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Creating an Inclusive Bicycle Level of Service: Virtual Bicycle Simulator Study

Authors
Griswold, Julia B., PhD
Aguilar, Edna
Wang, Han
et al.

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RESEARCH REPORT

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Creating an Inclusive Bicycle Level of Service: Virtual Bicycle Simulator Study

Julia B. Griswold, Ph.D., Safe Transportation Research and Education Center (SafeTREC), University of California Berkeley
Edna Aguilar, Graduate Student, Safe Transportation Research and Education Center (SafeTREC), University of California Berkeley
Han Wang, Graduate Student, Safe Transportation Research and Education Center (SafeTREC), University of California Berkeley
Md Mintu Miah, Ph.D., Safe Transportation Research and Education Center (SafeTREC), University of California Berkeley

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16. Abstract
Bicycle level of service (BLOS) is an essential performance measure for transportation agencies to monitor and prioritize improvements to infrastructure, but existing measures do not capture the nuance of facility differences on the state highway system. However, with the advancements in virtual reality (VR) technology, a VR bicycle simulator is an ideal tool to safely gather user feedback on a variety of bicycling environments and conditions. This research explored the benefits and limitations of using a VR environment to assess individuals' bike infrastructure preferences. We conducted a bicyclist user experience survey in person on SafeTREC's VR bicycle simulator and online and compared the results. The online survey consisted of showing participants pairs of VR videos of biking scenarios and asking them to choose the one that they preferred. To validate the online survey responses, we conducted in-person experiments with a VR bike simulator using the same pairs of videos. Our analysis indicates that 63 percent of the responses were consistent while a smaller percentage of responses (37 percent) changed after the simulator ride due to better perception provided by the simulator virtual environment. The outcome of this study helped to validate the online survey responses of the study.

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Disclaimer

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Executive Summary

Executive Summary

Bicycle level of service (BLOS) is an essential performance measure for transportation agencies to monitor and prioritize improvements to infrastructure. However, the current measures that Caltrans could use are either too data intensive (*1*) or do not capture the nuance of facility differences on the state highway system. Caltrans previously funded a UC Berkeley SafeTREC study to develop a segment-level BLOS model using an online bicyclist user experience survey, titled "Developing segment and intersection-level BLOS measures for the SHS." The purpose of this research is to validate the results of the online survey that was used to develop the BLOS measure via an in-person experiment using a virtual reality (VR) bicycle simulator.

With the improvements in VR technology, a VR bike simulator is an ideal tool to safely gather user feedback for a variety of bicycling environments and conditions. This study explored the benefits and limitations of using a VR environment to assess individuals' bike infrastructure preferences. In addition, we wanted to include groups that are typically underrepresented in research studies. To gather a more racially and economically inclusive sample, we reached out to various advocacy groups and cycling clubs, conducted the survey in Spanish in addition to English, and offered monetary incentives for participation.

The online survey consisted of showing participants pairs of VR videos of biking scenarios and asking them to choose the one that they preferred. To validate the online survey responses, we conducted in-person experiments with a VR bike simulator. These participants were shown the same pairs of videos and asked to choose their preferred scenario.

Results show that there is a discrepancy between responses from the online survey and the in-person experiment, but the degree of the discrepancy depends on how the results are analyzed. Eight individuals participated in person and viewed 76 pairs of scenarios. The majority of responses (64 percent) were not aligned with the online survey responses if the answer was based on a 5-point Likert scale. However, this percentage decreases to 37 percent when grouping responses into just two categories (scenario 1 or scenario 2). Finally, participants gave positive feedback regarding using a VR simulator to test bike infrastructure preferences. In particular, they expressed that the VR scenarios are more life-like than the videos from the online survey.

This research will enhance Caltrans' ability to address its strategic goals to "enhance and connect the multimodal transportation network" and "advance equity and livability in all communities" by targeting populations of cyclists that do not commonly participate in research to develop an inclusive BLOS measure designed for California's roads. This research will support the management needs of the Caltrans' Planning Division as well as the Active Transportation Program.

Contents

Introduction

Bicycle level of service (BLOS) is an essential performance measure for transportation agencies to monitor and prioritize improvements to infrastructure for bicyclists. However, the current measures that Caltrans could use are either too data intensive (*1*) or do not capture the nuance of facility differences on the state highway system (*2*, *3*). The existing empirical measures were developed by gathering survey responses to photos, videos, or real-world experiences of riding on facilities and then modeling the relationship between the objective attributes of the facility and the subjective response. In recent years, virtual reality (VR) technology has improved, making a virtual reality bicycle simulator an ideal tool to safely gather user feedback for a variety of bicycling environments and conditions. This technology creates an opportunity to increase the realism of the user experience survey for developing BLOS models.

It is also important to include a diverse sample of study participants to reflect the population of cyclists and potential cyclists in California. Gathering an appropriate sample for this type of research is a challenge due to the relatively small proportion of the California population that rides a bicycle and the challenge of recruiting cyclists from underrepresented groups, so-called "invisible cyclists" (*4*). A pilot BLOS study for California (*5*) showed that a user experience survey based on a convenience sample of cyclists could support both the classification of cyclists and the modeling of class preferences using latent class choice models.

