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ABSTRACT

Introduction: With growing freight operations throughout the world, there is a push for transportation systems to accommodate trucks during loading and unloading operations. Currently, many urban locations do not provide loading and unloading zones, which results in trucks parking in places that obstruct bicyclist's roadway infrastructure (e.g., bicycle lanes).
Method: To understand the implications of these truck operations, a bicycle simulation experiment was designed to evaluate the impact of commercial vehicle loading and unloading activities on safe and efficient bicycle operations in a shared urban roadway environment. A fully counterbalanced, partially randomized, factorial design was chosen to explore three independent variables: commercial vehicle loading zone (CVLZ) sizes with three levels (i.e., no CVLZ, Min CVLZ, and Max CVLZ), courier position with three levels (i.e., no courier, behind the truck, beside the truck), and with and without loading accessories. Bicyclist's physiological response and eye tracking were used as performance measures. Data were obtained from 48 participants, resulting in 864 observations in 18 experimental scenarios using linear mixed-effects models (LMM).
Results: Results from the LMMs suggest that loading zone size and courier position had the greatest effect on bicyclist's physiological responses. Bicyclists had approximately two peaks-per-minute higher when riding in the condition that included no CVLZ and courier on the side compared to the base conditions (i.e., Max CVLZ and no courier). Additionally, when the courier was beside the truck, bicyclist's eye fixation durations (sec) were one (s) greater than when the courier was located behind the truck, indicating that bicyclists were more alert as they passed by the courier. The presence of accessories had the lowest influence on both bicyclists' physiological response and eye tracking measures.
Practical Applications: These findings could support better roadway and CVLZ design guidelines, which will allow our urban street system to operate more efficiently, safely, and reliable for all users.

1. Background

With the presence of multiple modes sharing streets in urban areas, curb space has become a limited and high-demand commodity within the roadway network. Cities are responsible for deciding how curb space is managed, designed, and regulated for different transportation modes, including commercial vehicle parking and urban delivery activities. Factors that complicate curb space management include the high number of stakeholders and universally recognized urban planning policies (e.g., Smart Growth and Complete Streets) that promote compact development, mixed land-use and feasible multi-modal transportation options (NACTO, 2019). While these policies serve to improve the quality of life for residents and road users, they can often put bicyclists in danger by failing to acknowledge the potentially harmful interactions between this vulnerable road user group and commercial vehicles. Additionally, application standards do not support unique

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infrastructure necessities of freight activity and urban goods deliveries. These freight activities require the courier to walk around the vehicle, extend handling equipment and ramps, and maneuver goods; all of which require additional protected space beyond the dimensions of the vehicle, which is not accommodated by existing application standards.

Previous studies have found that curb use and demand by commercial vehicles is not met with adequate curb allocation (SCTL, 2019; Goodchild et al., 2018; Wygonik et al., 2015). Scenarios that illustrate the discrepancy between demand and supply include the parking of commercial vehicles on sidewalks, bike lanes, and turn lanes, extension of loading ramps and liftgates that impede crosswalks and sidewalks, and the staging of freight vehicles in locations that interfere with pedestrian and bicycle traffic. The conflicts with inadequate curb allocation for freight activity interfere with traffic operations and compromise the safety of both vulnerable road-users and the couriers. While North American data are limited, studies in the United Kingdom found an annual rate of 70 fatalities and 2,000 severe injuries in situations involving vehicles in and around workplaces. A large proportion of these crashes happen during collections or deliveries (Health and Safety Executive, 2019). Due to the absence of commercial vehicle loading zone (CVLZ) design standards in the United States, freight activity will continue to obstruct traffic flow and put couriers and vulnerable road users in danger. A study that was conducted in the City of Seattle looked at crash data between 2004 and 2014 involving only cyclists and trucks to quantify the rate of fatalities and serious injuries. The study found that during this period, the rate of fatalities and serious injuries (4% and 13.0%, respectively) for bicycle-truck crashes was higher when compared to the city average rate of fatalities and serious injuries (0.4 % and 7.6%, respectively; Butrina et al., 2016).

Across the United States, there are different rules regarding CVLZs, but generally require paid permits with signage to communicate the constraints in the loading zone. Additionally, there is no national standard for how CVLZs should be designated using curb paint, but in cities like Seattle and San Francisco, yellow curb paint is used to distinguish activities that include but are not limited to the loading/unloading of freight (SDOT, 2018; SFMTA, 2019). The Manual on Uniform Traffic Control Devices (MUTCD), commonly used as a resource for national roadway standards, discusses the standards for appropriate signage and grades but does not describe the standards for design dimensions for CVLZs (MUTCD, 2009). Guidelines are presented for urban parking lanes, including the width necessary for delivery vehicles as well as a bicycle route that provides space for bicyclists to maneuver around open doors in “A Policy on Geometric Design of Highways in Streets” by the American Association of State Highway and Transportation Officials (AASHTO, 2011).

The National Association of City Transportation Officials (NACTO, 2019) acknowledges the necessary operational envelope varies for different modes and that freight vehicles require additional space for hand truck and cart mobility (NACTO, 2016a). One of the distinguishing features for a commercial vehicle or light truck is its size in comparison to a personal vehicle. The defining definitions provided by NACTO for commercial vehicles and light trucks are 7–10 m (23–33 ft) long, and 2 m (6.5 ft) wide. Box trucks with a width of 2.4 m (8 ft) are recommended a parking space of 3.4 m (11 ft) wide to account for the buffer space needed for the door zone (NACTO, 2016b).

With the variety in different transportation modes occupying urban streets, it is critical to assess the safety and comfort level of more vulnerable road users like bicyclists, and a common characteristic used to gauge this is bicyclist stress. Many studies have classified bicycle stress using bikeability indices, stated preference surveys, and revealed preference surveys, but the issue with these methods is they describe “implied stress” versus induced stress while riding. Implied stress is the perceived comfort of bicyclists and can be measured by preference data and questionnaires, whereas induced stress is the psychological, physical, or emotional response an individual experiences to an event. To help bridge this gap, researchers have recently used physiological responses, such as Heart Rate Variability (HRV) and Galvanic Skin Response (GSR) to better understand cyclists’ responses to specific conditions and events (Doorley et al., 2015; Vieira et al., 2016; Caviedes et al., 2017; Fitch et al., 2017; Fitch et al., 2020; Cobb et al., 2021). While HRV is used to understand the fluctuations in time–space between an individual’s heartbeats (i.e., indication of physiological state), GSR is the measure of sweat glands and their response fluctuations exerted from specific events. Historically, GSR and HRV are commonly used in psychology studies, under controlled environments, to understand how participants react to events; however, recently HRV and GSR has been used as a metric to evaluate physiological responses of cyclists to events while riding in naturalistic conditions (i.e., in-field conditions). However, these naturalistic studies that used HRV or GSR to monitor bicyclists’ physiological response have been debated on their validity due to the inability to control for possible confounding variables in the naturalistic environment and whether HRV or GSR responses directly correlate with stress (Doorley et al., 2015; Vieira et al., 2016; Caviedes et al., 2017; Fitch et al., 2017; Fitch et al., 2020; Cobb et al., 2021).

