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Assessing the Perceived Safety of Cyclists with Virtual Reality

Vahid Balali, PhD

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16. Abstract
In 2022, 7,522 pedestrians and 1,084 bicyclists were killed and approximately 67,000 pedestrians and 46,195 bicyclists injured in motor vehicle crashes on public roadways in the United States, according to the Insurance Institute for Highway Safety (IIHS). The transportation industry is faced with a pressing need to bolster the safety of these vulnerable road users. This research develops models of design and environmental factors that influence bicyclists' and pedestrians' perception of safety using Virtual Reality (VR) technology and ultimately informs transportation infrastructure design to better accommodate non-motorized travelers. The goal of the bicycle element of this research is to develop models of design and environmental factors that influence bicycle safety perception. Preliminary findings show that VR-based Immersive Virtual Environment (IVE) simulators accurately replicate cyclists' speed profiles, heart rate variations, and head/gaze behaviors, highlighting their potential for improving roadway safety planning. This research indicates that IVE could be utilized to create a bike simulation that: tests various road environments exhibiting different types of bicycle infrastructure and varying traffic levels; how they affect users' behavioral changes through observation of their interactions; physiological reactions assessed via biometric sensors; perceptions of safety assessed via a post-simulation survey.

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Cyclist, safety, virtual reality, immersive virtual environment, observed behavior.

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Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu/research/2327

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Executive Summary

Recent data show an increase in cyclist fatalities, highlighting the urgent need for more comprehensive research on how various environmental and design factors affect cyclists' behaviors, attention, and awareness. Unlike the extensive studies available for automobile drivers, there is a significant gap in research for cyclists, primarily due to the inherent safety risks of real-world studies. To address this, our study explores the use of Immersive Virtual Environments (IVE) as a viable alternative for evaluating cyclist behaviors. The primary objective is to assess the effectiveness of an IVE bike simulator in replicating real-world conditions and its impact on cyclists' perceived safety and behaviors. By comparing cyclists' behaviors and perceived safety in real-life settings with those in the IVE bike simulation, we aim to validate the realism of these simulators. Additionally, we have integrated low-cost human sensing devices to create a multimodal data collection system, tracking participants' gaze, heart rate, and head movements. Preliminary findings from a pilot study involving six participants suggest that our IVE simulators successfully replicate cyclists' speed profiles, heart rate variations, and most head and gaze behaviors, demonstrating sensitivity to environmental changes. This indicates the potential of IVE simulators to provide valuable insights for safer roadway planning and design for all users.

1. Introduction and Background

More than ever, non-motorized travel safety is a critical issue in transportation research. While motor vehicle occupant fatalities, adjusted for Vehicle Miles Traveled, have generally been decreasing since the 1970s (with a small increase in 2015 and 2016), non-motorized traveler fatalities are increasing at alarming rates. According to the National Highway Traffic Safety Administration (2017),[1] the 2016 pedestrian fatality count was the highest since 1990, and the 2016 cyclist fatality count was the highest since 1991.

Cycling is a mode of transportation that is healthy for individuals and sustainable for the environment and transportation infrastructure, and by increasing the number of cyclists on the road, there is great potential to increase its safety profile through the safety-in-numbers effect.[2,3,4]

Cities in California have been experiencing a rapid increase in bicycle ridership over the past decade. This increase correlates with a rise in cyclist accidents. Cities with higher rates of cyclists exhibit lower fatality rates for all road users.[5] However, cyclists described as vulnerable road users are still discussed less than others in research. It has been shown that perceived cycling safety issues inhibit potential cyclists from choosing this mode of transportation.[6] While there exists a rich body of literature examining (cyclist, roadway, and environmental) conditions influencing measured

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safety outcomes (such as crash rates and injury severities),[7,8,9,10] cyclists' perceptions of safety are a relatively unexplored topic. Perceived safety refers to feelings of how safe cycling is; the reasons behind this feeling must be better understood, whether it involves concerns about heavy traffic, proximity to automobiles, bicycle infrastructure, or other elements of the environment.

