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Assessing Perceived Safety of Non Motorized Travel with Virtual Reality

Vahid Balali, PhD
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Project 2349
May 2025

CSUTC California State University Transportation Consortium

CALIFORNIA STATE UNIVERSITY LONG BEACH

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16. Abstract
Cycling is increasingly advocated as a healthier and more sustainable mode of transportation, as reflected in both scholarly literature and policy initiatives. Nonetheless, the escalation in bicyclist crash fatalities underscores deficiencies in extant roadway designs that inadequately safeguard these vulnerable users. A persistent challenge in the examination of bicyclist safety, behavior, and comfort is the paucity of comprehensive cycling data. To enhance understanding of cyclists' behavioral and physiological responses safely and efficiently, this investigation utilizes a bicycle simulator within an immersive virtual environment (IVE). Off-the-shelf sensors are employed to evaluate cyclists' performance metrics (speed and lane position) and physiological responses (eye tracking and heart rate). Participants navigate a virtual environment scaled to resemble a real-world street with a shared bike lane (sharrows) to evaluate how the introduction of a curbside bike lane and a protected bike lane with flexible delineators affects perceptions of safety, as well as cyclists' behavior and physiological responses. Data collected from 50 participants (across a diverse range of ages and genders) indicate that the protected bike lane design received the highest safety ratings and resulted in the lowest average cycling speed. Both the curbside bike lane and protected bike lane scenarios manifested in more focused gaze patterns than the sharrows scenario, implying that cyclists were more concentrated on the task when biking in designated lanes rather than sharing the roadway with vehicles. Furthermore, heart rate data imply that dedicated bike lanes (curbside or protected) may alleviate cyclists' stress levels. Female participants exhibited a particular preference for the protected bike lane design.

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Executive Summary

This research examines the efficacy of an Immersive Virtual Environment (IVE) bicycle simulator in clarifying bicyclists' physiological and behavioral responses to varied urban roadway configurations. The study employs a bicycle simulator augmented with mobile sensing devices to document the cyclists' behavioral and physiological responses on identical roadways replicated with three distinct configurations: shared bike lanes (implemented as sharrows or as-built), curbside bike lanes, and protected bicycle lanes with flexible delineators. The findings suggest that the IVE bicycle simulator serves as an effective and safe tool for analyzing cyclists' behavior and assessing roadway designs, thereby offering significant insights for enhancing the built environment. The outcomes of this study will provide an essential resource for human factors researchers, transportation engineers, and software developers in the design, development, and evaluation of pedestrian-to-vehicle interactions within connected environments, aimed at improving the safety and efficiency of these technologies for practical implementation.

1. Introduction and Background

Bicycling, as a traditional form of transportation, has experienced a revival in recent years as an adaptive measure to address urban challenges such as traffic congestion, land utilization issues, elevated energy consumption, air pollution, climate change, and physical inactivity (Flusche, 2012; Rupi & Krizek, 2019). This trend persisted during the COVID-19 pandemic, with substantial increases in bicycling activities observed across numerous countries, notwithstanding lockdowns and travel restrictions (Buehler & Pucher, 2021). Nonetheless, there has been an alarming increase in bicyclist fatalities over the past decade. According to the National Highway Traffic Safety Administration, fatalities among U.S. bicyclists have surged by over 35% since 2010 (National Highway Traffic Safety Administration, 2021).

A contributing factor to this increase may be attributed to the auto-centric design of many U.S. roadways, which frequently disregard the safety and comfort of vulnerable road users such as cyclists (Schultheiss et al., 2018). Despite advancements in vehicle safety for occupants through both active (e.g., electronic stability control, automatic emergency braking) and passive (e.g., seat belts, airbags) safety measures, specific design modifications intended to augment comfort—such as reduced window sizes, wider pillars, and larger headrests—may unintentionally heighten risks for other road users, including cyclists. A study examining 3,350 motor vehicle-bicycle collisions in the U.S. discovered that these vehicle design characteristics contributed to elevated crash risks for cyclists (Lusk et al., 2015). Furthermore, these safety technologies do not avert "looked-but-failed-to-see" errors, in which drivers fail to detect cyclists in sufficient time to prevent a collision (Herslund & Jørgensen, 2003; Koustanaï et al., 2008).

Furthermore, existing data sources regarding bicyclist safety exhibit significant limitations. Police crash reports predominantly emphasize vehicle-bicycle collisions resulting in fatal outcomes, whereas hospital data has recently gained prominence for offering real-world injury data from diverse accident scenarios, including single-bicycle crashes (Myhrmann et al., 2021). A study utilizing ambulance records in North America determined that cycle tracks were safer than roadway cycling, evidenced by a 28% injury rate, despite accommodating 2.5 times the number of cyclists compared to parallel roads lacking bicycle provisions (Lusk et al., 2011). Investigations into bike lane designs also indicate that various treatments can affect cycling behavior. For instance, research conducted in the Netherlands revealed that for older cyclists, shoulder and edge strip treatments facilitated safer distances from the verge and enhanced path efficiency (Westerhuis et al., 2020). A comparative analysis involving 70 young adults across five European cities demonstrated that physical separation between cyclists and vehicles alleviated stress levels (Teixeira et al., 2020). Even within protected bike lanes, differing degrees of separation can lead to varying risk levels for cyclists (Cicchino et al., 2020). While these studies underscore the critical importance of comprehending how roadway designs affect cycling behaviors and emotional responses, a considerable gap persists in research and data sources necessary for assessing the safety and comfort of vulnerable road users, particularly cyclists.

The insufficiency of pertinent data has been recognized as a primary constraint in numerous transportation and urban planning studies, especially those concentrating on bicyclists (Willberg et al., 2021). Consequently, it is imperative to formulate innovative methodologies to comprehensively understand the impact of diverse roadway conditions on bicyclists' behavior, perceived safety, and comfort during the design and planning stages. To achieve this, it is essential to examine and assess bicyclists' behavioral and psycho-physiological data across different roadway contexts.

A multitude of methodologies have been employed to gather data regarding bicycle safety, risk, comfort, and behavior, encompassing surveys, observational studies, naturalistic studies, and simulation studies. For example, interviews and surveys customarily inquire about participants' behaviors and comfort within specific design contexts, grounded either in their actual experiences or through hypothetical scenarios. Nevertheless, such subjective responses may not precisely depict participants' actions in real-world settings and are susceptible to hypothetical bias (Fitch & Handy, 2018). Observational studies, although effective in capturing real-world environmental changes and cyclists' reactions, do not facilitate the monitoring of physiological changes (Chidester & Isenberg, 2001). Naturalistic studies, employing instruments such as GPS, ECG, or mobile eye trackers to observe cyclists in real-world conditions, furnish more comprehensive data but entail potential risks for participants, including exposure to hazardous roadway scenarios or high-traffic regions (Stelling-Konczak et al., 2018). Furthermore, naturalistic studies encounter challenges in controlling environmental factors that may affect the outcomes, particularly concerning physiological and behavioral data, thereby complicating causal inferences (Fitch et al., 2020; Teixeira et al., 2020).