In 2015, a study was conducted in Cork, Ireland to evaluate the relationship between cycling risks related to HRV. Using both HRV, risk rating questionnaires, and travel diaries, the study found that roadways with higher traffic volumes and no bicycle infrastructure yielded higher average risk from cyclists (Doorley et al., 2015). However, the study did not account for physical exertion; thus, resulting in weak correlations between stress and cycling. In 2016, a study used an electrocardiogram (ECG) to measure variations in HRV to several scenarios (e.g., cycling when a car is overtaking) to determine cyclists physiological response and found that the highest responses occurred when vehicles were overtaking or when cyclists were riding passed parked vehicles; however, the study was not a representative sample (i.e., only one participant) and did not distinguish the infrastructure conditions on the roadway (Vieira et al., 2016). In 2017, a study used a GSR sensor to measure stress responses in four males and one female on a predetermined in-field ride (Caviedes et al., 2017). The study found that the highest levels of responses occurred in cyclists when riding in peak hour conditions and at intersections, while low levels of responses occurred when riding in separated facilities (Caviedes et al., 2017). The study did have limitations in that it was not a representative sample, focused primarily on male participants, and did not adequately account for differences in responses related to events versus responses from physical exertion. A study in 2017, and a follow up study in 2020, used HRV to evaluate how primarily females respond to various roadway conditions (Fitch et al., 2017; Fitch et al., 2020). The two studies found that roadways with lower traffic volumes and speeds yielded lower stress responses, and that wider bicycle lanes improve stress responses. Conversely, in 2021, a study was conducted in a bicycle simulator to evaluate GSR responses of cyclists to varying roadway conditions (e.g., traffic volumes, traffic speeds, and presence of bicycle infrastructure) and found that both presence of bicycling infrastructure and lower traffic volumes yielded lower physiological responses; however, vehicle speed did not significantly affect GSR responses (Cobb et al., 2021). Because the study was conducted in a bicycle simulator, roadway and environmental factors could be controlled; however, there is still debate on the relationship between GSR responses and actual stress of cyclists. While these studies set a valuable groundwork for future research related to physiological responses of cyclists, there is still much to be explored to ensure experiments control for environmental factors and limit the false positive responses (i.e., responses to events versus responses to exertion).

Another measurement that can be useful to assess bicyclist behavior is through visual attention. Little research has been done using eye-tracking data to measure the decision-making of bicyclists while riding in traffic. There have been studies that have used eye-tracking data as a performance metric when observing how drivers make decisions in reaction to their environment (Jashami et al., 2019). It is critical to understand where bicyclists are looking when riding in high-risk environments to gain insight into their decision-making process, and it may provide indication as to where they identify points of conflict.

No previous studies have been conducted that analyze the physiological response of bicyclists to events while monitoring both GSR and eye-tracking data. With the use of the bicycle simulator, the goal of our research is to overcome limitations from previous studies by controlling environmental and roadway conditions to more accurately quantify the relationship between physiological responses and certain environmental and roadway conditions. The goal of our research is to determine how the size of the CVLZ influences the stress responses of bicyclists by observing the physiological response to the size of the loading zone, the presence and position of a courier, and the presence of loading zone accessories. While physiological responses do not directly indicate stress, we can use these measurements as surrogate data to gain a clearer understanding of how different CVLZ designs and conditions can trigger higher stimulation rates in riders and can provide guidance on future CVLZ design that accommodates bicyclists.

2. Methodology

2.1. *Bicycling simulator*

Oregon State University (OSU) is home to a bicycling simulator that is comprised of an instrumented urban bicycle placed atop a stationary platform (Fig. 1. right). When using the bicycle simulator, the user is presented with a display on a 3.24 m $\times$ 2.54 m screen with horizontal and vertical visual angles of 109° and 89°, respectively. The image resolution is 1024 $\times$ 768 pixels. Researchers build the virtual environment and observe bicyclist subjects from a workstation in an adjacent room that is separate from the room with the simulator (Fig. 1.left).

The projected graphics have a refresh rate of 60 Hz. A 5.1 Logitech surround sound system is used to project ambient sounds around the bicycle while participants navigate the virtual environment. The computer system used is a quad-core host which runs Realtime Technologies *SimCreator Software* with a refresh rate that matches the graphics at 60 Hz. Performance measures, including speed, positioning, braking, and acceleration, are all captured with high accuracy using the simulator software (SimObserver). The simulated environment from the participants view is shown on the left in Fig. 1. Software packages such as Internet Scene Assembler (ISA), Simcreator, and Blender were all used to develop the virtual environment. JavaScript-based sensors were used in ISA to create the simulated test track, which displayed dynamic objects, like a courier walking alongside the bicyclist.

2.2. *Simulator environment*

The virtual environment was created to emulate a typical roadway containing varying types of commercial vehicle loading zones. The experiment used three cross-sections. The first cross-section included one roadway with two 3.65-meter travel lanes, two 1.84-meter bicycle lanes, and no loading zone, as shown in Fig. 2 on the left. The second cross-section included a roadway with a 3.5-meter loading zone, two 3.65-meter travel lanes, two 1.84-meter bicycle lanes, and one small loading zone of 3.5-meter width, as shown in Fig. 2 in the middle. The third cross-section included a roadway with two 3.65-meter travel lanes, two 1.84-meter bicycle lanes, and one large loading zone of 4.5-meter width, as shown in Fig. 2 on the right.

Ambient traffic was coded manually to provide each participant with the same number of vehicle encounters and to limit the number of conflicts the participant experienced. Ambient traffic was meant to emulate normal traffic conditions, with the bicyclists being passed by passenger cars about once every ten seconds (i.e., 360 vehicles/hour). To improve the experimental control, traffic was programmed to avoid passing the bicyclists during CVLZ interactions. All participants performed a calibration ride on the bicycle prior to beginning their experimental trial. Instructions were given to participants to abide by the traffic laws they typically would when bicycling. This calibration ride served to help participants adjust to the mechanics of the bicycling simulator and also helped determine whether participants were prone to simulator illness. Participants who experienced simulator sickness were removed from the study to limit their discomfort (Hurwitz et al., 2018).

2.3. *Shimmer3 GSR + Sensor*

Galvanic Skin Response (GSR) is a measure of variation in sweat glands as a reaction to various stimuli initiated by events. A Shimmer3 GSR + sensor was used to collect GSR readings in this study. The sensor was strapped to the wrists of participants, and the two electrodes were attached to the middle and ring finger of the non-dominant hand, as shown in Fig. 3. The non-dominant hand remained stationary on the handlebars throughout the experiment to mitigate false-positive GSR responses. To ensure that the simulated events and GSR readings could be synchronized, a Logitech C920 HD Pro Camera was integrated to record the participant runs. Upon completion of the experiment, the GSR and video data were processed using iMotions software (V8.3). This software allows GSR and video data to synchronize and be recorded with consistent time stamps.

GSR measurements were collected and reduced to provide average GSR peaks per minute for each individual and for the overall sample

Fig. 1. Simulated environment in the OSU bicycle simulator; Participant's perspective (*Left*); Researcher testing the environment (*Right*).