Mid-block crossings are particularly unsafe for pedestrians. Conflicts arise due to the reliance on nonverbal communication between users and the individual choices each user must make.[11,12] Connected Vehicle technology provides the opportunity to increase situational awareness for all users, potentially reducing the number of vehicle-pedestrian incidents. Previous research conducted by the Prime Investigator (PI) of this project involved the development of a mobile phone application that allows pedestrians to broadcast a message directly to approaching vehicles at mid-block crosswalks that notifies drivers, in-vehicle, of the pedestrian's presence and intent to cross the crosswalk.[13,14] As this study primarily focused on the drivers' reactions and perception of the application, it is paramount to investigate how pedestrians perceive this type of messaging and whether or not they become more reliant or trusting of this information and alter their behaviors at the mid-block crosswalk when attempting to cross.

Virtual Reality (VR) technology is now commonly used in many domains for its ability to give users a realistic experience and expose their natural behaviors through interactive and immersive environments. Recent studies have shown that VR is an effective tool with which to replicate

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realistic environmental settings at a low cost and reduced risk to the user.[15,16] With VR, human behaviors can be studied in settings/scenarios that (1) there is limited or no access to (e.g., the design of a new intersection that has not been built yet) or (2) are considered high-risk environments for collecting real-life data (e.g., cyclist safety or crash rates at an intersection and pedestrian crash rates at mid-block crossings). This makes VR an ideal medium with which to control different situations for cyclists and pedestrians and thus provide an accurate means for behavior studies. Additionally, these tools provide the freedom to control and manipulate different variables of interest when there is no access to them in real-life environments. By coupling VR tools with biometric sensors such as eye trackers and functional Magnetic Resonance Imaging caps, users' physiological information can be collected and analyzed in addition to behavioral information.

Past research using VR environments with non-motorized travelers has come from psychology and focused on training non-motorized travelers to safely use existing transportation infrastructure.[17,18,19] Very few recent works (from engineering) have started examining non-motorized travelers' reactions to new vehicle technology and transportation infrastructure.[20,21] Nonetheless, the current literature is focused on adapting and assessing the reactions of the non-motorized traveler to automobile-oriented transportation infrastructure design, a perspective that has largely failed non-motorized travelers in terms of safety. A cost-effective investigation of elements that influence cyclists' perceived safety (inferred via stated preference survey and revealed preference observed data) can inform targeted design approaches and policies to alleviate such concerns, and in turn, increase cycling rates and safety for all road users.

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This research proposes to assess non-motorized travelers' perceptions of safety and acceptance of technology, under existing and proposed transportation infrastructure environments, to inform better design guidelines for future transportation investments.

Before conducting experimental studies, the bicycle and pedestrian simulation environment must be tested and validated to ensure that (1) the cyclist and pedestrian simulator is calibrated with the VR environments and (2) the collected data is a proper representation of a real-world scenario (assessed through conducting benchmark studies between VR vs. physical settings). In the application of VR to cycling research, a few recent studies have shown bicycle simulators can be successfully built, and validated, and can have their environment replicated in VR.[22,23]

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2. Methodology

This project aims to help investigate cyclists' safety by creating a controlled test platform through a stationary bike and VR headset. The user can view a simulated road environment by wearing a Head Mounted Display (HMD) and pedaling on a bike that relays information in real time to the simulation. This setup makes it easy to study the reactions of a cyclist in different traffic scenarios, bicycle facilities, and environmental stimuli without endangering that cyclist.

This research used a bicycle simulator combined with an immersive 360-degree VR headset. A unisex city bicycle was placed on a bicycle stand, which provided resistance while cycling. The bicycle was equipped with a series of rotation sensors on the back wheel, pedal, brake, and handlebar to translate cyclists' movements in VR. Each rotation sensor consisted of a small microcontroller, a gyroscope, Bluetooth, and a Li-Ion battery. For this experiment, the steering sensor on the handlebar was disabled because steering causes severe motion sickness. Therefore, cyclists could only ride along a straight line. Immersive virtual reality was provided by an HMD. This HMD provided positional tracking; the virtual environment was rendered based on the position of the participant, thereby reducing motion sickness and providing a more realistic VR experience. Furthermore, participants could wear glasses underneath the HMD. Sensors on the bike sent electrical signals to the Arduino which processed the information and then passed it to the model. The model then ran that information through Unity simulation which was connected to the HMD.

