and truck maneuver ($F(2, 94) = 31.491$, $P < 0.001$) had significant effects on bicyclist lateral position. There was also a statistically significant interaction between the combined effects of pavement marking and

Table 5
Mean and Standard Deviation of Lateral Position (m) at Independent Variable Levels.

| Truck Maneuver | Descriptive Statistics | White Lane Markings | | Solid Green | | Dashed Green | |
|----------------|------------------------|---------------------|----------------|----------------|----------------|----------------|----------------|
| | | No Sign | Warning Sign | No Sign | Warning Sign | No Sign | Warning Sign |
| No Truck | M (SD) | 0.63 (0.13) | 0.59 (0.15) | 0.62 (0.29) | 0.65 (0.29) | 0.63 (0.21) | 0.62 (0.16) |
| Truck Parked | M (SD) | 1.08 (0.56) | 1.20 (0.73) | 0.97 (0.55) | 1.11 (0.70) | 1.08 (0.61) | 1.02 (0.50) |
| Truck Exiting | M (SD) | 1.05 (0.61) | 1.00 (0.60) | 0.87 (0.43) | 0.91 (0.57) | 0.92 (0.61) | 1.06 (0.72) |

truck maneuver on bicyclist lateral position ($F(4, 188) = 4.066, P = 0.008$). In terms of independent variables, truck maneuver had the highest effect on bicyclist lateral position, with about 40% of within-subject variance being accounted for by truck maneuver.

Two-way interactions were also considered in the pairwise comparison for both pavement marking and truck maneuver. Fig. 5 plots the lateral position estimated marginal means at each level of pavement marking and truck maneuver. As shown by this figure, the effect of pavement marking on lateral position is only apparent when a truck is present in the CVLZ (either parked or exiting).

Regardless of signage, pairwise comparisons showed that lateral position was significantly different for white lane marking and solid green bike lanes when a truck is parked in the CVLZ ($P = 0.030$), or when it is exiting ($P = 0.018$). Additionally, when a truck is parked, presence of a warning sign is only significantly effective in conjunction with solid green bike lane ($P = 0.050$). Further pairwise comparisons showed that when a truck is exiting the CVLZ, a warning sign is only significantly effective in conjunction with dashed green bike lane markings ($P = 0.025$). With no warning sign in place, pairwise comparison analysis showed that when dashed green pavement markings are applied in conflict areas, all levels of truck maneuver have a significant effect on mean lateral position ($P < 0.001$ for no truck compared to parked truck, $P = 0.001$ for no truck compared to exiting truck, and $P = 0.004$ for parked truck compared to exiting truck). With a warning sign in place, pairwise comparison analysis showed that when solid green pavement marking is applied in conflict areas, all levels of truck maneuver have a significant effect on mean lateral position ($P < 0.001$ for all pairwise comparisons). At all the levels of other factors, the difference in lateral position is only observed between the no truck condition against the parked truck condition (either parked or exiting).

4.3. Selected events

From the 288 total simulated conflicts between bicyclists and the exiting truck, four crashes occurred when the bicyclist attempted to overtake the exiting truck. Data were analyzed to identify the bicyclist behavior in terms of velocity and lateral position in each of these four

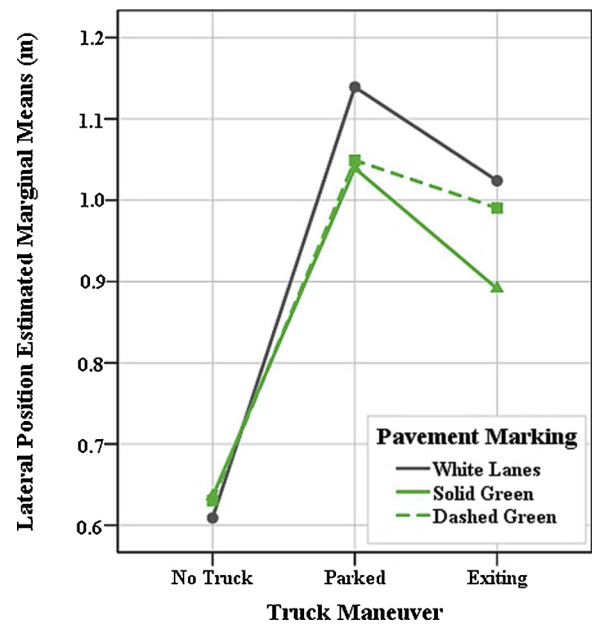


Fig. 5. Statistically Significant Two-Way Interactions on Lateral Position, According to ANOVA.

events.