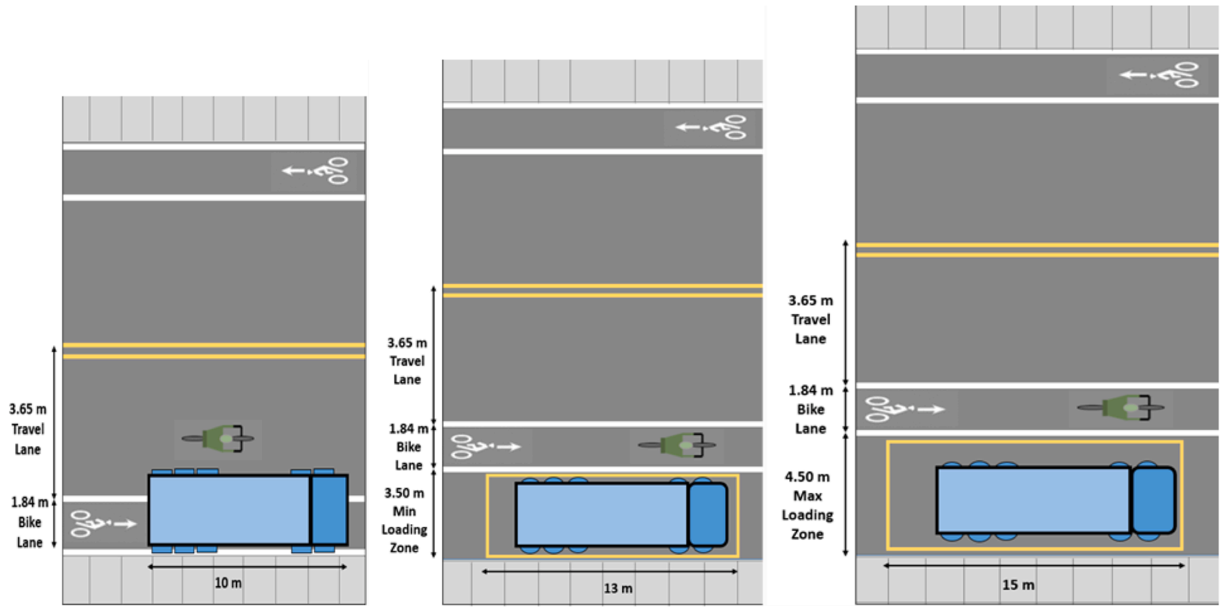

Fig. 2. Roadway cross-section. Roadway with two 3.65-meter travel lanes, two 1.84-meter bicycle lanes, and no loading zone (*Left*); Roadway with two 3.65-meter travel lanes, two 1.84-meter bicycle lanes, and one-small loading zone of 3.50-meter width (*Middle*); Roadway with two 3.65-meter travel lanes, two 1.84-meter bicycle lanes, and one-large loading zone of 4.50-meter width (*Right*).

Fig. 3. Shimmer3 GSR + attached to hand.

(iMotions, 2017; Terkildsen & Makransky, 2019; Krogmeier et al., 2019; Zou & Ergan, 2019). The purpose of using peaks per minute is to control for time within each scenario, as every participant's duration and GSR peaks varied. To develop the average peaks per minute, iMotions software (i.e., software used to process the GSR and video data) initially develops a baseline GSR reading for each participant based on their average responses throughout a scenario. The baseline is calculated through the iMotions software and was collected for about two minutes prior to the start of the experimental ride to ensure proper recording of the device and also to determine the individual base GSR response, as recommended by iMotions (iMotions, 2017). This baseline is calculated to normalize each participant's GSR output and to determine when individuals have peak responses. A peak response is determined based on any response having an excess of 0.01 μs for peak onsets and offsets less than 0 μs, and is used to determine the number of peaks and the subject average peaks per minute (iMotions, 2017). Following this, anytime an individual has an amplified response above the baseline, this is classified as a peak and recorded (iMotions, 2017).

2.4. Eye tracker

Eye-tracking data were collected during the study that captured where participants looked while riding in the bicycling simulator. These data were collected using an ASL Mobile Eye-XG platform with a sampling rate of 30-Hz and an accuracy of 0.5–1.0° (OSU, 2012). The correlation between the reflection of the three infrared lights on the eyeball and the pupil position of the participant was used to calculate gaze. A fixation occurs when gaze is directed toward a specific location and remains uninterrupted for a period of time (Green, 2007; Fisher et al., 2011). The period of time for no eye position movement required for the ASL Mobile Eye-XG system to recognize a fixation point is 100 ms. The dwell time between fixations is used to calculate the saccades. Saccades are defined as the movement of gaze from one fixation point to another. The total dwell time is found by summing the consecutively recorded fixation times and saccades in an area of interest (AOI).

After collecting participants' eye-movement data, fixation and dwell data, all were analyzed by AOI polygons with the ETAnalysis software suite. Researchers watched each video segment that included navigation through the loading zone (i.e., 18 per participant). These video segments were cropped to the length of time (i.e., generally 10–30 s) that the bicyclist passed by the loading zone. Researchers drew AOI polygons on individual video frames in a sequence separated by intervals of approximately 5–10 frames. The four AOIs that were explored in this experiment were truck, courier, hand truck, and traffic. Thus, a polygon of a rectangular shape was drawn around each target, i.e., AOI (truck, courier, hand truck, and traffic), while a bicyclist navigated the commercial loading zones, as shown in Fig. 4. The bicyclist's eye-tracking data started from approximately 82 ft before the parked truck and continued until the participant completely passed the truck. Once the data reduction was complete, the ETAnalysis software was used to calculate the total fixation duration in seconds (TFD) data on each of the 4 AOIs separately.

2.5. Experimental design

A factorial design was used to allow for the observation of the three independent variables separately. The independent variables included in the experiment were pavement marking, courier position, and

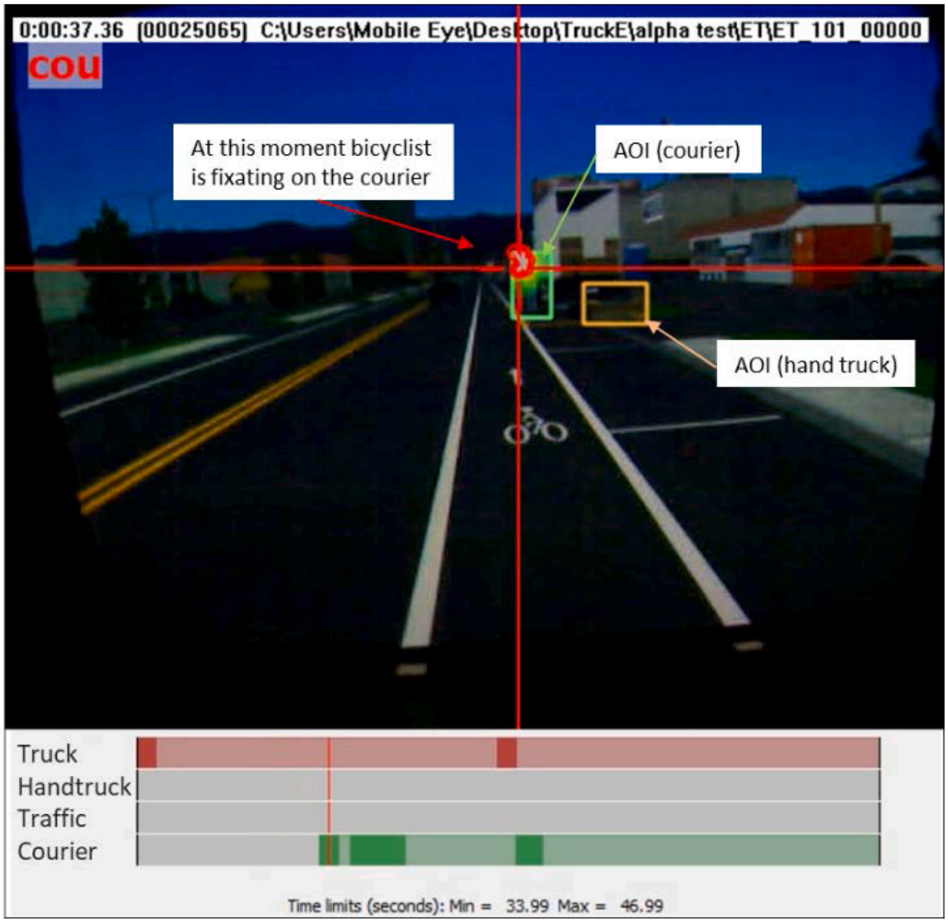

Fig. 4. Example of a bicyclist fixation pattern on the courier area of interest (AOI) and how AOIs were drawn and identified.

accessory (i.e., an accessory is an additional component (hand truck) that the truck courier would use to conduct truck loading and unloading operations), which are summarized in Table 1. Eighteen scenarios were included in the factorial design, all of which were presented to participants. Fig. 5 shows four examples of the 18 scenarios. Five different tracks, each ranging from approximately 2 to 4 min, were used to fully counterbalance scenario order to control for carryover effects and practice. Each participant experienced a randomized grid sequence (Jashami et al., 2020). Two (2) dependent variables were observed in the experiment: GSR data and eye-tracking data.