Participants answered a questionnaire before and after cycling in VR. This approach provided a consistent condition for all the participants, as the experiment was repeated under the same conditions for each individual. Participants bicycled through different environments in VR—which enhanced their understanding of the hypothetical designs—before answering the questions. There were four Likert scale questions on willingness to bicycle in each environment and five Likert scale questions on the perceived level of safety which were repeated after each scene to evaluate the subjective impression of the riders. Participants were encouraged to reflect on their accumulating experience while proceeding through the experiment; they were provided with their previous answers to the perceived level of safety questions to be able to give relative answers and hence can regrade as they complete each environment. This functionality was particularly devised to address the intrinsic challenge of descriptive surveys where scales are commonly designed in absolute terms (i.e., independence of Likert responses) even though participants, consciously or unconsciously, report scores in a relative sense by basing their later scores on previous ones.

The anticipated outcome of this research project is the creation of a system in which cyclist behaviors can be easily monitored and evaluated, providing a safe and effective method to conduct cyclist safety studies, cyclist training, and rehabilitation. The results will be used by human factors researchers, transportation engineers, and software developers in designing, developing, and testing pedestrian-to-vehicle interactions in connected environments to increase the safety and efficiency by these technologies for real-world deployment.

Additionally, to address pedestrians, the goal is to place them in an environment where they can naturally interact with vehicles without the safety concerns of a real-world experiment by utilizing VR technologies. Specifically, this research aims to study how pedestrians behave in scenarios where they have to cross the street at a mid-block crosswalk while interacting with multiple types of connected vehicle technologies, including the integrated mobile phone application mentioned earlier, or making do without these technologies. Furthermore, this research aims to alter this interaction by changing multiple factors in the experiment such as whether an approaching vehicle is autonomous with no driver. Pedestrians were observed and evaluated based on how and when they crossed, their physiological reactions (collected via integrated biometric scanners), and by conducting a post-test questionnaire aimed at understanding the pedestrians' perceptions of safety, technological acceptance, and level of interaction with vehicles.

2.1 Experimental Design

To achieve the research objectives, we conducted a pilot study benchmarking participants' cycling behaviors and performance in both a real-life environment and its corresponding Immersive Virtual Environment (IVE) setting. The study employed a within-subjects design to control for inter-subject variability. The IVE was meticulously developed to a 1:1 scale of the real-world environment.

The study corridor that was chosen is East Anaheim Road between North Studebaker Road and East Campus Drive in Long Beach, CA (Figure 1). This segment is frequently used by cyclists and has been identified as high-risk for vulnerable road users. During the development of the IVE model, we calibrated the scale of the road, surrounding buildings, and other roadway design features (e.g., markings and traffic lights) to ensure accurate 1:1 representation.

The selected section comprises two city blocks with specific features: a 4% downhill grade in the westbound direction, shared lane markings in both directions, traffic signals at the intersections of North Studebaker Road and Palo Verde Avenue, and a parking lane in the eastbound direction.

Figure 1. Illustration of Experimental Area

To accurately simulate traffic patterns and gather data on existing operating conditions, the research team collected approximately two weeks of video data at the selected corridor. This involved recording the number of cars and other roadway users passing through the corridor along with their speeds. With permission from the City of Long Beach and California State University, Long Beach, four cameras were installed along the East Anaheim Road corridor to capture the necessary video footage.

The team focused on peak traffic hours (7:00–9:00 AM and 4:00–6:00 PM), reviewing the footage to record traffic volumes during these times. These peak traffic volumes informed the design of the corresponding IVE settings, enabling the simulation of realistic traffic flow, including the number and speed of vehicles within the IVE.

A pilot test was conducted with the research team and transportation experts from California State University, Long Beach, who evaluated the realism of the IVE model and provided feedback for improvements. Figure 2(a) shows a Google Maps view of the corridor, while Figure 2(b) presents the corresponding IVE setting.