A nascent approach involves the employment of Immersive Virtual Environments (IVEs) for experimental studies, which mitigate hypothetical bias and offer a controlled, low-risk environment to evaluate cyclists' reactions to various roadway designs and conditions. Nonetheless, a principal challenge in previous IVE simulation studies has been the integration of human sensing techniques. Although IVE-based research has utilized physiological sensing to evaluate responses to designs for buildings (Francisco et al., 2018), hospitals (Chías et al., 2019), and other infrastructure systems (Awada et al., 2021), only a limited number of recent studies have incorporated physiological sensing for cyclists in IVE simulators (Cobb et al., 2021). A more exhaustive understanding of cyclists' psychological and physiological responses to diverse roadway designs and conditions remains necessary.

Despite some naturalistic investigations aimed at evaluating cyclists' behavior and physiological responses across varying contexts, these initial studies have already provided valuable insights (Guo et al., 2022; McNeil et al., 2015; Rupi & Krizek, 2019; Teixeira et al., 2020). In particular, psycho-physiological metrics such as heart rate (HR), gaze variability, and skin conductance have been identified as crucial indicators of potential alterations in cyclists' behaviors and perceptions in response to varying environmental conditions.

This investigation employs a bicycle simulator in conjunction with an immersive virtual environment (IVE) to overcome limitations identified in prior studies. Specifically, this study uses a repeated-measures experiment to assess bicyclists' physiological responses—specifically gaze variability and HR—in various urban roadway configurations. The utilization of IVE affords precise manipulation of environmental variables such as infrastructure design, traffic density, signal timing, vehicle velocity, classification, illumination, and meteorological conditions. This facilitates a more accurate examination of the relationships between bicyclists' behaviors (e.g., velocity, lane positioning) and physiological responses (e.g., gaze variability, HR). The data obtained serve as proxies to enhance understanding of how differing roadway conditions and infrastructure designs impact physiological stimulation levels.

In this study, we integrate human sensing instruments, such as wearable devices, with a bicycle simulator within an IVE to assess and model the psychophysiological and behavioral responses of bicyclists. We examine three roadway design scenarios: shared bike lanes (sharrows), conventional curbside bike lanes, and protected bike lanes with flexible delineators. For each scenario, HR, gaze variability, and speed are measured. Following comprehensive feature extraction from HR and gaze data, linear mixed-effects models are employed to compare the responses of bicyclists across the simulated environments.

The research encompassed a cohort of 50 individuals (23 females, 27 males; aged 18–68; comprising both students and faculty) and investigated the subsequent research inquiry: In what manner can protected or curbside bike lanes augment bicyclists' experiences concerning perceived safety, cycling behavior, and psychophysiological responses? The results illuminate the participants' subjective and objective predilections towards various forms of bicycle infrastructure. These outcomes offer practicable insights for policymakers endeavoring to enhance cycling experiences and potentially augment bicycle usage in various urban contexts.

This research commences with a comprehensive review of prior studies on bicycle safety conducted in naturalistic, simulated, and virtual reality (VR) settings. Subsequently, the investigation delves into how the physiological responses and gaze measurements of bicyclists can be utilized to enhance the understanding of their behaviors and physiological conditions, such as stress levels and cognitive load. The study then delineates the methodology of our experimental design, providing a detailed account of the experimental procedures. The results, comprising cyclists' HR, gaze variability, and cycling performance within each setting, are analyzed utilizing a linear mixed-effects modeling approach. Ultimately, the study concludes with a discourse comparing the observed physiological responses and scrutinizing the factors influencing the findings.

2. Literature Review

This section is categorized into comprehensive literature reviews of diverse studies concerning bicyclists' behavior, encompassing stated preference surveys, naturalistic observational studies, and bicycle simulator studies.

2.1. Stated Preferences Surveys

Surveys have been extensively employed to analyze the behavior of bicyclists, particularly in instances where empirical data is insufficient. When meticulously designed, surveys can effectively evaluate large cohorts of bicyclists and have been utilized to examine a diverse array of topics, including perceived safety and comfort (Chaurand & Delhomme, 2013; Abadi & Hurwitz, 2018). For example, Chaurand and Delhomme (2013) investigated the perceived risk of bicyclists and drivers in specific interactions. Their findings indicated that perceived risk is greater for drivers compared to bicyclists. Furthermore, the perceived risk for bicyclists is higher when interacting with a car than with another bicycle. Another study examined the perceived level of comfort of bicyclists near urban truck loading zones, considering varying conditions of truck traffic, bicycle lane marking types, and traffic signs (Abadi & Hurwitz, 2018). The results suggest that the presence of trucks in traffic significantly diminishes bicyclists' perceived comfort. Additionally, the study reveals that women are generally more affected by truck traffic than men.

Although these studies considerably enhance our comprehension of the impact of contextual settings on bicyclists' perceived risk and comfort, they are often plagued by challenges such as constraints on external validity. For example, these studies may be affected by an intention-behavior gap, wherein participants' survey responses may not accurately reflect their actual responses in a naturalistic setting (Fitch & Handy, 2018). Specifically, Fitch and Handy (2018) reported that imagined ratings of comfort while biking may exhibit a negative bias, reaching a differential of up to 15% in comfort and safety compared to real-world situations. Moreover, surveys and subjective measures generally do not facilitate an understanding of the temporal dimension of the effects of specific contextual elements on bicyclists. For instance, concerning perceived comfort, it is difficult to ascertain the exact moment a bicyclist experiences discomfort or the degree to which discomfort varies among different individuals and locations. In contrast, physiological measures may serve as surrogate metrics to comprehend the duration of the effects of contextual elements on participants. Surveys are also employed to assess self-reported rates of crash involvement and the consequences thereof (including the benefits of cycling for physical and mental health and potential health repercussions of crash involvement), supplementing official crash reports (Robartes & Chen, 2018; Myhrmann et al., 2022).