2.6. Participant

Consent form was signed and obtained from all participants prior to the beginning of the experiment. The informed consent document provides an overview of the objectives of the study, and potential risks and research benefits associated with using the simulator. A pre-simulator survey was completed after consent and before the simulator portion of the experiment. In the pre-survey, participants were asked demographic questions, including gender, age, race, household income, and highest level of education. Fifty participants (26 women, 24 men) participated in the simulator study. During the pre-ride survey, participants were asked whether they had participated in other simulator experiments, and 78 % of them replied with "yes," and the remaining replied with "no." Due to simulator sickness and eye-tracker calibration issues, two women were not included in the study, which yielded a total of 48 participants. While for the GSR data, 46 participants were used in the analysis due to additional missing data. It was expected that a large proportion of the participants would be OSU students, but an effort was made to include participants that would represent all ages. Participant ages ranged from 18 to 74 years, which consisted of 24 women (M_{age} = 29.84, SD_{age} = 7.48) and 24 men (M_{age} = 36.45, SD_{age} = 15.57). The distribution of age and other demographic variables are presented in Table 2.

In addition to the demographics, participants were asked other questions (e.g., bicycling experience, type of trips, level of comfort) during the pre-ride survey, as shown in Table 3. Participants most frequently bicycled weekly 1–5 miles (22.0%) and 5–10 miles (22.0%), and for recreation (34.7%) and exercise (33.7%). Additionally, over 68% of participants classified themselves as "Enthused and Confident" cyclist typology.

After participants completed the bicycling simulator portion of the experiment, they were asked to complete a short survey regarding the bicycle simulator functionality and the scenarios they encountered during their ride in the simulator.

Table 1
Experimental Variables and Levels.

Variable	Level	Level Description
LoadingZoneSize	0	No CVLZ – Truck in bike lane
	1	Min CVLZ – Size of vehicle only
	2	Max CVLZ – Size of vehicle plus desired operational footprint (4.5 m)
Courier Position	0	No Courier
	1	Courier Behind Vehicle
	2	Courier on Driver's Side
Accessory	0	No Accessory
	1	Accessory (i.e., Using a Hand Truck)

Fig. 5. Experimental Design Scenarios: (a) Scenario with accessories, and no CVLZ or courier; (b) Scenario with accessories, minimum CVLZ, and no courier; (c) Scenario with accessories, maximum CVLZ, and no courier; (d) Scenario without accessories, maximum CVLZ, and courier on driver's side.

Table 2
Participant demographics.

Demographics	Categories	Number of Participants	Percentage of Participants
Age	18–24 years	11	22.0 %
	25–34 years	21	42.0 %
	35–44 years	13	26.0 %
	45–54 years	1	2.0 %
	55–59 years	0	0.0 %
	60–64 years	1	2.0 %
	65–74 years	3	6.0 %
Education	High school diploma or GED	3	6.0 %
	Some College	8	16.0 %
	Trade/vocational school	1	2.0 %
	Associate degree	2	4.0 %
	Four-year degree	9	18.0 %
	Master's Degree	23	46.0 %
	PhD Degree	4	8.0 %
Race	Asian	7	14.0 %
	Black or African American	2	4.0 %
	White or Caucasian	33	66.0 %
	Other	3	6.0 %
	Hispanic or Latino	4	8.0 %
Income	Less than $25,000	10	20.0 %
	$25,000 to less than $50,000	15	30.0 %
	$50,000 to less than $75,000	7	14.0 %
	$75,000 to less than $100,000	10	20.0 %
	$100,000 to less than $200,000	5	10.0 %
	Prefer not to answer	3	6.0 %

Table 3
Participant Bicycling Habits.

Bicycling Habit	Possible Responses	Number of Participants	Percentage of Participants
Bicycling Mileage Per Week	Never	6	12.0 %
	Less than 1 mile	7	14.0 %
	1–5 miles	11	22.0 %
	5–10 miles	11	22.0 %
	10–20 miles	8	16.0 %
	20–50 miles	6	12.0 %
	50 + miles	1	2.0 %
Type of Cyclist	Strong and Fearless	5	10.0 %
	Enthused and Confident	34	68.0 %
	Interested but Concerned	11	22.0 %
	No Way No How	0	0.0 %
Riding Purpose	Commuting to work/school	30	30.6 %
	Recreation	34	34.7 %
	Exercise	33	33.7 %
	None	1	1.0 %

2.7. Statistical modeling

To better understand the results, a Linear Mixed Effects Model (LMM) model was chosen for the analysis because: (a) of its ability to handle the errors generated from repeated subject variables as the participants are exposed to all scenarios (Bamney et al., 2021); (b) it can handle fixed or random effects; (c) categorical and continuous variables can easily be accommodated; and (d) the probability of Type I error occurring is low (Jashami et al., 2019). The sample size for this study was 48 participants, which is greater than the minimum required (e.g., larger than 20 participants) for a LMM analysis (Barlow et al., 2019). The LMM is formulated as shown in Eq. (1),

$$y_{ij} = \beta_0 + \beta_1 x_{ij} + b_i + \varepsilon_{ij}, b_i \;\; \mathrm{N}\left(0, \sigma_b^2\right), \;\; \varepsilon_{ij} \;\; \mathrm{N}\left(0, \sigma_\varepsilon^2\right) \tag{1}$$

where β_0 is the intercept at the population level, β_1 is the slope, b_i is the random intercept of the i^{th} participant that is following a mean normal distribution with variance σ_b^2, and ε_{ij} is the error. Hence, b_i and ε_{ij} are assumed to be independent.

The model was developed using the statistical software STATA for Windows (version 17) to consider the independent variables of loading zone size, courier position, and accessories. These variables were included in the model as fixed effects, while the subject variable was included in the model as a random effect.

3. Results

As mentioned previously, two measures of bicyclist performance were evaluated: GSR reading and bicyclist's visual attention. The GSR reading was calculated while the bicyclists navigated the commercial loading and unloading zones. Similarly, the bicyclist's eye-tracking data were analyzed from the point when the participant approached the loading zone and continued until the participant completely passed it.

3.1. Post-survey results

To verify the authenticity of the simulated bicycling task, participants were asked to subjectively evaluate the performance of the bicycle simulator. The ratings ranged from 0 to 100, where 0 was defined as completely different from real-world experience, and 100 was defined as entirely as real-world experience. The average score for this question was 75.08.

Evaluating whether bicyclists had ever experienced specific scenarios and how they felt was another goal of the research. To investigate these questions, bicyclist comfort was evaluated in the post-ride survey. Participants were asked whether they had ever ridden in a bike lane that had commercial vehicle conflicts. Forty participants (80%) indicated that they had experienced the conflict before, 8 participants (16%) stated that they had not experienced the conflicts before, and 2 participants (4%) were unsure.

Individuals were then asked in which scenario did they feel most comfortable. Forty-five participants (90%) indicated "The commercial vehicle far from the bike lane (wider loading zone)" they felt the most comfortable with, followed by 4 participants (8%) indicating "The commercial vehicle adjacent to the bike lane (narrow loading zone)" and 1 participant (2%) indicating "The commercial vehicle in the bike lane (no loading zone)" (Fig. 6).

As a follow-up question, participants who indicated "yes" that they had experienced an obstruction in the bicycle lane, were presented two additional questions regarding their experience with obstructions in the bike lane and their typical responses to avoiding them when in the bike lane. As shown in Fig. 7, of the 45 participants who answered "yes" to having experienced obstructions in the bike lane, 39 participants (87%) indicated that they made similar actions to avoid the obstruction in the simulator that they would in real-world conditions, 4 participants (9%) indicated they made different actions in the simulator that they would in the real world to avoid the obstruction, and 2 participants (4%) indicated they were unsure.