Figure 2. Comparison of (a) Real Road and (b) IVE Environments; (c) Video Collection System of IVE Bike Simulator; (d) Heart Rate Distribution of Experiment

2.2 Data Collection

This section details the hardware components selected for both simulators. Figure 2(c) illustrates the appearance of each simulator. Both simulators were equipped with HTC Vive Pro VR headsets and their corresponding controllers. Table 1 provides a cost estimation of the IVE framework compared to a comparable real-world 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 offers significant cost savings in hardware and planning while eliminating safety concerns for test subjects. At the time of this experiment, the initial setup cost of the virtual environment was approximately $3,500. This included $1,500 for the HTC Vive Pro Eye with controllers and base stations and $50 for two web cameras used to collect room video data. The software used to integrate all virtual reality videos is OBS Studio, which is open-source and free for research purposes. For eye tracking within the IVE, the Tobii Pro Unity SDK was used, which is also free for research purposes.

The authors developed documentation and code examples to set up and access eye-tracking data from the HTC Vive Pro Eye. In contrast, on-road tests require more flexible and expensive eye-trackers, such as SMI or Smarteye Pro eye-tracking glasses, along with costly software licenses.

Additionally, real-world road tests pose risks to researchers and participants due to unforeseen accidents, especially during busy traffic hours. Conversely, the risk to participants and researchers in an IVE is minimal. Therefore, if the IVE setting accurately represents real-world conditions, it can provide valuable insights into designing and managing roadway systems to ensure the safety and comfort of all users.

The following equipment was specifically chosen for the bicycle simulator:

(1) Wahoo Kickr Smart Trainer: power measurement system of ± 2% for accurate, realistic resistance feedback.

(2) Wahoo Kickr Climb: adaptive, real-time indoor bicycle grade simulator attached to the front fork of the bicycle that accurately raises or lowers the front end of the bicycle based on on-road grade.

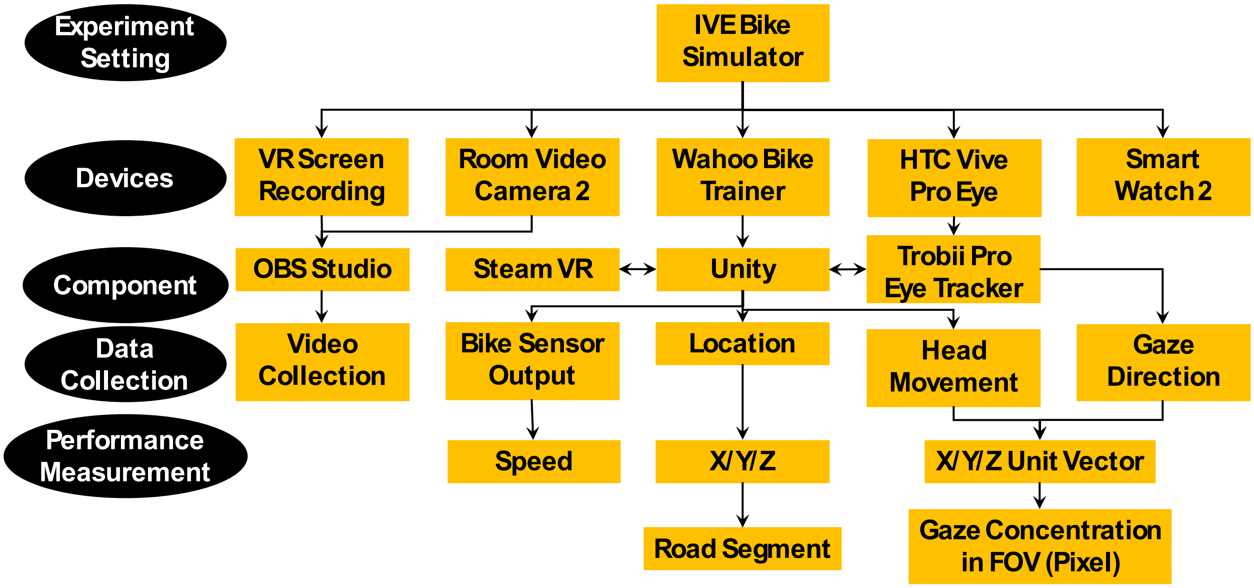
(3) Wahoo Kickr Headwind: adaptive, real-time variable speed vortex fan capable of reaching wind speeds experienced by cyclists on the road.