2.2. Naturalistic Studies

The advancement of mobile sensing technologies has facilitated the collection of mobility data from a wide range of modalities. Within this domain of research, numerous naturalistic studies have explored bicyclists' behaviors and physiological responses, such as HR, heart rate variability (HRV; Doorley et al., 2015), and gaze (Rupi & Krizek, 2019). For instance, variations in ambient light levels can influence bicyclists' environmental perception by altering gaze reactions (Uttley et al., 2018). These studies provide preliminary evidence regarding the relationship between infrastructure design and cycling stress; however, variations exist across different cities and road types (Fitch et al., 2020; Teixeira et al., 2020). In the study conducted by Fitch et al. (2020), using a BodyGuard II heartbeat-to-beat interval measuring device, the HRV outcomes from 20 female participants indicated that only local roads (without a dividing yellow line and characterized by low car speed and volume) consistently offered reduced stress to participants in comparison to collector roads (medium- to high-volume roads with striped traffic division) and arterial roads (high-volume, multi-lane). A limitation noted in the study is the exclusion of environments with protected or curbside bike lanes, thereby preventing the results from indicating comparisons between those designs and existing ones (Fitch et al., 2020). The absence of environmental control (e.g., traffic, weather, etc.) may be the primary source of uncertainty, undermining the results' interpretability and highlighting the need for further research.

Moreover, only a limited number of human sensing devices are applicable in naturalistic settings due to their invasive nature. For example, electroencephalogram (EEG) measurement devices are more suited for laboratory testing. This has implications for participants' behavior and safety, potentially leading to compromised data quality. Finally, the potential risks associated with injuries and fatalities pose ethical concerns for naturalistic studies. For instance, Stelling-Konczak et al. (2018) conducted a study in real traffic settings examining teenage bicyclists' glance behavior while listening to music. That study was terminated after fourteen participants when findings showed that a notable percentage of participants cycling with music exhibited diminished visual performance (Stelling-Konczak et al., 2018).

2.3. Bicycle Simulators

The progress in VR and bicycle simulation over the last decade has resulted in a significant increase in their utilization by researchers, designers, and engineers for assessing human responses to alternative infrastructure designs. The integration of immersive virtual environments (IVE) and instrumented physical bicycle simulators offers a high degree of immersion and flexibility in experimental designs. Additionally, it facilitates user engagement and permits the subjective analysis of participants to gain a deeper understanding of their behavior and preferences concerning changes in simulated environments (Nazemi et al., 2021). For example, Xu et al. (2017) evaluated the behaviors of 30 participants within an IVE by designing a straight path with four sections featuring varying traffic conditions. The outcomes of this experiment suggested that the presence of a bike lane under low traffic conditions notably enhanced cyclists' lane-keeping performance

(Xu et al., 2017). A more recent study explored cycling behaviors in an IVE between a keyboard-controlled bicycle and an instrumented bicycle that allowed participants to pedal. The findings revealed greater variance in the instrumented bicycle experiments across various measurements, including speed, head movement, acceleration, and braking behaviors (Bogacz et al., 2020). Validation studies were also conducted to compare bicycling behavior between IVE bicycle simulators and naturalistic studies (O'Hern et al., 2017). Despite the limited number of validation studies, promising results have been demonstrated regarding the validity of cycling performance metrics such as lane position and speed (O'Hern et al., 2017). However, most studies related to IVE are predominantly focused on observing cycling behaviors and preferences without exploring the psychophysiological responses of cyclists.

3. Methodology

The objective of this project was to examine cyclist safety by developing a controlled experimental platform utilizing a stationary bicycle and a virtual reality headset. Participants were able to experience a simulated road environment through the use of a Head Mounted Display (HMD) while pedaling on a bicycle that transmitted data in real time to the simulation. This configuration facilitated the analysis of cyclist responses to various traffic scenarios, bicycle infrastructures, and environmental stimuli without exposing them to danger.

The methodological approach of this study involved the utilization of a bicycle simulator in conjunction with an immersive 360-degree VR headset. A unisex city bicycle was mounted on a bicycle stand, which imparted resistance during cycling activities. This bicycle was outfitted with a comprehensive set of rotation sensors affixed to the rear wheel, pedal, brake, and handlebar, facilitating the translation of bicyclists' movements into the VR environment. Each rotation sensor comprised a compact microcontroller, a gyroscope, Bluetooth capability, and a lithium-ion battery. Within the confines of this experiment, the steering sensor located on the handlebar was rendered inactive due to its propensity to induce severe motion sickness, thereby restricting bicyclists to linear movement. Immersive virtual reality was delivered via an HMD equipped with positional tracking capabilities; the virtual environment was dynamically rendered contingent upon the respondent's position, thereby mitigating motion sickness and enhancing the realism of the VR experience. Additionally, the design permitted the wearing of glasses beneath the HMD. The sensors affixed to the bicycle discharged electrical signals to an Arduino unit, which processed the information and subsequently transmitted it to the computational model. The model then utilized Unity simulation to process this data, maintaining connectivity with the HMD.

Participants completed a questionnaire both prior to and following the bicycling simulation in VR. This methodology ensured uniform conditions for all participants, allowing the experiment to be replicated under identical circumstances for each individual. Participants navigated through diverse virtual environments, which facilitated their comprehension of the theoretical designs before responding to inquiries. The study included four Likert scale questions assessing the participants' willingness to bicycle in each environment and five Likert scale questions appraising the perceived safety level, which were repeated after each scenario to gauge the subjective perceptions of the riders. Participants were encouraged to contemplate their cumulative experiences throughout the experiment; they were furnished with their previous responses to the perceived safety questions, enabling them to provide relative assessments and adjust their ratings upon completing each environment. This feature was specifically designed to address the inherent challenge of descriptive surveys, where scales are typically constructed in absolute terms (i.e., independent Likert responses), yet participants, either consciously or unconsciously, tended to report scores relatively by referencing their subsequent scores to the preceding ones.

The projected outcome of this research initiative was the development of a system that facilitated the systematic observation and assessment of cyclists' behavior, thereby offering a secure and effective mechanism for conducting studies on cyclist safety, training, and rehabilitation. The findings of this research were intended to serve as a vital resource for human factors researchers, transportation engineers, and software developers in the design, development, and evaluation of pedestrian-to-vehicle interactions within connected environments, in order to enhance the safety and efficiency of these technologies for practical implementation.

To address the interaction of pedestrians with vehicular systems, the objective was to simulate an environment where participants could engage with vehicles without the inherent safety hazards of real-world experimentation, using VR technologies. Specifically, this research sought to examine pedestrian behavior in settings where they had to traverse a midblock crosswalk while interacting with various forms of connected vehicle technologies or in the absence of such technologies, including the previously mentioned integrated mobile phone application. Moreover, this study intended to modify these interactions by altering several experimental conditions, such as the presence of an autonomous vehicle without a driver. Pedestrians' actions were systematically observed and assessed based on the timing and manner of their crossing, their physiological responses (measured via integrated biometric scanners), and through the administration of a post-experiment questionnaire designed to gauge pedestrians' perceptions of safety, their acceptance of technology, and their levels of engagement with vehicular systems.