Table 7 summarizes the characteristics of the three bicyclists who were involved in the observed bike-truck crashes. One of the participants was involved in two crashes. All bicyclists were less than 25 years old and used their bicycle on a daily basis to commute to school or work.

The Case A occurred in a scenario with solid green pavement marking and a warning sign, the Case B occurred in a scenario with white lane markings and no warning sign, the Case C involved a scenario with dashed green pavement marking and a warning sign, and finally, the Case D scenario included white lane markings with no warning sign. Table 8 summarizes bicyclist performance in terms of mean and maximum velocity and lateral position during the crash

Table 6
Repeated-Measures ANOVA Results on Lateral Position (m).

| Source | $F(v_1, v_2)$ | P | η_p^2 |
|---|-----------------|---------|------------|
| Within-Subject Factors | | | |
| Pavement Marking | 5.678 (2, 94)* | 0.005 | 0.108 |
| Signage | 4.805 (1, 47)* | 0.033 | 0.093 |
| Truck Maneuver | 31.491 (2, 94)* | < 0.001 | 0.401 |
| Pavement Marking × Signage | 1.671 (2, 94) | 0.194 | 0.034 |
| Pavement Marking × Truck Maneuver | 4.066 (4, 188)* | 0.008 | 0.080 |
| Signage × Truck Maneuver | 1.249 (2, 94) | 0.288 | 0.026 |
| Pavement Marking × Signage × Truck Maneuver | 1.942 (4, 188) | 0.105 | 0.040 |

Note: F denotes F statistic; v_1 and v_2 denote degrees of freedom; η_p^2 denotes partial eta squared.

* Statistically significant at 95% confidence interval.

Table 7
Characteristics of Bicyclists with Crashes.

| Case | Age | Gender | Bicycling Frequency | Riding Purpose | Riding Duration | Crash Experience | Downtown Experience |
|---------|-----|--------|---------------------|------------------------|----------------------|------------------|---------------------|
| A | 19 | Female | Daily | Commute to School/work | Less than 10 minutes | No | Yes |
| B and C | 24 | Male | Daily | Commute to School/work | 10-20 minutes | No | Yes |
| D | 24 | Male | Daily | Commute to School/work | 10-20 minutes | Yes | Yes |

events and non-crash events in data set.

One concern that might arise from the analysis of crash events is if these specific participants were gaming the simulation trials, thus creating bias dependent measures. As shown in Table 8, such a concern is minimal in this study. Focusing on non-crash events, a comparison of velocity between selected participants and the remainder of the dataset showed that except for one participant in Case D, all other participants were within one standard deviation from the mean velocity of the remainder of the dataset. Similarly, a comparison of lateral position was conducted with only one participant in Case A being more than one standard deviation away from the mean lateral position of the remainder of the dataset.

5. Discussion

Bicycle-truck conflicts in dense urban environments create severe safety concerns, and this study aimed to focus on understanding bicyclist behavior while encountering truck traffic in proximity of a CVLZ. This study attempted to shed further light on engineering treatments that could be influential on bicyclist response to the aforementioned conflict. To better understand the results of repeated-measures ANOVA, significant effects on bicyclist performance are visualized and further discussed in this section.

5.1. Velocity

Fig. 6 plots velocity distribution, aggregated at each 2 m under different levels of truck maneuver and pavement marking. In this figure, and similar subsequent figures, the x-axis represents travelled distance along the bike lane, considering the beginning of CVLZ as the 0 position. The positioning of parked vehicles, bicycle stencil, warning sign, pavement markings, and truck (parked or exiting) is identical to the test environment. Data captured from each of the 48 participants is plotted every 2 m (small red dots). In addition, mean (large blue dot) and standard deviation (blue bars) values at each 2 m are overlaid on the participants' data.