(4) ANT+: wireless protocol used for communications between the Wahoo training equipment and desktop computer.

(5) Physical Trek Verve bike: the main body structure of the bicycle simulator.

The data collection framework and system architecture for measuring cyclists' behaviors and physiological responses are illustrated in Figure 3. The IVE bike simulator utilized HTC Vive Pro Eye headsets and accompanying controllers to track interactions within the IVE. This VR headset featured an integrated Tobii Pro eye tracker with movement tracing capabilities, providing seamless integration compared to traditional eye tracking systems (such as screen-based or eye-tracking glasses). The spatial positioning of the controllers, attached to the handlebars, enabled the system to detect actions such as turning and braking.

Figure 3. System Architecture and Data Framework



The VR environments were designed and programmed in Unity and operated through the Steam VR platform. Using Unity C# scripts, all headset and controller movements were tracked and extracted. An instrumented Trek bicycle was utilized for the experiments, connected to Unity via Wahoo indoor cycling training equipment. This setup allowed for the collection of real-time data on speed, instantaneous power, and distance traveled and also provided haptic feedback to participants.

Additionally, two external video recording devices captured participants' movements during the IVE experiments. These recordings were used to monitor and analyze participants' movements and reactions. The participants' view within the IVE was recorded using OBS Studio software, which integrated all videos with uniform timestamps and frames per second. Furthermore, two Android smartwatches equipped with the "SWEAR" app were used to track participants' physiological signals, such as arm movement and heart rate.

2.3 Experiment Procedure

In this pilot study, five participants (mean age = 20.3, *SD* = 3.3) were recruited. All participants were 18 or older with normal color vision and familiarity with the chosen corridor.

Upon arrival at the lab, participants were asked to wear Android smartwatches and complete a pre-experiment survey capturing demographic information. Before the formal experiment, participants engaged in a training scenario to familiarize themselves with the virtual environment, navigation, and calibration of the eye tracker and bike simulator. The experimental task involved cycling to the end of the experimental area, as shown in Figure 1. After completing the experiment, participants were invited to sign up for an on-road study scheduled for a few weeks later. The IVE experiments took approximately half an hour to complete.

For the on-road experiments, the same model of the bicycle was used, instrumented with sensors to collect a range of variables as depicted in Figure 3. All on-road tests were conducted on clear weather days during peak traffic hours. The procedures for the on-road study mirrored those of the IVE experiments.

2.4 Performance Metrics and Analysis

To evaluate the validity of the IVE bike simulator in different contextual settings, performance data were analyzed separately for different road segments. As illustrated in Figure 1, Road Segment 1 spans the area between Intersections 1 and 2 and includes a 4% downhill grade with a wall on the right, blocking the parking lot. Road Segment 2 is a level road with a parking lot visible to cyclists.

As shown in Figure 3, the following metrics were measured 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 heart rate (beats per minute). Performance measurements include the average and standard deviation for each road segment. Performance data from the on-road and simulator experiments were compared to assess both the relative and absolute validity of the simulator.

In this context, the term 'validity' refers to the simulator's ability to accurately represent real-world cycling conditions. Two primary forms of validity were assessed:

- Absolute Validity: Direct comparison of values from simulator and on-road testing.
- Relative Validity: Comparison of patterns or effects observed, even if absolute validity is not established.

Absolute validity was evaluated using paired sample *t*-tests at a significance level of 0.05. If absolute validity was not established, Pearson correlations were used to assess relative validity between the two settings.

3. Results and Discussion

Among the five participants, one participant's eye-tracking data and another participant's heart rate data were missing from the IVE experiment. Consequently, these data were excluded from the analysis.

The on-road experiment exhibited a higher average speed and standard deviation compared to the IVE experiment. However, the difference in average speed was not significant for either road segment 1 ($p = 0.09$) or segment 2 ($p = 0.23$). The standard deviation of speed showed a significant difference for both segments (segment 1: $p = 0.04$, segment 2: $p = 0.002$). Pearson correlations for speed were positive for both segments, with significance achieved only for segment 1 ($r = 0.865$, $p = 0.026$), indicating relative validity for this segment.