3.1 Experimental Design

This study examines the effects of various roadway configurations on the physiological states of bicyclists, employing an IVE and a bicycle simulator. The independent variables encompass demographic factors (age, gender, bicycling attitude, and experience with virtual reality), the perceived realism of the IVE, and three categories of roadway design:

- Constructed shared bicycle lane settings (sharrows)
- Curbside bike lane
- Bicycle lanes safeguarded by pliable demarcation devices

The dependent variables examined in this study include the following:

- Perceived Safety Ratings, obtained via surveys;
- Cycling Performance Metrics, encompassing speed and lane position;

- Eye-tracking outputs, comprising gaze variability, percentage of road center fixation, mean fixation duration, and gaze entropy, all evaluated for gaze distribution and potential distractions;

- Heart Rate Metrics, consisting of mean heart rate and heart rate change points, are analyzed to assess stress levels.

The study tests the following hypotheses:

- **Hypothesis 1:** Variations in perceived safety ratings are anticipated across different bike lane infrastructure designs.

- **Hypothesis 2:** The design of bike lane infrastructure will impact the lateral positioning within lanes as well as the speed of cycling.

- **Hypothesis 3:** The introduction of curbside and protected bike lane configurations will augment gaze concentration directed towards the bicycling activity, thereby suggesting an elevation in attention and focus within these particular settings.

- **Hypothesis 4:** Stress levels, quantified through heart rate measurements, will exhibit variation among participants cycling in curbside or protected bike lanes, as opposed to those cycling in sharrows.

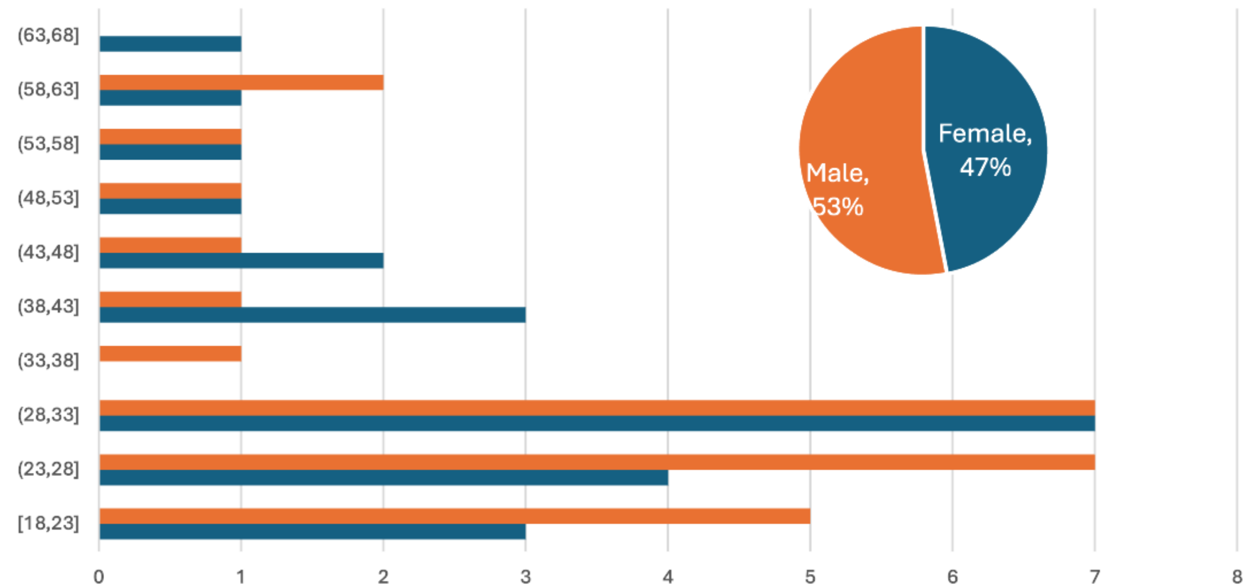
- **Hypothesis 5**: Age and gender may have an impact on the preference for types of infrastructure, but they do not affect cycling behavior and psychophysiological responses.

Through the examination of these variables and hypotheses, this study seeks to elucidate the influence of roadway designs on the safety perceptions, behavior, attention, and stress levels of bicyclists within urban cycling contexts.

3.2 Participants

A cohort of 51 individuals was enlisted for the experiment. The majority comprise local cyclists, university students, and faculty members acquainted with the study corridor. All participants are aged 18 years or older and do not exhibit color blindness. During the course of the study, one individual was unable to complete the experiment due to motion sickness. Consequently, data from 50 participants were analyzed, consisting of 23 females and 27 males. The mean age of these participants is 34.1 years with a standard deviation of 12.9 years, although one participant did not disclose age information; the age distribution is depicted in Figure 1. A significant proportion of participants are habitual cyclists. Among the 25 participants who declared precise biking distances, the self-reported weekly biking distance spans from 0.5 miles to 60 miles, with an average distance of 15.1 miles.

Figure 1. Age and Gender Distribution of Participants



	[18,23]	(23,28]	(28,33]	(33,38]	(38,43]	(43,48]	(48,53]	(53,58]	(58,63]	(63,68]
Male	5	7	7	1	1	1	1	1	2	0
Female	3	4	7	0	3	2	1	1	1	1

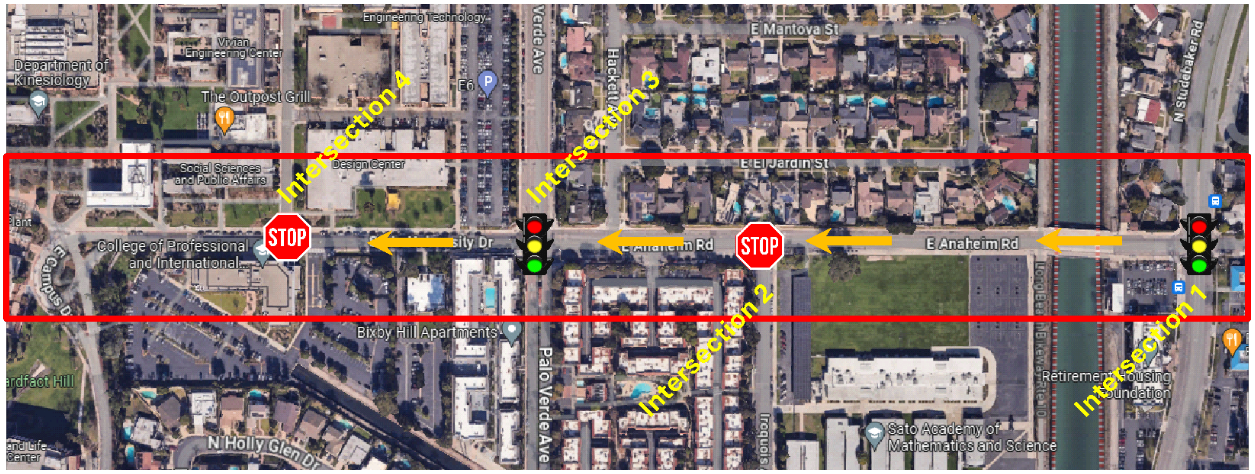
3.3 Road Environment and Alternative Designs in IVE

A pilot study was conducted to benchmark participants' cycling behaviors and performance across both a real-world setting and an equivalent IVE. A within-subjects design was implemented to control for variability between subjects. The IVE was carefully constructed to be a precise 1:1 scale representation of the real-world environment.