This study sought to achieve two things: to enhance the survey with a racially and economically diverse sample to help understand how and whether the cycling preferences of underrepresented communities differ from other groups, and to validate the use of online videos against a VR simulator as a tool to better understand bicycling behavior.

Background

In recent years, VR has accelerated from a novel technology primarily for entertainment purposes to an industry-spanning tool with applications ranging from research, prototyping, and training. Although headset display is a significant breakthrough in simulation technology, immersive simulation is a mature field of science firmly rooted in human factors and psychology.

Although a more primitive training apparatus could arguably be considered a simulator, the earliest recognized simulation devices were mechanical flight simulators developed in the early 20th century (*6*, *7*). Lacking modern audio-video media capabilities, they were primarily focused on providing a tactile interface for training pilots on the ground. Flight simulators steadily evolved from simple mechanical devices to sophisticated computerized flight simulations and moving platforms with six degrees of freedom (*8*). In the late 20th century, the automotive industry began developing its own driving simulators for industry (e.g., prototype mock-ups, safety, and even insurance-related research). These simulators typically consist of a stationary vehicle with a roadway environment projected in front of the vehicle (*7*).

These driving simulators eventually branched into other modes, such as trains, bicycles, and even pedestrians. However, bicycles and pedestrians present a unique challenge in connecting the movement controls (e.g., pedals and walking) to the simulated environment. This challenge was typically solved using a cave automatic virtual environment (CAVE) in which users wear 3D glasses that provide stereoscopic display as well as track the user's movements in the environment (*9*, *10*). Although feasible, the elaborate system limits use to all but the most dedicated and funded research facilities.

With the rapid advancement and increasing affordability of commercially available VR technology over the past decade, a growing number of research-based bicycle simulator labs set up around the world. Headset-based VR systems not only solve the perception of distance more easily (*11*), but offer several other advantages over traditional CAVE-based systems.

- **Simplicity**—Rather than a computing cluster to support multiple fixed-projection screens in a CAVE system, VR requires only a single computer and headset display unit to achieve full omnidirectional display.
- **Cost**—These simpler VR systems are generally less expensive than complex CAVE-based systems with proprietary parts and software.
- **Flexibility**—VR is no longer constrained to a dedicated CAVE facility and can be scaled to a room of almost any size.
- **Community support**—A large development community populated by a variety of professions offers greater support and more development software options, not just proprietary software used by niche industry professionals or academic research.
- **Enhanced data collectio**n—VR offers a variety of unique or native data collection options, such as eye tracking, head movement, and other measurement capabilities directly integrated into headsets.

However, VR-based simulation is still a relatively new research tool and has not yet reached the mature level of institutional acceptance. Validation studies found that bicycle VR provides statistically reliable results for most measures, such as lane position, passing distance, head movements, and acceleration, but found that some measures still require further calibration in some cases, such as speed (*11*, *12*). Still, the ever-growing and advancing field of VR continues to gradually gain acceptance as a scientific tool providing a promising research method for evaluating a variety of psychological or human factor questions regarding bicycling and bicycle infrastructure (*13*, *14*).

Much like historical simulator research, there are two main veins in this research: simulators that focused on recreating the *physical* tactile realism of riding a bicycle on the road for the purpose of safety or other training (*15*–*19*), and simulators that focused on *visual* immersive realism for the study of perceptions of infrastructure or bicyclist behavior (*13*, *20*–*25*).

Research Objectives

The objective of this research was to conduct a bicyclist user experience survey in person on SafeTREC's VR bicycle simulator. We took advantage of SafeTREC's established relationships with community organizations to reach out to a broad base of racially and economically diverse California cyclists to participate in the simulator experiment. We used incentives to attract participation from populations that do not normally participate in research to address equity principles of providing financial support for individuals' contributions to research (*26*). We compared the responses between the videos in the online survey and the immersive experience in the simulator to validate the use of videos.

BLOS Development Overview

The first part of this project was developed under the Caltrans-funded study, "Developing segment and intersection-level BLOS measures for the SHS" (65A0801, Julia Griswold, PI). The report for that study provides a comprehensive account of the methodologies employed to create the BLOS metric. This report focuses on the second part of the study, which involved inviting survey respondents to ride the simulator in person to compare their simulator responses to their online survey responses.

The BLOS metric that was developed in the initial study comprised these parts.