Fig. 6 includes scenarios in which a main effect was observed for truck maneuver and pavement marking on bicyclist velocity. As shown on Fig. 6a, without any engineering treatments in place, and when no truck is present in the CVLZ, bicyclists keep a consistent velocity while traversing the conflict area ($M_{Velocity} = 5.66$ m/s, $SD_{Velocity} = 0.83$ m/s). Truck maneuver has a decreasing effect on mean velocity. In fact, with a truck parked in the CVLZ (Fig. 6b) and with a truck exiting the CVLZ (Fig. 6c) bicyclists on average reduced their velocity by 7.4% ($M_{Velocity} = 5.24$ m/s, $SD_{Velocity} = 1.12$ m/s) and 24.4%

($M_{Velocity} = 4.28$ m/s, $SD_{Velocity} = 1.35$ m/s), respectively. While the reduction in mean velocity due to presence of a truck could potentially introduce additional safety, it does not guarantee a consistent behavior as there are several outliers and a larger variance in velocity distribution. For example, as shown in Fig. 6c, two of the participants increased their velocity to more than 10 m/s to overtake the exiting truck. As documented in selected events section, both were involved in a crash with the simulated truck. However, the application of solid green pavement marking appears to reduce mean velocity by additional 7.9% ($M_{Velocity} = 3.94$ m/s, $SD_{Velocity} = 0.92$ m/s). As shown in Fig. 6d, when a truck is exiting the CVLZ, solid green pavement marking also decreased variance and removed outliers as no participant was observed to ride faster than 7.5 m/s while traversing the conflict area.

5.2. Lateral position

Fig. 7 includes scenarios in which a main effect was observed for truck maneuver, pavement marking, and signage on bicyclist lateral position. As shown in Fig. 7a, with the dashed green pavement marking in place and without any truck in the CVLZ, bicyclists kept a consistent position in the bike lane while traversing the conflict area ($M_{Lateral} = 0.63$ m, $SD_{Lateral} = 0.21$ m). Presence of a truck significantly influenced bicyclist lateral position. As shown in Fig. 7b, when a truck is parked in the CVLZ, bicyclists moved considerably to the left, toward the travel lane (71.4% increase in average lateral position), creating a safety buffer between themselves and the truck ($M_{Lateral} = 1.08$ m, $SD_{Lateral} = 0.61$ m). When the truck is exiting, bicyclists were seen everywhere on the road (Fig. 7c). Thirty one bicyclists (64.6% of all bicyclists) moved to the left, toward the travel lane, to avoid the conflict with exiting truck. From this group, 5 bicyclists completely moved into the adjacent travel lane. On the other hand, seventeen bicyclists (35.4% of bicyclists) moved toward the right edge of the bike lane, two of whom completely moved into the loading zone area. On average the exiting truck increased bicyclist lateral position by 46.0% ($M_{Lateral} = 0.63$ m, $SD_{Lateral} = 0.21$ m). There is a similar pattern in bicyclist behavior when a truck is exiting and no engineering treatment is in place (Fig. 7d) with a 66.7% increase in bicyclist mean lateral position ($M_{Lateral} = 1.05$ m, $SD_{Lateral} = 0.61$ m).

With the dashed green pavement marking in place, presence of a warning sign when a truck is exiting the CVLZ made bicyclists move more toward and into the adjacent travel lane. In fact, compared to the no warning sign scenario (Fig. 7c), the presence of a warning sign (Fig. 7e) increased the average bicyclist lateral position by 15.2% ($M_{Lateral} = 1.06$ m, $SD_{Lateral} = 0.72$ m). This finding confirms that bicyclists perceived the warning sign as an indication of a potential hazard

Table 8
Bicyclist Performance during Bicycle-Truck Crash Events.

| Performance Measurement | Case A | Case B | Case C | Case D |
|---|--------|--------|--------|--------|
| Max Velocity at the Selected Event (m/s) | 7.58 | 10.61 | 11.12 | 10.32 |
| Mean Velocity at the Selected Event (m/s) | 6.33 | 10.02 | 10.55 | 10.09 |
| Mean Velocity for Non-Crash Events (m/s) | 4.00 | 4.06 | 3.98 | 4.06 |
| Mean Velocity for Selected Participant for Non-Crash Events (m/s) | 4.73 | 5.07 | 5.07 | 6.49 |
| Max Lateral Position at the Selected Event (m) | 5.35 | 4.17 | 4.33 | 4.26 |
| Mean Lateral Position at the Selected Event (m) | 4.03 | 3.14 | 3.00 | 3.40 |
| Mean Lateral Position for Non-Crash Events (m) | 0.87 | 0.99 | 0.98 | 0.99 |
| Mean Lateral Position for Selected Participant for Non-Crash Events (m) | 2.16 | 1.14 | 1.14 | 0.60 |