The selected study corridor comprises East Anaheim Road, spanning from North Studebaker Road to East Campus Drive in Long Beach, California (Figure 2). This segment is heavily utilized by cyclists and has been classified as high-risk for vulnerable road users. In the process of developing the IVE model, the scale of the road, adjacent buildings, and various roadway design elements (e.g., markings, and traffic signals) were calibrated to achieve an accurate 1:1 representation.

The designated area consists of two city blocks characterized by specific attributes: a 4% downward gradient in the westbound direction, shared lane markings present in both directions, a traffic signal located at the intersection of North Studebaker Road and Palo Verde Avenue, and the presence of a parking lane in the eastbound direction.

Figure 2. Illustration of Experimental Area



In order to precisely simulate traffic flow patterns and collect empirical data on the current conditions of operation, the research team systematically gathered roughly two weeks of video surveillance data at the designated corridor. This process entailed documenting the quantity of automobiles and other road users traversing the corridor, as well as recording their velocities. Upon obtaining authorization from the City of Long Beach and California State University, Long Beach, a total of four cameras were strategically positioned along the East Anaheim Road corridor to obtain the requisite visual recordings.

The research team concentrated on peak traffic periods, specifically from 7:00 to 9:00 AM and 4:00 to 6:00 PM. During these intervals, they meticulously analyzed the recorded footage to document traffic volumes. These documented traffic volumes played a pivotal role in the formulation of the IVE settings, which facilitated the simulation of realistic traffic patterns, encompassing both the quantity and velocity of vehicles within the IVE environment.

An initial experimental trial was executed in collaboration with the research team and transportation experts from California State University, Long Beach. Their role was to assess the authenticity of the IVE model and to furnish suggestions for enhancements. Figure 3(a) depicts a Google Maps representation of the corridor, whereas Figure 3(b) illustrates the corresponding IVE configuration.

Figure 3. Comparison of Real Road (a) and IVE (b) Environments; Video Collection System of IVE Bike Simulator (c); Heart Rate Distribution of Experiment (d)

3.4 Data Collection

This section delineates the selection of hardware components for both simulators. Figure 3(c) depicts the configuration of each simulator. Both simulators are furnished with HTC Vive Pro VR headsets along with their respective controllers. Table 1 presents a cost analysis of the IVE framework in relation to a comparable empirical road test.

Table 1. Cost Comparison Between the IVE and Naturalistic Studies

Cost	IVE	Real Road Test
Environment Building	$3,500	Thousands to millions for road reconstruction
Additional Bicycle Components	$1,200 (Wahoo Kickr Climb + Wahoo Kickr Headwind + Wahoo Kickr Smart Trainer + ANT)	$500 (Smartphone + software)
Headset	$1,500 (HTC VIVE Pro EYE)	> $10,000 (Eye Tracking Glasses Like SMI or Smart Eye Pro)
Cameras	$50 (2 web cameras, $25 each)	$700 (2 GoPros, $350 each)
Eye-Tracking Software	Free (Tobii Pro Unity SDK + Self-Developed Code)	$1,300 per year (iMotion academic)
Video Recording & Integration	Free (open-sourced OBS studio)	Video integration requires a lot of label work
Safety Concerns	Very low	Potential risk to researchers & participants in the real road environment

The IVE-based framework provides considerable cost efficiencies in terms of hardware and planning, while concurrently mitigating safety concerns for test subjects. At the time this experiment was conducted, the initial setup cost for the virtual environment was estimated to be approximately $3,500. This amount encompasses $1,500 for the HTC Vive Pro Eye inclusive of controllers and base stations, and an additional $50 allocated for two web cameras employed for the collection of room video data. The software utilized for the integration of all virtual reality videos is OBS Studio, which is an open-source solution that incurs no cost for research purposes. For eye-tracking functions within the IVE, the Tobii Pro Unity SDK was implemented, which is also available at no cost for research purposes. The researchers created comprehensive documentation and illustrative code examples to facilitate the configuration and retrieval of eye-tracking data from the HTC Vive Pro Eye.

The following equipment was specifically chosen for the bicyclist simulator:

1) The Wahoo Kickr Smart Trainer is a power measurement system with a precision of ± 2%, ensuring accurate and realistic resistance feedback.

2) The Wahoo Kickr Climb is an innovative adaptive simulator, designed for real-time indoor cycling, which attaches to the bicycle's front fork. It precisely adjusts the elevation of the bicycle's front end in accordance with the gradient of simulated road conditions.