1. **Designing the VR videos**—We created 30 videos using a VR environment. Each video shows a different roadway segment with varying types of bike infrastructure, traffic, and roadway conditions.
2. **Designing the survey**—The survey comprised two sections. In the first section, demographic information and information about respondents' biking habits and preferences were collected. The second section included choice questions—respondents were asked to choose their preferred route between 15 pairs of random videos shown to them.
3. **Estimating a latent class choice model (LCCM)**—An LCCM is a type of discrete choice model that aims to uncover similarities in the way individuals make decisions. It accounts for unobserved or latent heterogeneity in decision-making behavior. Two models were estimated: a three-class and a four-class model. The models revealed that the survey population could be segmented into the following classes.
    - Road-cycling enthusiasts—Individuals that like biking on multi-lane roads with bike lanes that have no barriers, such as median or bollards, separating them from traffic.
    - Occasional recreational bicyclists with a high sensitivity to bike infrastructure—Individuals who have a strong preference for streets with bike facilities, like bike lanes, buffers, and barriers.
    - Occasional recreational bicyclists with a low sensitivity to bike infrastructure—Individuals who have a medium response to streets with bike facilities.

- Indifferent to bike infrastructure—Individuals who have a neutral response to bike facilities.

4. **Developing a segment BLOS metric**—A BLOS metric was built using the utility equations from the four-class LCCM. The metric shows the probability that a user from a particular class will ride on a road given its unique bike infrastructure features versus a road with no bike infrastructure.

Equity in BLOS Development

Central to making the BLOS metric inclusive is ensuring extensive participation from underrepresented communities in the survey. Because the survey serves as the basis for the BLOS development, the greater the diversity of responses captured, the more representative the BLOS metric becomes.

To increase the reach of the survey, we coordinated with community-based organizations that work with underrepresented groups. Initially, we established a partnership with two organizations to support our efforts. However, as the project progressed, our communication with one of them deteriorated, facing challenges in reaching our designated points of contact and receiving no responses to our emails. We also conducted the survey in English and Spanish. To encourage participation, we offered $10 gift cards to whoever filled out the survey using the survey link that their community-based organization (CBO) provided. Only individuals who received an email from a participating CBO could receive the gift card. The survey link distributed to the rest of the participants did not contain an option to request a gift card.

We collaborated closely with Poder, an organization that works with Latino immigrants along with Black, Indigenous, and other underinvested communities of color. Poder helped to review the survey to ensure that it was understandable to their members. They also helped with distributing the survey to their members by sending it via email and by setting up two iPads in their office so that walk-in visitors could take the survey. We also shared the survey using the email list of past participants in SafeTREC's Community Pedestrian and Bicycle Safety Training Program (CPBST), which works with underserved communities.

In addition, we sent the survey to bike advocacy groups and cycling clubs based in areas all across the state to distribute to their mailing lists. Some of the groups and clubs contacted were:

- Bike East Bay
- San Francisco Bicycle Coalition
- Active San Gabriel Valley
- Bicycling Monterey
- Sacramento Area Bicycle Advocates
- Bike Lodi
- West Hollywood Bicycle Coalition
- Marin Cyclists
- Bike Davis
- California Bicycle Coalition
- Velo Girl

Despite our efforts to increase participation from underrepresented communities, our survey did not capture a significant number of responses from those groups. In total, we received 1,654 responses, of which 46 were from individuals who were members of Poder or CPBST. However, after data cleaning, only 15 of those responses were from members of our partner CBOs. Compared to the total number of cleaned responses, 894, CBO members represented only 1.7 percent of our sample. While it is possible that members of the other organizations we contacted (bicycle clubs and advocacy groups) were historically underrepresented, our survey results indicate the vast majority of respondents identified as White (83 percent) and not Hispanic (78 percent). Interestingly, 6 percent of respondents identified as American Indian or Alaska Native, which is six times higher than the overall representation of this demographic in the entire state of California. The percentage of participants from other races also fell below their respective share in the state's population (Table 1).

The limited presence of underrepresented communities in the initial pool reduced the likelihood of having a diverse range of participants attend the in-person experiment and consequently participate in the full study. Despite having contacted all CBO members and offering to cover their travel expenses to come to the university and providing a $100 gift card incentive for participating in the in-person experiment, we were unable to recruit a single member of a CBO to try the simulator.

In light of our challenges in demographically broadening the participation, we offer some lessons learned for future research projects that aim to be inclusive.

- **Cultivate and strengthen partnerships with trusted community leaders.** Establishing robust working relationships with community leaders and CBOs is crucial to enhancing participation of underrepresented groups. These formal and informal leaders can possess personal connections within their communities and help encourage participation. It is important to maintain these partnerships throughout the project to allow for follow-up requests and coordination.
- **Be proactive about following up.** While we received an ample number of responses, we did not send reminders to contacts about forwarding the survey to their networks. Furthermore, by following up with contacts, it is possible to track who received the survey and identify barriers to participation and gaps in the sample, and thus reach out to specific contacts that can help fill those gaps.
- **Remove barriers to incentive.** Qualified survey participants were required to provide their email address to request a gift card, which may have discouraged some respondents participating. To address this issue, we recommend simplifying the process for accessing incentives while implementing safeguards to prevent potential abuse.