Finally, participants were asked their typical responses to avoiding obstructions in the bike lane. As shown in Fig. 8, "take the travel lane (ride in the travel lane)" had the highest response rate (29 participants), followed by "ride between obstruction and traffic," which was selected by 26 participants. Very few participants selected "stop your bike and wait for obstruction to clear" and "dismount your bike and walk around obstruction," with only 7 and 4 participants indicating them, respectively.

3.2. GSR reading

After a participant progresses through the area of interest, the software calculates the peaks per minute for the individual based on their relative amplified responses. Mean (μ) and standard deviation (SD) values for GSR readings for each treatment variable level are reported in Table 4.

An LMM was used to estimate the relationship between the independent variables and participant's mean GSR reading (peaks per minute), which is appropriate given the repeated measures nature of the experimental design, where each participant experienced each scenario (Jashami et al., 2019). In addition, gender was also included in the model as an independent variable. These variables were included as fixed effects and participants' ID as random effects. The results of the GSR model are shown in Table 5. The random effects were significant (Wald $Z = 4.21$, $p < 0.001$), which suggests that it was necessary to treat the participant as a random factor in the model.

All independent variables, with the exception of accessories, were found to have a significant impact on the GSR reading of the bicyclists. Regardless of the courier position and accessories, a bicyclist encountered with a parked truck in the maximum loading zone had the lowest GSR reading compared to minimum loading zone ($p = 0.049$) or no loading zone ($p = 0.001$). The second significant variable was courier position. When bicyclists rode in a scenario that had a courier on the side of truck, the participants had about 2 peaks/min more than the no courier condition ($p = 0.026$) and about 1.5 peaks/min more than when the courier was located behind the truck ($p = 0.05$). Gender was also considered in the analysis. A previous study that was conducted in a

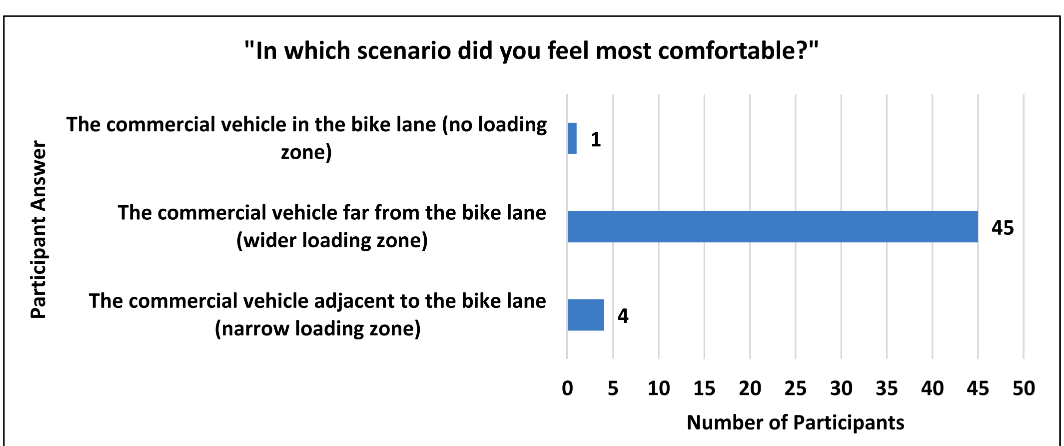

Fig. 6. Participants Most Comfortable Scenario.

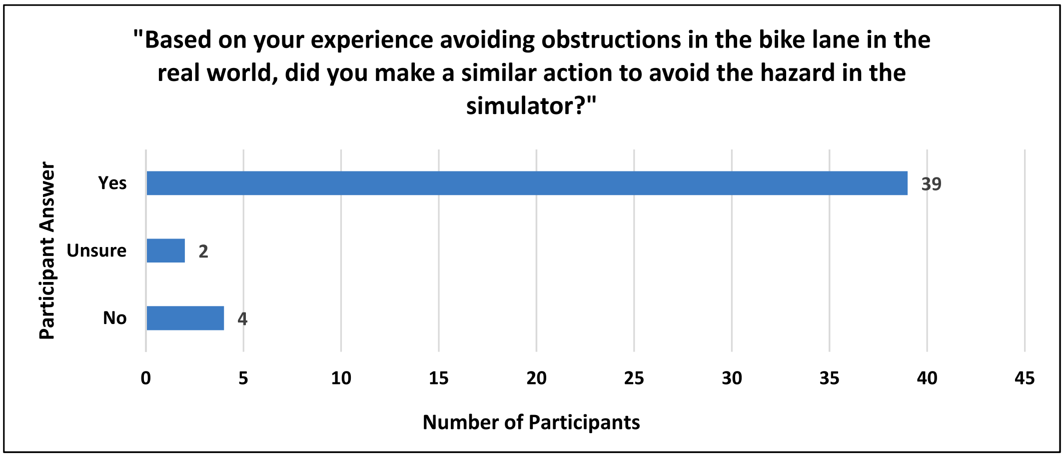

Fig. 7. Participants Decision to Make Similar Action to Avoid Hazard in Real-World.

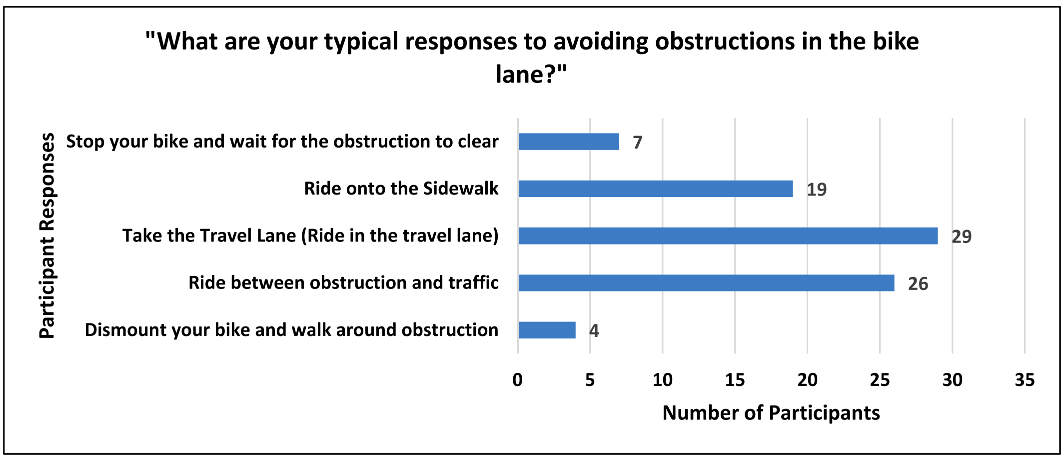

Fig. 8. Participants Typical Responses to Avoiding Obstructions in Bike Lane.

Table 4
Mean and Standard Deviation of GSR readings at treatment variable level.

Commercial Vehicle Loading Zone (CVLZ)	Descriptive Statistics	No Accessories			Hand Truck		
		No Courier	Behind	Beside	No Courier	Behind	Beside
No CVLZ	μ	16.16	16.50	17.78	14.04	15.66	18.35
	(SD)	(10.42)	(11.53)	(12.83)	(11.61)	(12.16)	(12.94)
Min CVLZ	μ	14.38	14.61	16.93	16.00	13.25	16.37
	(SD)	(10.82)	(11.74)	(10.15)	12.06)	(11.67)	(11.92)
Max CVLZ	μ	13.13	11.88	15.63	12.55	15.91	12.51
	(SD)	(10.50)	(12.45)	(12.90)	(10.60)	(10.69)	12.02)

bicycling simulator environment found that females have a higher level of stress, as measured by GSR, when compared to males (Cobb et al., 2021) while riding in uncomfortable conditions (i.e., shared travel lane vs. bike lane). This finding matches the LMM output. Regardless of other variables, females had 2 peaks/min more than males. Age was tested and found to be statistically not significant.