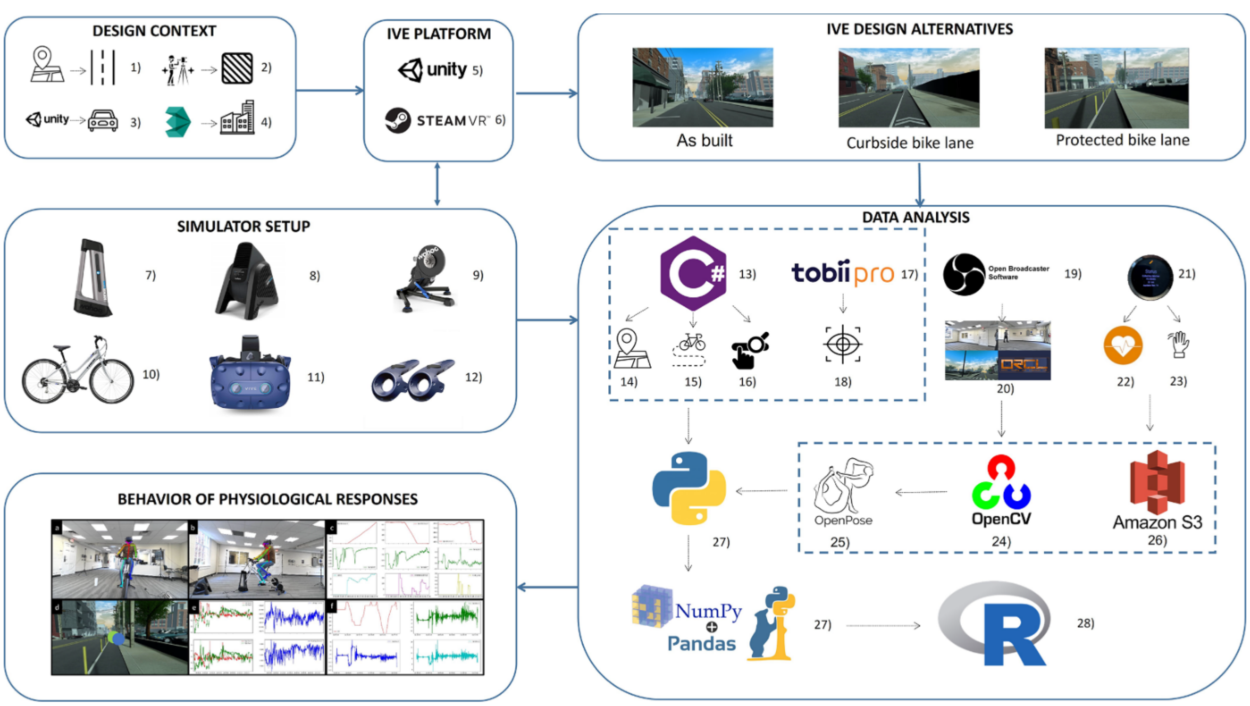
3) The Wahoo Kickr Headwind is an adaptive vortex fan with variable speed capabilities in real-time, designed to replicate the wind speeds encountered by cyclists on the road.

4) ANT+ is a wireless communication protocol employed for the transmission of data between Wahoo training equipment and a desktop computer.

5) The Trek Verve bicycle serves as the foundational structure of the cycling simulator.

The data collection framework and system architecture designed to evaluate cyclists' behaviors and physiological responses are illustrated in Figure 4. The IVE bike simulator utilizes HTC Vive Pro Eye headsets in conjunction with complementary controllers to observe interactions within the IVE environment. This virtual reality headset features an integrated Tobii Pro eye tracker with movement-tracking capabilities, ensuring a seamless integration in comparison to traditional eye-tracking systems, such as screen-based systems or eye-tracking glasses. The spatial configuration of the controllers, attached to the handlebars, enables the system to determine actions such as turning and braking.

Figure 4. System Architecture and Data Framework



The VR environments were meticulously designed and programmed utilizing the Unity platform and were operated through the Steam VR interface. Employing Unity's C# scripting capabilities, comprehensive tracking and data extraction of headset and controller movements were achieved. For the experimental framework, a Trek bicycle equipped with instrumentation was implemented and interfaced with Unity through the Wahoo indoor cycling training apparatus. This configuration facilitated the acquisition of real-time data regarding velocity, instantaneous power output, and distance traversed, while also providing participants with haptic feedback.

In addition, two external video recording devices were used to capture the movements of participants during the IVE experiments. These recordings facilitated the monitoring and analysis of participants' movements and reactions. The participants' perspective within the IVE was recorded utilizing OBS Studio software, which synchronized all videos with consistent timestamps and frames per second. Moreover, two Android smartwatches, installed with the "SWEAR" application, were utilized to monitor participants' physiological signals, including arm movement and heart rate.

3.5 Data Processing

This section elucidates the data preprocessing procedures necessary for extracting valid information, inclusive of time synchronization and feature extraction for modeling purposes. Data procured from various sensors are operational at divergent frequencies, thus necessitating distinct resampling for each sensor:

- Cycling performance and video data were resampled to 30 Hz.
- Eye-tracking data underwent resampling at 120 Hz.
- HR data were resampled to 1 Hz.

The entirety of the data was curtailed to encompass only the interval from the commencement of participants' pedaling to their passage through the third intersection in the IVE. Subsequently, the process entailed integrating the raw 3D gaze direction data from the eye tracker with the point-of-view videos. This transformation transmuted the 3D gaze directions into 2D coordinates within the video, thereby allowing for visualization of participants' observational foci in the virtual environment. As depicted in the lower left of Figure 4, the green and blue dots delineate the gaze points for the left and right eyes respectively. The preprocessing scripts pertinent to eye-tracking data are available publicly online (Guo, 2022) to promote transparency and reproducibility.

3.5.1 Gaze Entropy

Two distinct types of gaze entropy measures have been identified: stationary gaze entropy (SGE) and gaze transition entropy (GTE). SGE offers an evaluative metric for the predictability of fixation locations, thereby reflecting the extent of gaze dispersion throughout a specified viewing interval (Shiferaw et al., 2019). The calculation of SGE is performed utilizing Eq. (1):

$$H(x) = -\sum_{i=1}^{n} (p_i)(p_i) \quad (1)$$

H(x) represents the SGE value for a sequence of data x with a specified length n, with i serving as the index for each distinct state, and p_i denoting the proportion of each state within x. The computation of the SGE necessitates the partitioning of the visual field into spatial bins corresponding to discrete state spaces to establish probability distributions. The coordinates are particularly segmented into spatial bins measuring 100 × 100 pixels. To determine the trend of the SGE, it is computed within a rolling window spanning one second (comprising 120 data points within the gaze raw data).

GTE is obtained through the application of the conditional entropy equation to first-order Markov transitions of fixations, utilizing the subsequent equation:

$$H_c(x) = -\sum_{i=1}^{n} (p_i)\sum_{i=1}^{n} p(i,j)p(i,j) \quad (2)$$

In this context, $H_c(x)$ represents the value of GTE, and p(i, j) denotes the probability of a transition occurring from state i to state j. The definitions of the additional variables remain consistent with those provided in SGE Equation (1).

3.5.2 Heart Rate Change Point Detection

In order to examine abrupt variations in bicyclists' HR, a Bayesian Change Point (BCP) analysis was conducted. An increase in HR is frequently linked to heightened stress levels, anxiety, or negative emotions. Through the application of change point detection to the HR time series, specific instances were identified that correspond to elevated stress levels during the biking scenarios. This methodology is grounded in preceding studies that employed BCP for HR analysis (Tavakoli & Heydarian, 2021; Tavakoli et al., 2021; Guo et al., 2022).

The analysis utilized the BCP model as introduced by Barry and Hartigan (1993), which presumes a constant mean in the dataset while identifying junctures where the mean exhibits alterations. This model was implemented in the R programming environment (R Core Team, 2013) utilizing the BCP package (Erdman & Emerson, 2007), facilitating robust and reliable detection of HR change points. This methodology offers insights into the physiological responses of bicyclists under varying roadway design scenarios.