Survey Results

After data cleaning, we received 909 valid responses, which were carefully filtered from the original pool of 1,645. Table 1 summarizes the demographic data of the survey respondents. To assess the representativeness of the survey sample, we included California demographic data for comparison. Overall, the majority of respondents identified as White (83 percent), not Hispanic (78 percent), male (61 percent), and between ages 21 and 40 (70 percent). Based on California's population, the survey sample is skewed.

Table 1. Demographic characteristics of survey respondents

	Survey Respondents		California	
	Count	**Percent**	**Count**	**Percent**
Sample Size	909	100	39,455,353	100
Gender				
Male	553	60.8	19,714,044	50
Female	349	38.4	19,741,309	50
Non-binary	7	0.8		
Race				
White	748	82.3	20,553,732	52.1
American Indian or Alaska Native	60	6.6	360,607	0.9
Asian	28	3.1	5,887,396	15.0
Black or African American	22	2.4	2,233,258	5.7
Native Hawaiian or Pacific Islander	21	2.3	148,278	0.4
Other	17	1.9	6,036,865	15.3
Two or more races	13	1.4	4,235,217	10.7
Ethnicity				
Hispanic	200	22	15,593,787	39.5

Notable differences in biking habits are evident between frequent and infrequent bicyclists. Frequent bicyclists, which amounts to 91 percent of the sample, are individuals who ride a bike every day or a few times a week. Infrequent bicyclists ride a few times a month, rarely, or never (9 percent). Whereas a significant percentage of infrequent biker's ride only for recreation (47 percent), frequent bikers ride for a variety of reasons, including recreation, commuting, or as the mode of travel to run errands (Figure 1). Furthermore, the age of frequent bikers is concentrated between 21–39, while the age distribution of infrequent riders is wider (Figure 2).