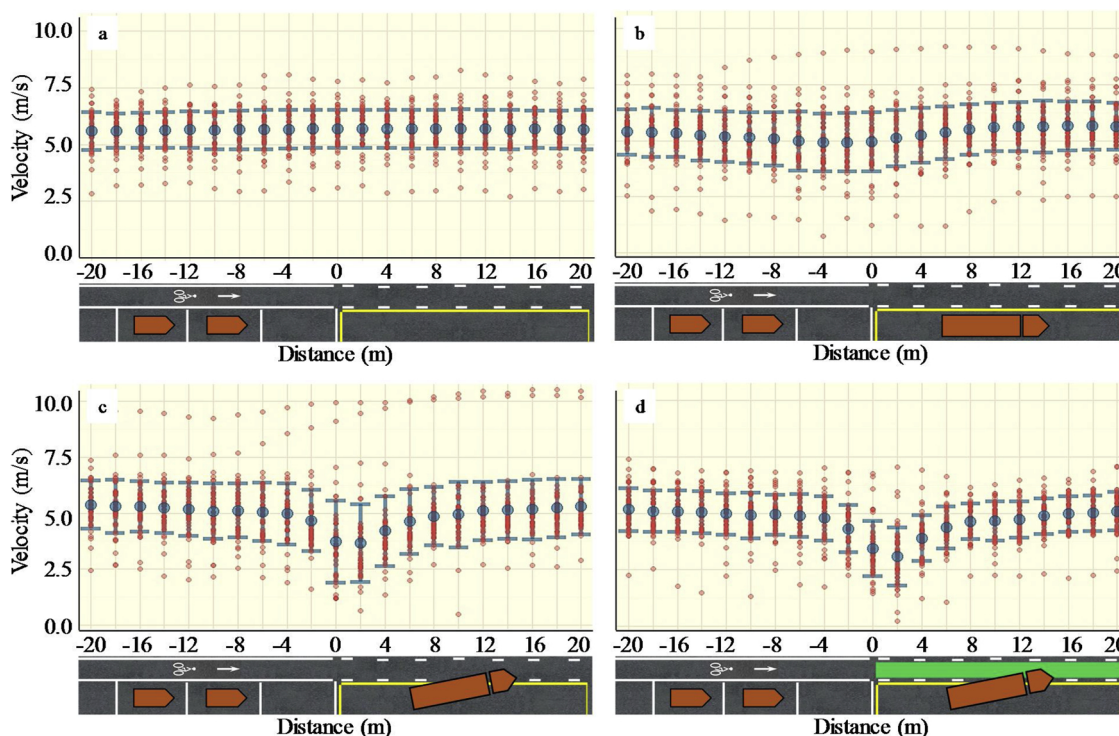


Fig. 6. Effect of Truck Maneuver and Pavement Marking on Velocity.

on the conflict area and therefore attempted to avoid it by moving further away from the truck. When a truck is exiting the CVLZ, the presence of the solid green pavement marking instead of the dashed green, kept bicyclists in the bike lane to a greater extent, reduced the variance, and removed outliers. Compared to the dashed green (Fig. 7c), the solid green pavement marking (Fig. 7f) reduced bicyclist mean lateral position by 5.4% ($M_{Lateral} = 0.87$ m, $SD_{Lateral} = 0.43$ m).

The influence of engineering treatments on bicyclist lateral position and its safety implication depend on the interpretation of safe bicycling behavior. If in a bicycle-truck interaction, a situation is considered safe when the bicyclist maintains a lateral position within the boundaries of the bicycle lane, then solid green pavement marking without any warning sign in place could create satisfying outcomes. However, if a safe behavior is defined as moving toward the travel lane to create a buffer between parked or exiting truck and bicycle, then warning sign could be helpful. In each of the cases, the effect of velocity should also be considered in conjunction with lateral position. As discussed, presence of a truck decreased bicyclist mean velocity. As such, if bicyclists move into travel lane and at the same, reduce their velocity, it could potentially increase the risk of crashes between bicycles and other motor-vehicles on the road.