In the downhill road segment, participants on the real road exhibited greater control over their speed, leading to a larger variance in speed standard deviation. This can be attributed to the challenge of replicating real-world elements within the VR environment. Factors such as user weight, which affects acceleration and speed in real-world conditions, were not considered in the IVE bike simulator. Additionally, road friction played a role; on the real road, participants often freewheeled without pedaling, whereas in the IVE, they continued pedaling to maintain speed.

For head movements, paired t-test results showed no statistically significant differences, except for the up and down head movements in road segment 1 ($p = 0.002$). The Pearson correlation for up and down head movements in segment 1 was positive but not statistically significant ($r = 0.689$, $p = 0.20$). Video recordings from the HoloLens 2 revealed several manholes on the real road (4 in segment 1 and 7 in segment 2) that were not modeled in the IVE. The absence of pedestrian models in the IVE may also explain the significant differences in vertical head movement. This suggests that in real-road conditions, cyclists lower their heads to attend to obstacles like manholes or other roadway conditions and contextual settings.

There were no significant differences in left and right gaze directions. However, for up and down gaze directions, only the average in road segment 1 was not significant. Participants exhibited significantly more up-and-down scanning behaviors on the real road than in the IVE for both segments. The average gaze center was lower in on-road tests for road segment 2. Pearson correlations did not establish relative validity for other pairs, including mean up-and-down gaze direction in segment 2 ($r = -0.276$, $p = 0.653$) and the standard deviation of up-and-down gaze for both segment 1 ($r = -0.660$, $p = 0.226$) and segment 2 ($r = 0.013$, $p = 0.984$). The gaze direction trend mirrored head movements, with more frequent up-and-down scanning due to the complexity of real road conditions.

4. Conclusion

This study aimed to evaluate the effectiveness of an IVE bike simulator in understanding cyclists' behaviors using multiple low-cost human sensing devices. A pilot study was conducted both in an IVE and on a real road, employing various sensors to ensure comparable data output. The study established both absolute and relative validity across several cyclist performance measures. While most performance metrics demonstrated absolute validity, certain features from eye-tracking data, particularly in the vertical direction, did not achieve either absolute or relative validity. This discrepancy may be attributed to changes in road geometry, the presence of other road users, and hardware limitations, especially with the headsets used in the study. Overall, the results suggest that the IVE bike simulator holds potential for further exploration in understanding cyclists' behaviors.

Despite these positive findings, the study faced several limitations. Firstly, the small sample size of participants restricts the generalizability of the results. Future experiments with a larger sample size are planned to address this limitation. Secondly, participants were unable to change bike gears within the current IVE bike simulator, as it does not support gear changes. Consequently, the gear was consistently set at a middle level for all experiments, potentially affecting speed variations. Lastly, the study did not annotate or collect specific events within the real-road condition, a crucial aspect given the event-based nature of psychophysiological data. Future studies will aim to incorporate and integrate such event-specific information into the IVE design.

Further research should include a broader age range of participants, validate additional sensor measurements, and explore various locations to enhance the robustness and applicability of the findings.

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About the Author

Vahid Balali

Vahid Balali, Ph.D., is the principal investigator and an Associate Professor in the Department of Civil Engineering and Construction Engineering Management at California State University, Long Beach. Dr. Balali's research focuses on visual data sensing and analytics, virtual design and construction for civil infrastructure and interoperable system integration, and smart cities in transportation for sustainable decision-making.

Dr. Vahid Balali is a recipient of the 2020 Early Academic Career Excellence Award from California State University, Long Beach. He was also selected as one of the Top 40 under 40 by *Consulting-Specifying Engineer* for the year 2017 and the top young professional in California by *Engineering News-Record* for the year 2016. He received the 2014 second-best poster award from the Construction Research Congress, as well as the 2013 CMAA National Capital Chapter Scholarship award. He is currently an associate member of ASCE and CMAA, a committee member of the ASCE Data Sensing and Analysis and ASCE Visual Information Modeling and Simulation committees, and a friend member of relevant TRB committees. He is also serving as a reviewer of several top journals. He is actively collaborating with industrial partners and is involved in professional and outreach activities.

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