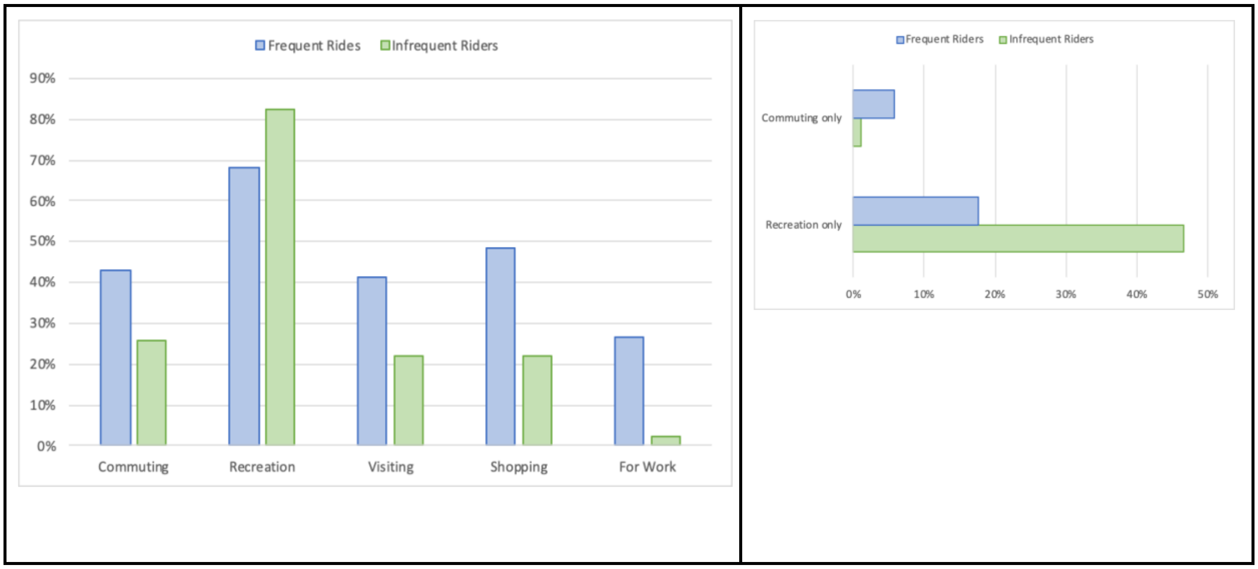

Figure 1. Trip purposes of frequent vs. infrequent riders

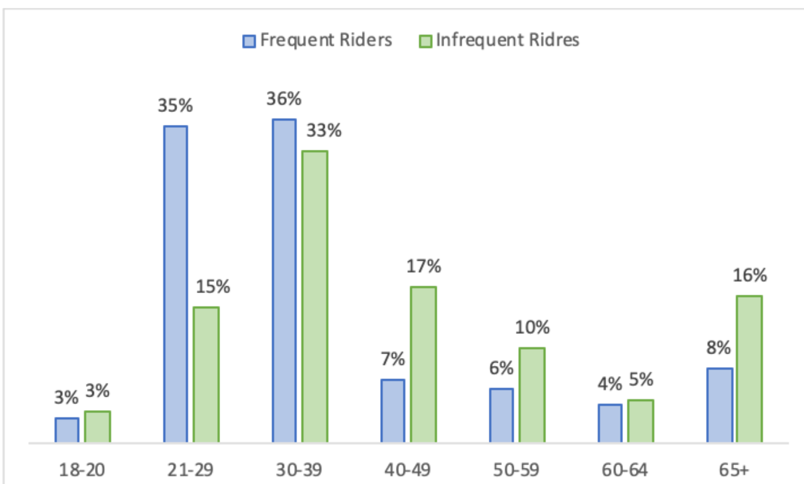

Figure 2. Age distribution of frequent vs. infrequent riders

Significant differences in level of comfort are also present between frequent and infrequent bicyclists (Table 2). Particularly noteworthy is the contrast between the two groups regarding their feelings of safety and comfort while biking. Merely 33 percent of infrequent riders strongly or somewhat agree that they feel secure while bicycling, in contrast to 62 percent of frequent riders who share this sentiment. Furthermore, while the majority of infrequent bikers enjoy biking (81 percent), 78 percent expressed that they would bike more if they felt more at ease. This underscores the potential influence of safety perceptions on the reluctance of infrequent bikers to engage in an activity that they enjoy.

Concerning bike infrastructure preferences, both frequent and infrequent bicyclists consider infrastructure an important factor when selecting routes, with a slightly larger share of infrequent bikers expressing that it is important. In particular, infrequent bikers place a higher priority on roads with low-speed traffic (71 percent), whereas frequent bikers are more concerned about separation from cars (62 percent). For both groups, road traffic volume is not as important when selecting routes.

Table 2. Bike infrastructure preferences and level of biking comfort

	Frequent Riders		Infrequent Riders	
	Count	**Percent**	**Count**	**Percent**
Sample Size	823	91	86	9
Extremely or very important				
Marked bicycle lanes	487	59	55	64
Roads with low traffic	417	51	50	58
Separation from cars	510	62	55	64
Roads with low-speed traffic	453	55	61	71
Strongly agree or somewhat agree				
Bicycling is a high-risk activity	340	41	44	51
I would bike more if it felt safer and more comfortable	597	73	67	78
I feel safe and comfortable riding a bicycle	514	62	28	33
I would like to ride a bicycle more than I currently do	529	64	66	77
I like riding a bicycle	583	71	71	81

Overall, our survey collected some diversity of responses from individuals with varying biking habits and perceptions on biking. The vast majority of respondents are frequent bikers between the ages of 21–40 that like to bike and do so for a variety of purposes, but in particular for recreation. This aligns with our expectations because the survey was primarily distributed to bicycle clubs and advocacy groups whose members possess a high level of biking skill and interest. Yet, despite the prevailing trend, we did notice differences in biking experience and infrastructure preferences between frequent and infrequent bikers. Notably, there are significant differences in the two groups' perceptions of safety. Unlike frequent bicyclists, infrequent bicyclists largely do not feel safe and comfortable on a bike, even though they do like riding one.

Bicycle Simulator

The VR bicycle simulator is an innovative creation borne from the collaborative efforts of a UC Berkeley graduate student with SafeTREC researchers. Merging advanced technology with a meticulous design approach, the simulator serves as an instrumental platform for immersive research, interactive training, and experiential learning. The simulator consists of these off-the-shelf components.

Wahoo KICKR Smart Trainer

The Wahoo KICKR smart trainer translates the physical cycling into the virtual domain. Using an array of precision sensors, the device captures and translates critical metrics, such as pedal power, cadence, and resistance adjustments. By adeptly mirroring real-world terrains and challenges, participants have an authentic cycling experience within the controlled confines of their physical environment.

HTC VIVE Pro Headset

The HTC VIVE Pro headset establishes a sensory connection, amalgamating real and virtual elements and rendering intricate details and lifelike environments. Its high-fidelity visual and auditory components envelops participants in a meticulously crafted virtual landscape. Through the headset, cyclists traverse captivating terrains and navigate dynamic scenarios, heightening the authenticity of their virtual cycling experience.

Unity Engine

Integral to the simulator's functionality is the Unity Engine, a software framework known for its rendering of intricate virtual environments. This dynamic engine integrates the lifelike graphics, fluid animations, and responsive interactions, creating a coherent and engaging simulation. The Unity Engine facilitates the dynamic interplay between participant input and virtual response, fostering a fluid and authentic cycling experience.

Dell Precision 5820 Tower Workstation

The Dell Precision 5820 Tower Workstation is the computational backbone of the VR bicycle simulator, orchestrating the intricate processes required for real-time simulation rendering. The workstation's formidable processing capabilities contribute to a seamless and uninterrupted virtual environment. It effectively manages the complex algorithms and computations demanded by the Unity Engine, ensuring that the participant's experience remains uninterupted.