All possible interactions among the independent variables were also investigated and graphically illustrated in Fig. 9. These plots help to examine the dependent behavior of a variable on the value of another while other variables are constant. The y-axis in this figure shows the mean GSR reading (peaks/min). The x-axis in Fig. 9 of plots a, b, and c shows the three levels of loading zone size treatment, while plots d and e show the three levels of the courier position. Fig. 9, plot a, illustrates the interaction between the levels of loading zone size and courier position. Regardless of accessories, on average, participants had higher GSR reading when the courier was walking alongside the truck with both no loading zone and minimum loading zone compared to maximum loading zone, as shown in Fig. 9 plot a. The minimum loading zone size did not differ from the maximum loading zone size in terms of bicyclist performance measures. However, in the presence of a courier on the driver's side of the truck, the minimum CVLZ tended to be the most stressful scenario for bicyclists since they often veered from the bike lane toward the adjacent vehicular travel lane. Meanwhile, while holding the courier position and accessories constant, female bicyclists had higher GSR reading compared to males at all three loading zone sizes, as shown in Fig. 9, plot c. A similar trend was observed when holding the pavement marking and accessory variables constant, as shown in Fig. 9, plot e. The standard error and mean of these variables are depicted in Fig. 10.

Table 5
Summary of Estimated LMM Models of GSR Reading.

Variable	Levels	Estimate	Std. Error	P
Participant random effect (SD)	–	(6.71)	–	<0.001*
Constant	–	13.62	1.66	<0.001*
Loading Zone Size	No CVLZ	2.83	0.82	0.001*
	Min CVLZ	1.61	0.81	0.049*
	Max CVLZ	Base	–	–
Courier Position	No Courier	−1.81	0.82	0.026*
	Behind	−1.60	0.82	0.050
	Beside	Base	–	–
Accessories	No Acc	0.29	0.67	0.666
	Acc	Base	–	–
Gender	Female	2.18	2.09	0.297
	Male	Base	–	–
Summary Statistics				
R2	0.35	Observations		812
−2Log Likelihood	6053.93	Participants		46
BIC/AIC	6067.31/ 6064.76	Observations/ Participant		18

[*] significance level is 0.05.

3.3. Visual attention

While the bicyclists traversed the loading zone area, the number and duration, in seconds, of participants' fixations on AOI (the truck/loading zone) were recorded, with a total fixation duration (TFD) of 0 s (indicating that the participant did not look at the target). The Average Total Fixation Duration (ATFD) was calculated by averaging all participants' total fixations using an AOI. Mean (μ) and standard deviation (SD) values for TFD for each treatment variable level are reported in Table 6.

A modeling approach similar to the one that was followed for the GSR reading was used to statistically examine differences in mean TFD. The results of the model are shown in Table 7. The LMM results showed that when participants rode in a scenario that included the presence of a hand truck (variable), the TFD on the truck was not statistically significant ($p = 0.138$), but the loading zone size was significant for both levels ($p < 0.001$). Regardless of the courier position, this suggests that bicyclists fixate on the truck for exactly the same period for both conditions with or without a hand truck. The random effect was statistically significant (Wald $Z = 4.10$, $p < 0.001$). Interestingly, participants encountering no loading zone or minimum loading zone were spending a longer time (i.e., approximately 0.5 s) observing the truck ($p < 0.001$) as compared to the maximum loading zone. These findings are also illustrated in Fig. 11 on the top.

Additionally, TFD of bicyclists on courier AOI and traffic was also calculated, as illustrated in Fig. 11. The y-axis shows the mean fixation duration with 95 % confidence interval, and the x-axis shows the levels of loading zone variables at different courier positions. As shown at the bottom in Fig. 11, bicyclists fixated more on the courier when walking alongside the truck compared to when the courier was behind the truck. As shown in Fig. 11, in general, bicyclists spent a longer time observing the courier and the truck when they encountered no loading zones or minimum loading zones. The mean TFD on the traffic was higher when the truck was obstructing the bike lane compared to the minimum and maximum CVLZ.

4. Discussion

Many urban locations provide no to minimum loading and unloading zones, which results in trucks parking in places that obstruct the entire or part of bicyclist's roadway infrastructure (e.g., bicycle lanes). Results show that bicyclists were less comfortable and had higher visual scanning while riding in the minimum loading zone condition, especially when the courier was on the driver's side. One possible solution could be

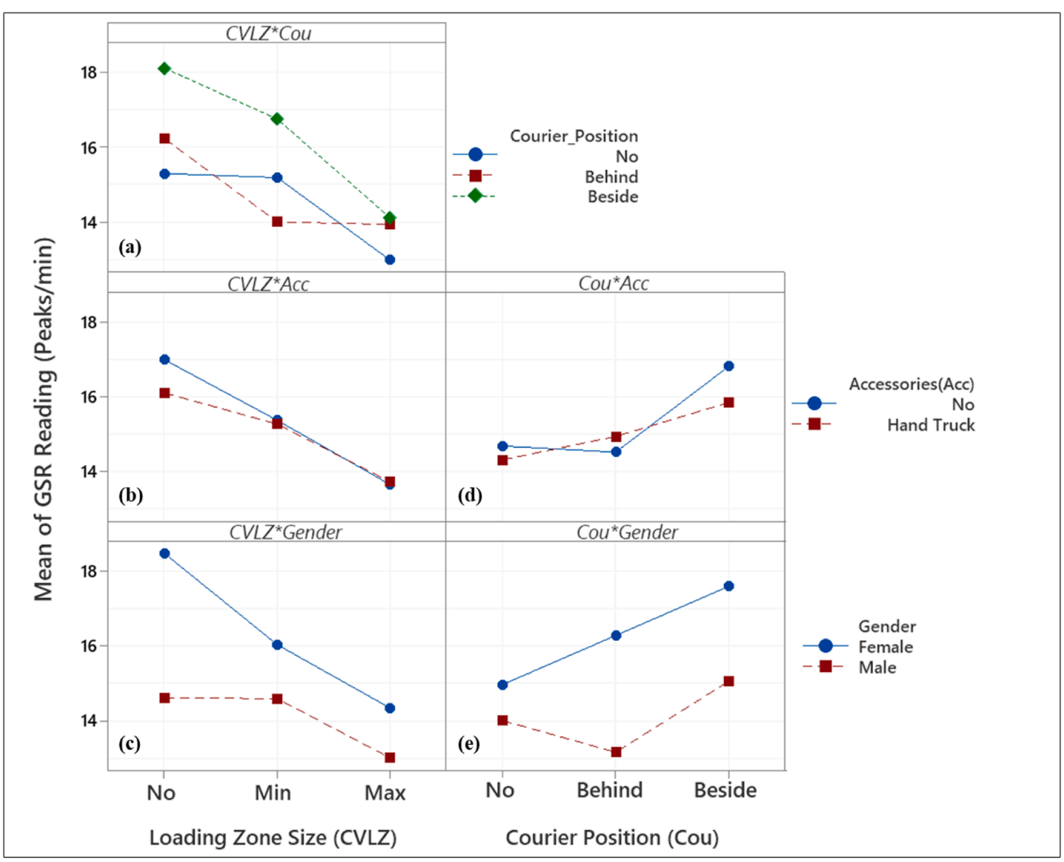

Fig. 9. Two-way interactions on mean GSR reading.