5.3. Special events

Four crashes were observed between bicycles and exiting trucks. Fig. 8 depicts the lateral position of both parties along with bicyclist velocity. Each plot begins 2 s before the truck starts to move and continues until 1.6 s after left corner of the truck's front bumper is stabilized in the vehicular travel lane. As shown in Fig. 8, in response to the simulated truck maneuver, all four bicyclists decided not to stop or slow down, but to pedal faster (increase their velocity) and move toward the center of travel lane to overtake the truck. To avoid moving into the opposing travel lane, all four bicyclists changed direction back toward bicycle lane. This happened simultaneously with reduction in their velocity. However, the bicyclists misjudged their position relative to the truck and were hit by the simulated exiting truck.

In Cases A, B, and C collision happened approximately 6.6 s after the

start of the truck maneuver and in Case D it happened 6.8 s after. Therefore bicyclists had enough time to react appropriately to avoid the collision. Collisions happened while bicyclists had very high velocity (Case A = 6.82 m/s, Case B = 9.49 m/s, Case C = 9.63 m/s, and Case D = 10.03 m/s). At this velocity, bicycle and truck conflicts could certainly have severe consequences.

For the observed crashes, one important factor to consider is the impact of engineering treatments. There is an equal split in the occurrence of crashes, with and without engineering treatments in place, suggesting the influence of engineering treatment on crash outcomes may be minimal. Case A and Case C included both colored pavement marking and warning sign while Case B and Case D included no engineering treatments. With the presence of engineering treatments, bicyclist's shift in lateral position, happened more quickly, as they diverted toward travel lane prior to the CVLZ. However, this did not help them evade the exiting truck. Additionally, there was no pattern observed in bicyclist velocity as Case A had the lowest and Case C had the highest velocity at the time of collision.

6. Summary and conclusions

In this paper, high-fidelity full-scale bicycling simulator at OSU was used to examine the interaction of bicycles and trucks in the vicinity of CVLZ in urban areas and to investigate the influence of engineering treatments on bicyclist performance. Specifically, a factorial design with three levels of pavement marking (white lane marking, solid green, and dashed green), two levels of signage (no sign and warning sign), and three levels of truck maneuver (no truck, parked trucked, and exiting truck) was developed. Bicyclist performance was measured in terms of velocity (m/s) and lateral position (m). The simulation experiment was successfully completed by 48 participants, including 24 women and 24 men. Repeated-measures analysis of variance (ANOVA) and pairwise comparisons were used to study the effect of truck maneuver and engineering treatments on bicyclist performance.

The results of this study demonstrate a consistent narrative related to how bicyclists interact with trucks near urban CVLZ and how different levels of engineering treatments are effective. Overall, the results