Experimental Scenarios

This study considered 10 pairs of the same scenarios that were used for the online survey. The videos were created using a virtual reality environment. One advantage of VR is that it enables the development of scenarios where all design elements can be controlled. Therefore, all traffic conditions and bike infrastructure variables could be adjusted as necessary. We designed 30 road segments, each one representing one of the variable combinations listed in Table 4 in the Appendix. The virtual world and its design elements (e.g., street furniture, cars, buildings) were selected to resemble Californian streets as much as possible. All videos show the full width of a road along with the buildings, sidewalks, and street furniture that are adjacent to it. The weather and position of the sun were also adjusted so as not to become elements of distraction for viewers. For instance, selecting a particular time of day in the world was crucial to eliminate sun glare and build shadows that could inadvertently affect viewers' experience while "riding" on the road. The videos also include the sound of vehicles passing by. The velocity of the car's speed also impacts the loudness of the approaching vehicle. Some of the limitations of the experiment scenarios were lack of real vibration and feeling of wind flow.

Design of the In-Person Experience

For the in-person experiment, participants were asked to read and sign a consent form. Next, they were asked to get on the bike and put on the VR headset. Both the bike and the headset could be adjusted to the participant's height and head size. When comfortable in the VR gear, the participant was dropped into a random scenario to ride for 30–60 seconds to get familiar with the virtual world and the bike simulator. Once adjusted, the participant. was dropped in the first scenario and rode for 10–20 seconds. Then they were dropped in the second scenario for another 10–20 seconds. After that, they were asked to answer the following questions verbally.

If you had to choose one route for your trip, which would you choose?

- Definitely Route A
- Probably Route A
- Indifferent
- Probably Route B
- Definitely Route B

If these were the only two options available, would you choose to ride a bike?

- I would not ride a bike.
- I would ride a bike.

Participants were asked to ride in 20 different scenarios (10 pairs of videos) and were asked the same questions after every pair. The pairs of videos that they were shown were the exact same pairs they were shown on the online survey. They were allowed to pause or end the simulation at any moment they wanted to. When the simulation ended, we asked participants what they thought about their experience and to share any comments or recommendations they had, which were recorded by research staff.