3.6 Statistical Modeling

A Linear Mixed Effects Model (LMM) was employed to examine the response variables among participants. The LMM was considered suitable for this study due to its capacity to accomplish the following: formally delineate both group-level and individual behavior patterns; account for variability between and within participants, thereby acknowledging group and individual differences; and integrate additional covariates to augment the robustness of the analysis (Krueger & Tian, 2004). This methodological approach enables a more nuanced comprehension of the factors influencing bicyclists' behavior and physiological responses in the virtual environment.

The LMM is designed to capture variability among participants (Brown, 2021; Fox, 2002). Analogous to simple linear regression, an LMM estimates fixed effects, including the influence of varying roadway scenarios on participants' HR or gaze metrics. Furthermore, LMM integrates random effects to accommodate individual differences among participants.

For instance, the impact of a bicycle lane on HR may vary among participants—one participant may encounter a 20% increase in HR, whereas another may experience only a 10% increase. By incorporating both fixed and random effects, Linear Mixed Models (LMM) offer an in-depth analysis that encompasses group-level trends as well as individual variability. An LMM is delineated as:

$$y = X\beta + bz + \in \tag{4}$$

In Equation (4), the dependent variable, denoted as y, may include measures such as heart rate or gaze. The matrix X represents the predictor variables, while β signifies the vector of fixed-effect regression coefficients. The matrix b encapsulates the random effects, and z is the set of coefficients corresponding to each random effect. The term $\in$ refers to the error term associated with unexplained residuals. Furthermore, the constituents of both the b and $\in$ matrices are as follows:

$$b_{ij} \sim N(0, \omega_k^2), (Cov(b_k, b_{k'})) \tag{5}$$

$$\in_{ij} \sim N\left(0, \sigma^2 \gamma_{ijj}\right), \left(Cov\left(\epsilon_{ij}, \epsilon_{ij'}\right)\right) \tag{6}$$

The LMM is utilized through the application of the lme4 package in R, as documented by Bates et al. (2007).

In order to evaluate participants' physiological responses across diverse roadway environments, a variety of behavioral and physiological measures were structured as dependent variables within distinct LMMs as detailed in Table 1. These dependent variables consisted of:

- cycling performance, encompassing speed, and lateral lane position;
- eye tracking metrics, including SGE (Spatial Gaze Entropy);
- GTE (Temporal Gaze Entropy);
- PRC (Percentage of Road Center Fixation) and mean fixation length; and

HR metrics, comprising mean HR and the number of HR change points.

The independent variables encompassed the following:

- the design of roadway infrastructure, which included the as-built shared lane (sharrows), curbside bike lane, and protected bike lane;
- demographic factors, namely age group (classified as either younger or older than 35) gender; and cycling attitude, which was inferred from pre-survey responses;
- prior experience with virtual reality, determining whether participants had previous experience with virtual environments; and

perceived realism, which refers to participants' perception of realism regarding bicycle speed and braking within the IVE.

The models were further developed to incorporate interactions between age and gender with roadway design, aiming to discern potential demographic variations. Each participant was considered as a random effect to accommodate individual variability.

For any statistically significant effects identified in the LMMs pertaining to roadway design, post hoc comparisons were executed utilizing Fisher's Least Significant Difference (LSD) test for handling multiple comparisons (Williams & Abdi, 2010). The entirety of the statistical analyses was performed with a 95% confidence interval ($\alpha = 0.05$).

3.7 Performance Metrics and Analysis

In order to assess the validity of the IVE bike simulator across varying contextual environments, performance data were independently analyzed for distinct road segments. As depicted in Figure 2, Road Segment 1 extends over the area between Intersections 1 and 2 and encompasses a 4% downhill gradient, accompanied by a wall on the right-hand side obstructing the view of the parking lot. In contrast, Road Segment 2 consists of a level road with a parking area openly visible to cyclists.

As illustrated in Figure 3, the subsequent metrics were quantified as indicators of participants' performance: cyclist speed (km/h), head movements (three-dimensional unit vector), gaze direction (focus within the current field of view), and HR (beats per minute, BPM). Performance measurements comprised the average and standard deviation (SD) for each road segment. Performance data from the on-road and simulator experiments were compared to evaluate both the relative and absolute validity of the simulator.

Here, validity pertains to the simulator's capability to precisely mirror real-world cycling conditions. Two principal forms of validity were evaluated:

- Absolute Validity: A direct comparative analysis of values obtained from simulation and empirical road testing.

Relative Validity: The assessment of comparative patterns or effects observed, notwithstanding the lack of established absolute validity.

Absolute validity was assessed through paired sample *t*-tests, employing a significance threshold of 0.05. In instances where absolute validity was not confirmed, Pearson correlations were utilized to evaluate the relative validity between the two settings.

4. Results & Discussion

The findings suggest that roadway design exerts a significant influence on cycling performance. Among the three designs assessed, participants demonstrated the lowest cycling speeds within the protected bike lane as opposed to the other two configurations. On average, a decrease in speed was observed when participants were separated from the vehicle lane. Nevertheless, this outcome stands in contrast to a comparable IVE study conducted by Cobb et al. (2021), which revealed that cyclists exhibited slower speeds in scenarios devoid of a bike lane relative to those with a bike lane. Multiple factors might explain these discrepancies:

1) **IVE Settings:** In the study conducted by Cobb et al. (2021), the forward view was presented on a screen. Conversely, the present study employed a head-mounted display, which implies that differences in IVE settings have the potential to affect bicyclists' responses, as indicated by the findings of Bogacz et al. (2020) and Guo et al. (2022).

2) **Road Environment:** The IVE utilized in this study was designed to replicate a real-world road known to the local participants, which may have had an impact on their behavioral responses.

3) **Vehicle Behavior:** In the simulation, vehicles were randomly generated based on empirical real-world traffic patterns and followed predetermined routines in the vehicle lane. In the shared-lane scenario, vehicles approaching from the rear would decelerate and trail the participants until the lane was unobstructed, frequently resulting in a clear path ahead for the bicyclists. Some participants indicated an increased motivation to ride at a faster pace in the absence of passing vehicles. On average, a lower number of vehicles overtook participants in the as-built design (0.77) as opposed to the curbside bike lane (0.88) and the protected bike lane (1.03).

4) **Traffic Volume and Speed:** The volume of traffic observed in the experiment was comparatively low, with a mean of 0.9 vehicles passing each participant, which is less than that reported in related studies. The simulated road, modeled after Water Street, maintained a speed limit of 25 mph, with vehicles within the IVE adhering consistently to this limit. These factors imply that the influence of roadway design on cycling speed may be contingent upon the volume of traffic and the velocity of vehicles.