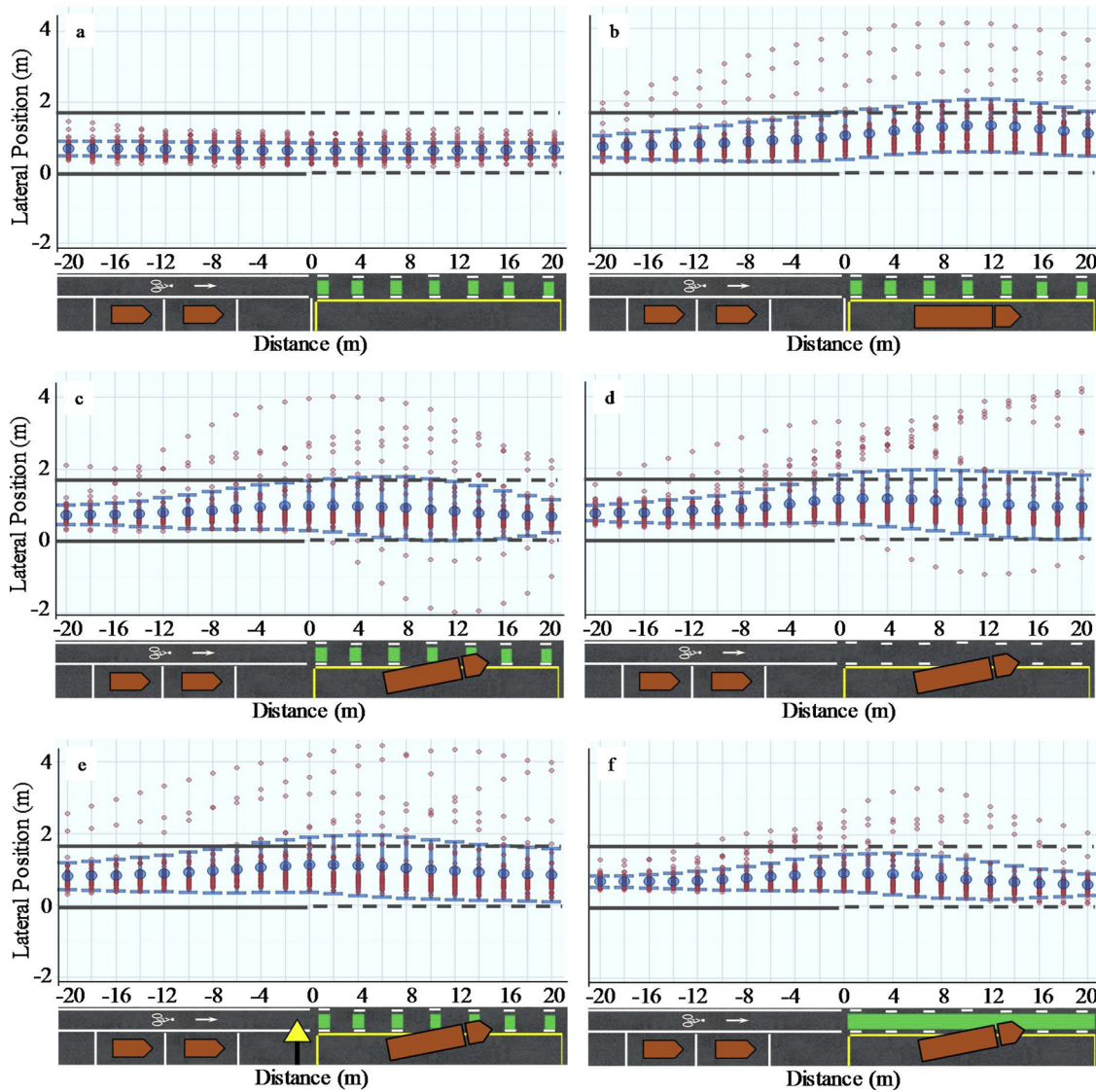


Fig. 7. Effect of Truck Maneuver, Pavement Marking, and Signage on Lateral Position.

show that truck presence does have an effect on bicyclist’s performance, and this effect varies based on the engineering treatments employed. There may be an increased risk of a crash associated with truck operations in urban CVLZ, especially when no engineering treatment is used. The primary findings of this study include the following:

- Pavement marking and truck maneuver had significant effects on bicyclist velocity. When a truck is exiting the CVLZ, a bicyclist on a solid green pavement marking had a significantly lower velocity than a bicyclist on white lane markings. Truck maneuver had a decreasing effect on mean velocity, with a truck exiting the CVLZ causing the lowest mean velocity.
- Pavement marking, signage, and truck maneuver had significant effects on bicyclist lateral position. Lateral variability was significantly higher for white lane marking compared to solid green bike lanes when a truck is parked or exiting the CVLZ. Under specific combinations of pavement marking and truck maneuver, bicyclists shifted their position toward the left edge of the bike lane and into the adjacent travel lane in the presence of a warning sign. Truck maneuver had an increasing effect on mean lateral position, with a parked truck causing the highest departure from the right edge of the bike lane.
- During bicycle and truck crashes, bicyclists misjudged their relative

position with exiting truck and were hit while having high velocity.

Depending on the desired bicyclist performance while approaching a CVLZ with a truck in it, different engineering treatments could be distinctly effective.