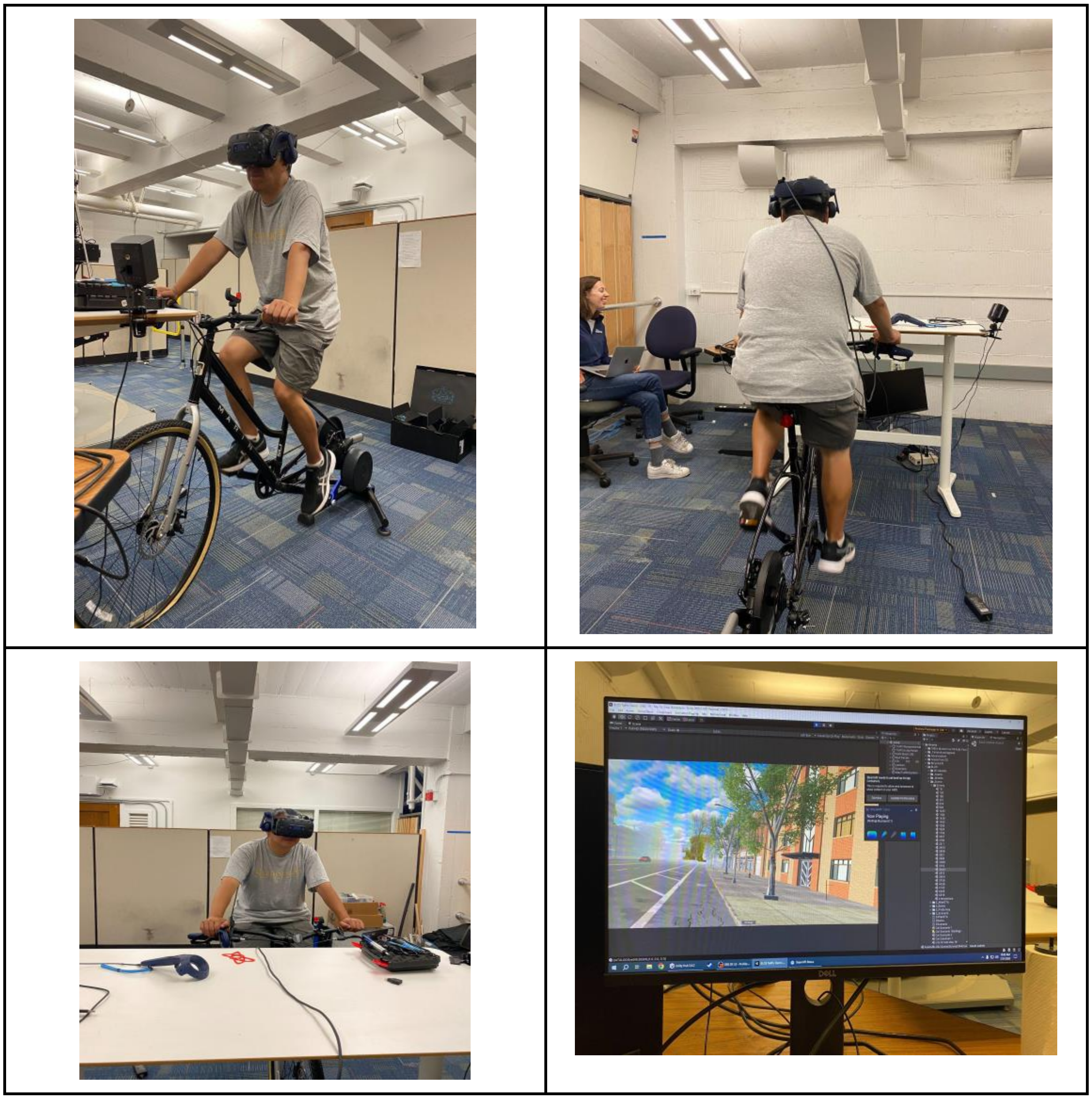

Figure 3. Subject riding the bicycle simulator

Results

Eight individuals participated in the in-person experiment, mostly composed of individuals who bike frequently. Table 3 shows the demographic breakdown of the participants.

Table 3. In-person participants' demographic characteristics (sample size of 8)

	Percent	Trip Distance	Percent
Gender			
Male	37.5	< 5mi	12.5
Female	62.5	5–19 mi	12.5
Race/Ethnicity		20-40 mi	25.0
White	75.0	> 40 mi	50.0
Asian	25.0		
Hispanic	0.0		
Bike Frequency			
Every day	25.0		
A few times a week	62.5		
A few times a month	12.5		

The majority of the participants were aged between 30 and 59 years.

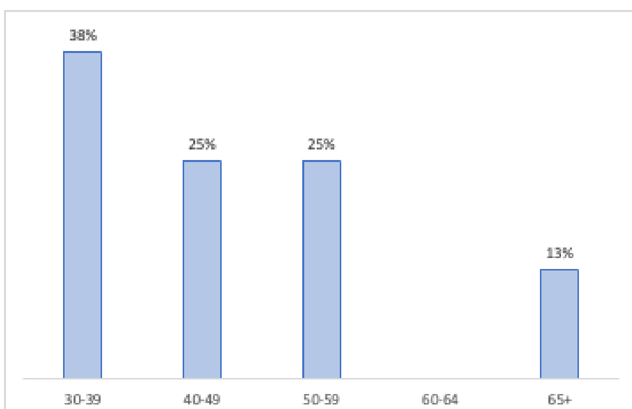

Figure 4. In-person participants' age distribution

Overall, there were differences between how participants responded online versus in person. The in-person and online survey asked the same choice question, and participants responded by providing a response from the same 5-point response scale (Definitely A, Probably A, Indifferent, Probably B, Definitely B). Out of 76 responses, 64 percent were different from the online response (Figure 5). In other words, 64 percent of responses did not match the answer provided on the 5-point response scale.

However, when we interpret “Definitely A” and “Probably A” as choosing just “A,” and similarly for “B,” we found that 63 percent of responses chose the same alternative.

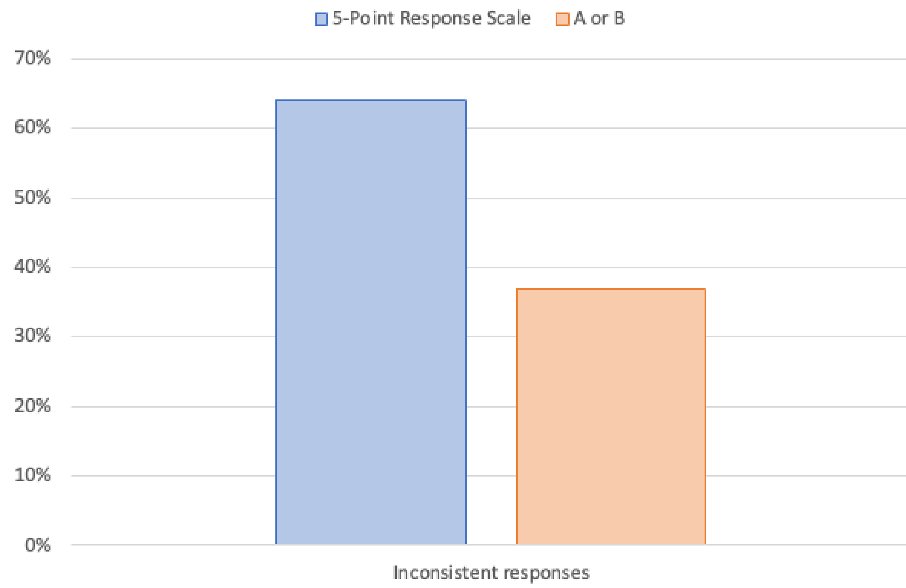

Figure 5. In-person responses vs. online responses

We observed a range of variations in responses between the online survey and the in-person experiment. Participants’ responses could vary drastically. For example, there were cases where participants went from Definitely A in the online survey to Definitely B in person, or vice versa. Participants’ responses also shifted moderately. For instance, some responses changed from Indifferent to Probably or Definitely. Responses could also slightly change, with answers shifting from Probably A to Definitely A, or vice versa. However, the number of Indifferent responses increased in the in-person experiment.