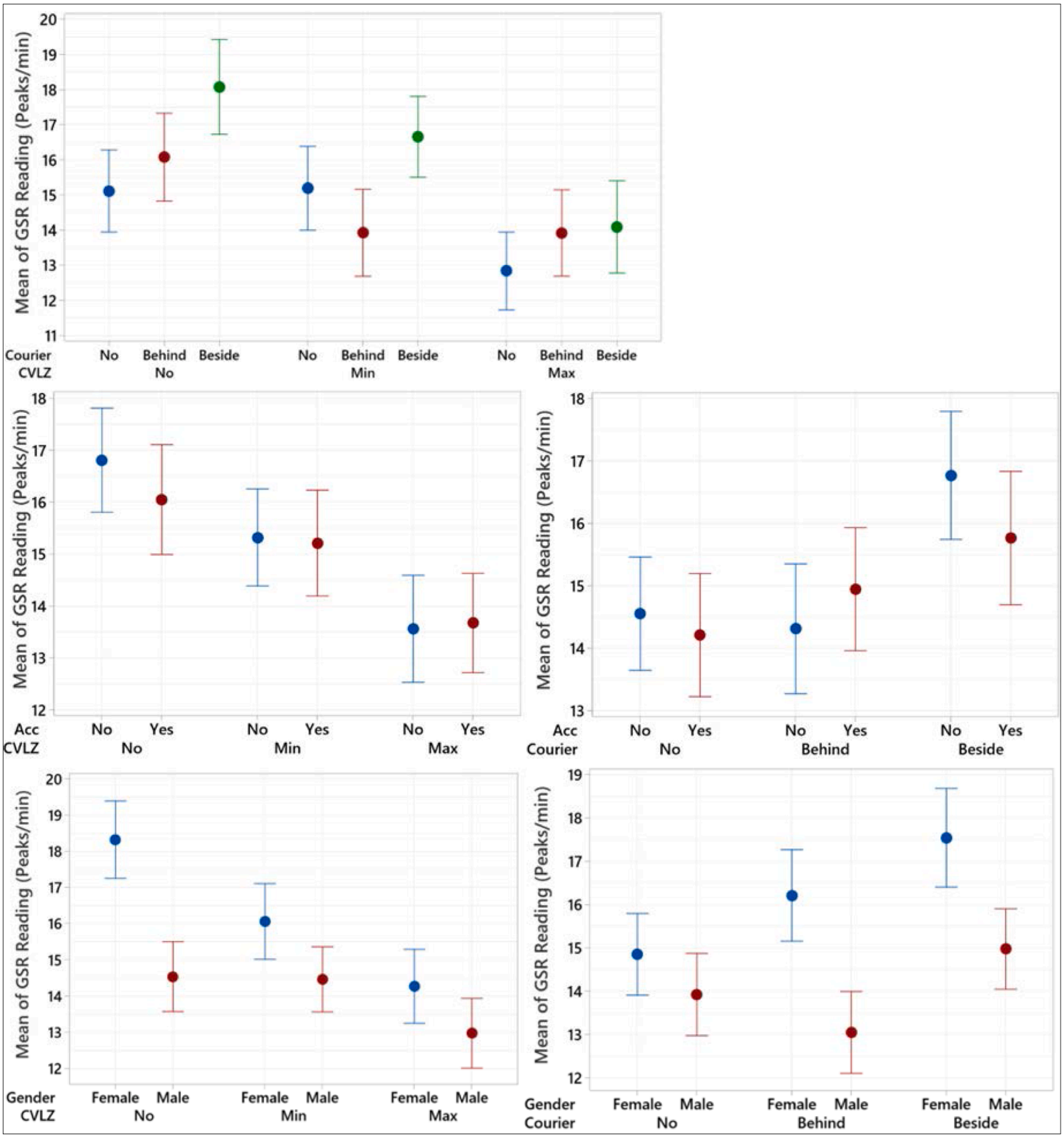

Fig. 10. Interval plots of all possible two-way interactions among variables on mean GSR reading with mean and standard error.

Table 6
Mean and Standard Deviation of TFD at treatment variable level.

Commercial Vehicle Loading Zone (CVLZ)	Descriptive Statistics	No Accessories			Hand Truck		
		No Courier	Behind	Beside	No Courier	Behind	Beside
No CVLZ	μ	0.98	0.44	0.41	0.58	0.38	0.28
	(SD)	(1.48)	(0.87)	(0.69)	(0.74)	(0.79)	(0.59)
Min CVLZ	μ	0.68	0.42	0.19	0.52	0.73	0.24
	(SD)	(0.69)	(0.66)	(0.36)	(0.72)	(0.98)	(0.44)
Max CVLZ	μ	0.54	0.20	0.11	0.32	0.26	0.12
	(SD)	(0.65)	(0.38)	(0.28)	(0.47)	(0.46)	(0.31)

placing barriers on the left side of the bike lane to prevent the interaction between bicyclists and traffic from the travel lane. Additionally, in situations where only a minimum loading zone could be designed due to space restrictions, the courier should minimize the time they occupy the bike lane to move along the vehicle and use the passenger side (i.e., similar to UPS drivers design, where they use the passenger door to load/unload the vehicle). Furthermore, policy considerations regarding the width of the bicycle lane are recommended. A study found that lateral distance deviations exceeded the width of the bicycle lane in the scenario where the truck was parked in the minimum loading zone, which indicates that bicyclists were using the traveled way (i.e., outside of the bicycle lane) to bypass or navigate around the truck, and ultimately putting themselves in unsafe scenarios (Jashami et al., 2020). If bicyclists react to this scenario and require space outside of the bicycle

Table 7
Summary of Estimated LMM Models of Total Fixation Duration (seconds).

Variable	Levels	Estimate	Std. Error	P
Participant random effect (SD)	–	(0.34)	–	<0.001*
Constant	–	0.05	0.07	0.489
Loading Zone Size	No CVLZ	0.25	0.05	<0.001*
	Min CVLZ	0.20	0.05	<0.001*
	Max CVLZ	Base	–	–
Courier Position	No Courier	0.37	0.05	<0.001*
	Behind	0.17	0.05	0.001*
	Beside	Base	–	–
Accessories	No Acc	0.06	0.04	0.138
	Acc	Base	–	–
Summary Statistics				
R2	0.24	Observations		855
−2Log Likelihood	1709.91	Participants		48
BIC/AIC	1723.40/ 1694.66	Observations/ Participant		18

* significance level is 0.05.

lane to feel safe when passing a truck, this could justify the need to increase the width of a bicycle lane when a minimum loading zone is present. Eye tracking data revealed interesting results regarding bicyclists' total fixation duration during the experiment. For instance, one possible interpretation of why bicyclists fixated more on the courier (alongside the truck scenario) is that bicyclists may have worried that they would hit the courier, so they kept glancing at the driver until the loading zone was passed. Moreover, bicyclists had lower TFD on the truck AOI when passing the maximum loading zone as compared to others. This gives bicyclists enough time to scan the surroundings while passing the maximum loading zone instead of fixating on the truck. This was reflected in the GSR results, where bicyclists felt more comfortable driving along the maximum loading zone than having a commercial vehicle parked exactly at or beside the bike lane. On the other hand, bicyclists fixated more on the truck during the minimum or no loading zone. This finding supports the GSR results, where bicyclists felt uncomfortable riding along a commercial vehicle parked exactly at or beside the bike lane. This also aligns with other studies that found that a more complex task for bicyclists (i.e., traversing an intersection when there is a left-turning vehicle) would increase their GSR level and scanning patterns (i.e., visual attention) (Scott-Deeter et al., 2023; Cobb et al., 2021). Additionally, TFD from bicyclists on the traffic AOI was relatively high. This result fits, as bicyclists were observing the traffic constantly to find a gap and use the travel lane while maneuvering around the truck or courier. This observation is consistent with other studies that identified a direct correlation between risk perception and visual attention. These studies utilized various data sources, including: (1) simulator data; (2) video data captured from the point of view of a user while riding a bicycle in a natural environment; then, the videos were watched by participants using eye tracking device; or (c) subjects participated in real-world bicycling situations while instrumented with ASL eye-tracking device (Abadi et al., 2022; Frings et al., 2014; Rupi & Krizek, 2019). To that end, prior research has not yet succeeded in quantifying perceived risk and establishing its correlation with visual attention. However, in the present study, perceived risk was assessed through GSR (i.e., a stress-level measurement) and subsequently linked with TFD. With that in mind, the triangulation of perceived risk, GSR, and visual attention in this paper offers valuable insights and highlights the potential for further investigation in future studies.