Conversely, conducting on-road experiments necessitates the use of more adaptable and costly eye-tracking devices, such as SMI or Smart eye Pro eye-tracking glasses, in addition to expensive software licenses. Moreover, conducting road tests in real-world environments presents inherent risks to both researchers and participants due to unexpected accidents, particularly during periods of heavy traffic. In contrast, the risk to participants and researchers within an IVE is considerably reduced. Consequently, if an IVE setting accurately emulates real-world conditions, it can offer valuable insights into the design and management of roadway systems, thus enhancing the safety and comfort of all users. Several participants observed that the width of the protected bicycle lane appeared more constricted than anticipated. Consequently, they adjusted their velocity and sustained reduced lateral proximity to the curb to mitigate the risk of impacting the flexible delineators.

Concerning lateral lane positioning, the LMM produced marginally significant results. Participants showed a tendency to position themselves at a greater distance from the vehicle lane in the presence of a dedicated bike lane, thereby increasing lateral spacing during the passing of vehicles. This behavior is consistent with the findings of prior studies (McNeil et al., 2015; Nazemi et al., 2021) and plausibly augments comfort and safety for cyclists.

Although the majority of the 50 participants evaluated the protected bike lane with flexible delineators as the safest design, post hoc analyses demonstrated minimal distinctions between the curbside bike lane and protected bike lane scenarios. Notably, in contrast to the participants' perceptions, the American Association of State and Highway Transportation Officials (AASHTO) had advised against the construction of protected bike lanes since 1974 (Lusk et al., 2013).

With regard to cycling behavior, both the protected and curbside bike lanes elicited analogous effects in the majority of scenarios. The protected bike lane condition was correlated with a reduced average cycling speed and a lane position proximate to the curb. In contrast, the curbside bike lane configuration demonstrated a marginally increased concentration of gaze. Aside from these distinctions, there was scant evidence to suggest substantial divergence between the two designs concerning cycling behavior or physiological responses.

The findings elucidate a disparity between participants' subjective safety assessments and their objective behavioral responses. To facilitate the broader adoption of cycling among the general populace, public education initiatives centered on these results might assist in bridging the gap between perceived and actual safety benefits associated with various roadway designs.

The study also identified gender differences in stated preference outcomes, with female participants demonstrating a stronger inclination towards the protected bike lane design and exhibiting lower perceived safety assessments for the sharrows. Nonetheless, no statistically significant disparities were detected between genders or age categories in terms of cycling performance, eye-tracking measures, or HR metrics. These outcomes are consistent with prior investigations indicating reduced cycling participation rates among female bicyclists (Mitra & Nash, 2018) and a pronounced preference for increased separation from motor traffic relative to males (Aldred et al., 2017). The present study substantiates these findings, proposing that protected bike lanes could potentially mitigate the gender disparity in cycling by enhancing the perceived safety among female bicyclists (Dill et al., 2014; Aldred et al., 2017).

Notably, despite the similarity in cycling behavior and physiological responses across genders, female participants reported distinct perceived safety ratings, underscoring the influence of subjective safety perceptions on the willingness to engage in cycling. This indicates that the design of infrastructure addressing these perceptions may foster increased cycling participation. Although some studies note minor gender differences in cycling behavior (Cobb et al., 2021), the current study showed that female cyclists had more favorable associations with protected bike lanes compared to male cyclists, reinforcing the proposition that such infrastructure can enhance equity in cycling participation.

It is noteworthy that the majority of participants in this study were habitual bicyclists, which renders them unrepresentative of the general populace. Moreover, empirical support for stronger preferences among older individuals is scant (Aldred et al., 2017). Nevertheless, this study incorporated a balanced number of male and female participants, rendering it a valuable reference for subsequent research on gender disparities in bicycling. The sample also encompassed a broad age range, although younger cyclists constituted a larger proportion. Despite the sample size being inadequate for a comprehensive age group comparison, no statistically significant difference was discerned in perceived safety ratings, cycling behavior, or psychophysiological responses among older bicyclists.

A significant observation is that the realism of speed within the IVE demonstrated a more pronounced correlation with physiological responses than did the realism of steering. This correlation may be contingent upon the specific task, given that the experimental roadway was primarily linear, necessitating minimal steering maneuvers aside from a few turns near the second intersection. Furthermore, experiments utilizing IVEs present the advantage of engaging a higher proportion of female and risk-averse participants compared to on-road studies, thereby creating an inclusive framework for examining diverse populations.

5. Conclusion

This study assessed the effectiveness of an IVE bike simulator in comprehending cyclists' behavior by utilizing multiple low-cost human sensing devices and investigated bicyclists' physiological and behavioral responses to diverse urban roadway designs. Through a pilot study conducted both in an IVE and on an actual road, the research established both absolute and relative validity for several cyclist performance measures. Although most metrics demonstrated absolute validity, certain eye-tracking features, particularly in the vertical direction, failed to achieve validity, likely due to factors such as changes in road geometry, the presence of other road users, and hardware limitations of the headsets employed.

The study utilized a bicycle simulator in conjunction with mobile sensing devices to document the behavioral and physiological responses of cyclists on the same roadway replicated with three distinct designs: shared bike lane (sharrows or as-built), curbside bike lane, and protected bike lane with flexible delineators. Principal findings from the 50 participants, who represent a balanced gender distribution and diverse age cohorts, are as follows:

1) The design of the protected bike lane achieved the highest ratings in terms of perceived safety.

2) Individuals participating in the protected bike lane scenario demonstrated the lowest cycling velocities and the maximum lateral distance from the vehicle lane, indicating enhanced safety in bicycling behavior attributable to decreased speeds and augmented separation from vehicular traffic.

3) Cyclists exhibited enhanced concentration on the cycling task within curbside and protected bike lane environments, as demonstrated by gaze metrics, which suggest diminished distractions in comparison to the shared bike lane.

4) Dedicated infrastructure, including curbside or protected bike lanes, was associated with decreased stress levels among cyclists, as evidenced by a lesser degree of HR variability in contrast to shared bike lanes.

5) Although gender differences were apparent in the perceptions of roadway design safety, there were no significant variations in cycling performance or physiological responses based on gender or age.

6) The IVE bicycle simulator has demonstrated high efficacy and safety as an instrument for assessing cyclists' behavioral and physiological reactions to various roadway configurations, thereby providing significant insights for the formulation of the constructed environment.

The results underscore the potential of the IVE as a robust, efficient, and secure platform for the analysis of cyclist behavior and the evaluation of roadway designs. The insights derived from this investigation can contribute to the development of strategies aimed at enhancing cyclist safety, comfort, and overall cycling experiences within urban settings.

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