Discussion

This study sought to validate survey responses using a simulator study from a diverse demographic of bicyclists in California to develop BLOS metrics. The research team used a virtual bicycle simulator and tested eight subjects who rode a total of 76 pairs of scenarios (10 per participant). After each pair of scenarios, we recorded their response and compared it to the online survey.

In addition to collecting responses, we asked participants about their experience with VR. Overall, individuals had a positive response about the effectiveness of VR in mimicking real-life biking scenarios. Despite some of the limitations of the simulator (e.g., cannot move the steering wheel or brake), participants found the VR experience to be more life-like than watching the videos, which in turn allowed them to make a more realistic decision about the route alternatives they prefer. The immersive experience improved their perception of the road and its features and allowed a more life-like experience as they could hear and see cars driving right next to them. This latter point, in particular, was emphasized as a feature that heavily contributed to making the scenarios more realistic than the videos. The ability to see the cars driving next to them heightened their senses and allowed some to fully consider their preferences from a safety perspective. Furthermore, the VR world made the road conditions more visible (e.g., pavement cracks), a feature participants mentioned that they had not noticed while watching the videos. Finally, participants noted that the experiment itself was fun, more effective than the videos, and did not make them feel dizzy.

Participants also recommended ways to improve the simulator experience. Aside from wanting to be able to steer, participants mentioned adding vibrations to the bike to feel the cracks on the pavement and adding a fan to feel the wind of cars passing by and as the bike moves faster. Participants also noted that sometimes it was difficult to remember the scenario that they had ridden on previously to be able to make a choice between the pairs of scenarios. This could be improved by decreasing the wait time between the two scenarios, something that would require more processing power from the computer because the delay was due to the long loading times of the scenarios.

This study has some limitations that open future research opportunities. Our validation of the survey through a simulator experiment is limited given the small sample size that lacked demographic diversity. The outcomes of this study do not provide the ability to validate the bicycling behavior of different underrepresented groups to justify transportation equity. The future research should be conducted with a more representative group of people to prioritize transportation equity and generalize the research outcomes validity.

Conclusion

The study aimed to conduct a bicyclist user experience experiment in person using a virtual reality simulator and compare the in-person survey responses to the survey responses after viewing the videos online. This study created 30 virtual road environments by mimicking California state highways to conduct simulator experiments. We tested 76 scenarios for eight subjects and found that the majority of responses (64 percent) were not aligned with the online survey response. However, this percentage decreased to 37 percent when grouping responses into just two categories (A or B) instead of using a 5- point response scale. Most participants (98 percent) agreed to continue riding their bicycle if the shown infrastructure or route were the only two options for traveling to their destination. Due to the limited number of participants, this study did not separate the validation of the study by demographics, which can be covered in future studies.

The participants do respond differently when immersing themselves in a virtual reality world, which speaks to the potential that VR simulators have in allowing researchers to better understand bicycle preferences without compromising individual safety. All in-person participants confirmed that the VR experience has more life-like features and allows users to interact with their environment in a more realistic manner. The sounds of approaching vehicles and the ability to bike on a road with moving traffic heightens users' awareness of their surroundings and encourages them to bike in a way that they would in real life. The VR simulator enables users to better assess their preferences and level of comfort compared to a 2-D video.

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Appendix

Table 4. Independent variables used for the design of the virtual scenarios

Variable Name	Description	Values
Context	Urban or rural setting	Rural one-lane per direction Urban one-lane per direction Urban multi-lane per direction
Traffic volume	Average daily traffic on road	Low: < = 3,000 Medium: 3,000–6,113 High: > 6,113
Speed	Vehicle speed on road	Low: 25 mph Mid: 40 mph High: 55 mph
Heavy Vehicle (HV) Proportion	Proportion of traffic volume that is heavy-duty vehicles	No HV: 0% Low: 3% Mid: 6% High: 9%
Bike lane width	Width of the bike lane	0 ft (no bike lane and no shoulder) 2 ft (no bike lane, only shoulder) 5 ft (one-way Class II; one-way Class IV) 8 ft (two-way Class IV)
Buffer width	Width of the buffer	0 ft (no bike lane and no shoulder) 3 ft 7 ft 11 ft (8 ft parking lane + 3 ft buffer)
Barrier height 1	Height of the barrier	0 ft (no physical barrier) 0.5 ft (raised island) 3 ft (flexible or inflexible barrier)
Barrier height 2	Height of the second barrier Only applies when bike facility is a bike lane protected by a parking lane	0 ft (no physical barrier) 0.5 ft (raised island) 3 ft (flexible or inflexible barrier)
Pavement quality	Quality of bike lane pavement	Bad (many cracks) Good (some cracks) Perfect (smooth, no cracks)