- Velocity reduction: Solid green pavement marking in the bicycle lane adjacent to the CVLZ without a warning sign.
- Lower divergence from right-edge: Solid green pavement marking in the bicycle lane adjacent to the CVLZ without a warning sign.
- Higher divergence from right-edge: White lane marking (no colored pavement marking on conflict area) with a warning sign in place.

One major concern with any type of simulation study, human-in-the-loop or otherwise, is the external validity of the results. The question is to what extent the simulator evokes the same behavior as it would be experienced in real-world scenarios. While there is abundant empirical literature regarding the validity of driving simulators, to the best of authors’ knowledge, there is only one such study regarding the validity of bicycling simulators. [Horne et al. \(2018\)](#) proposed a framework to investigate speed perception in bicycling simulator using OSU facility ([Fig. 1](#)). Employing the apparatus of the present study, [Horne et al. \(2018\)](#) stated that their proposed framework could make

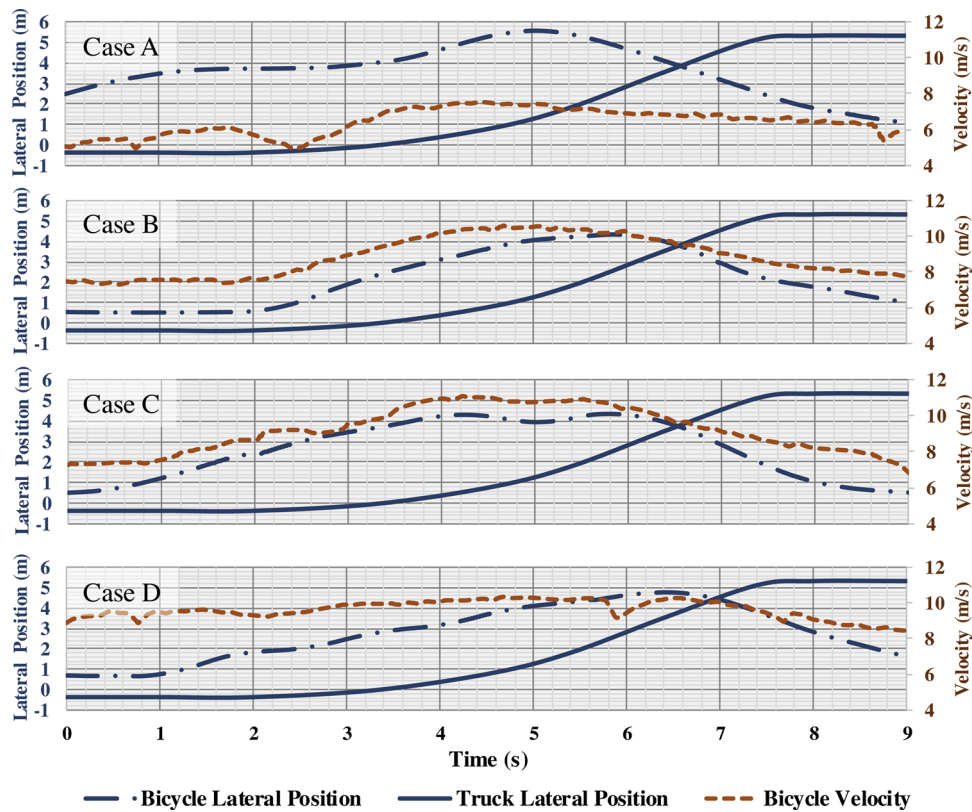


Fig. 8. Velocity and Lateral Position Distribution for Special Events.

simulation more representative of the real-world cycling experience. Apart from this single study, given the clear similarities between driving and bicycling simulators, the validity concept seems transferable between these two platforms. A considerable portion of literature regarding the external validity of driving simulators has focused on absolute validity against relative validity. While absolute validity refers to the identical effect size of variables in simulated and real-world scenarios, relative validity refers to direction or relative effect size of variables (Fisher et al., 2011). Previous studies showed that in driving simulators, relative validity has been obtained for both speed and lateral position (e.g., Kaptein et al., 1996). However, a future study could specifically compare the findings of the present paper with those of real-world experiments.

Acknowledgments

This work has been funded by the US Department of Transportation's University Transportation Center Program, Grant #DTRT13-G-UTC40 through the Pacific Northwest Regional University Transportation Center (PacTrans).

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