Nevertheless, the present study is not without limitations. A basic limitation of within-subject design is fatigue and carryover effects, which can cause participants' performance to degrade over the course of the experiment as they become tired or bored. The order of the grids was randomized, and the duration of the test drives was relatively brief to minimize these effects. Additionally, the visual display of the bicycle simulator used in this study did not provide a peripheral field of view for participants. While the peripheral vision was limited and bicyclists could not view the coming vehicles before they entered the loading zone, surrounding sound systems were used so bicyclists could hear traffic sounds. Additionally, the experiment was performed in a simulated environment. Although the designed scenarios were based on real-world conditions, participants might behave differently than in real life. Even with this potential source of deviation, the relative validity of scenarios provides a robust means to differentiate the experimental factors when compared to other studies. Using an instrumented bicycle experiment in an urban area with a similar setup could help validate the results of this study. The simulation and design were based on commercial vehicle parking designs in the United States and would likely have to be adjusted to be applicable to other cities and countries throughout the world. The design of the simulator was based on suburban/urban conditions and may not be applicable to all bicycling conditions integrated with commercial vehicle loading and unloading zones in many larger metropolitan cities both in the United States and throughout the world. Moreover, simulator studies are usually limited to the sample size and the number of scenarios and variables. One of the ways in which the independent variables were limited was by limiting adjacent vehicles from passing the bicyclists when transitioning across the commercial vehicle loading zones, which could be considered as a factor in future experiments. A network environment connecting both bicycling and heavy vehicle simulators would also help in the investigation of the interaction behavior between these two road users, which warrants further research.

5. Conclusions

This study was designed to examine bicyclist behavior while operating loading and unloading zones that present potential safety concerns. Performance measures of eye tracking and GSR data were collected using Oregon State University's (OSU) Bicycling Simulator, where precise measurements were recorded to better understand the behavior of participants in a simulated bicycling environment. Depending on the desired bicyclist response when approaching truck loading/unloading activities, different recommended treatments could be distinctly effective based on the output of the bicycling simulator experiment. The bicyclist's GSR reading and visual attention performance measures were used to evaluate alternative engineering treatments. Results from both devices match with each other and show that the no-loading zone condition (i.e., when truck obstructs the bike lane) and the courier on the driver's side generated a higher GSR reading and limited visual search patterns, as bicyclists are trying to shift their position toward the left edge of the bike lane and into the adjacent travel lane, while avoiding conflict with other transportation modes. The extra buffer in the CVLZ for the courier impacts bicyclists' performance measures positively; therefore, providing enough buffer for the courier to move around the vehicle is recommended. What this research shows is that the more visual attention yielded by bicyclists directly correlates with physiological responses, indicating that visual attention could be an indicator of a bicyclists' comfort level while riding. This type of result can also be seen in other areas of transportation where pedestrians may yield higher levels of stress when focusing (i.e., higher eye fixations) to find gaps in traffic while crossing the street.

In states where bicyclists are permitted to use the sidewalk for riding, access to the sidewalk should be designed to accommodate bicyclists when a delivery truck is anticipated to obstruct the bike lane due to loading/unloading activities. Thus, placing an additional curb ramp upstream of the CVLZ is recommended to allow the bicyclist to transition to the sidewalk, if legally permitted. The downside of this recommendation is the potential risk generated from the interaction between bicyclists and pedestrians.

The results from this study could support better roadway and commercial vehicle loading zone design guidelines to operate safely. For example, since the results of this paper showed that if bigger commercial

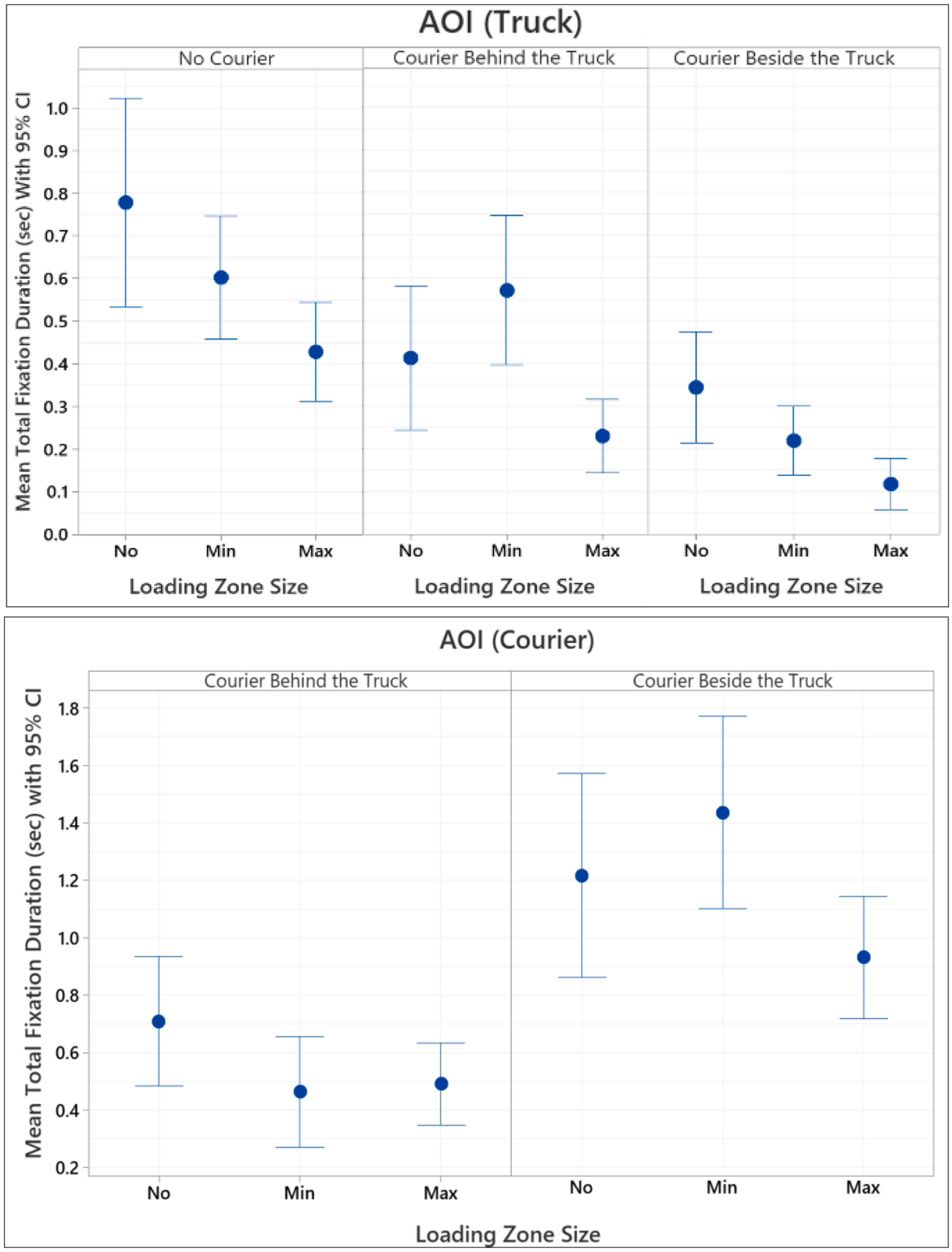

Fig. 11. Interval plot of mean total fixation duration (sec) on the parking truck (*top*) and the courier (*bottom*) across loading zone size and courier position.

vehicle loading zones are designed on urban streets, both truck couriers and bicyclists operate more safely (e.g., bicyclists and truck couriers had greater distance between each other) with less risk of conflict. However, if space is limited within the urban street, the minimum-sized commercial vehicle loading zone can be utilized, but the truck courier operations should occur to the side of the sidewalk, rather than the vehicle travelway. This will eventually allow our urban street system to operate more efficiently, safely, and reliably for all users.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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