Autonomous Vehicle-Cyclist Interaction: Peril and Promise

Ming Hou
University of Calgary
Calgary, Canada
ming.hou@ucalgary.ca

Karthik Mahadevan
University of Toronto
Toronto, Canada
karthikm@dgp.toronto.edu

Sowmya Somanath
University of Victoria
Victoria, Canada
sowmyasomanath@uvic.ca

Ehud Sharlin
University of Calgary
Calgary, Canada
ehud@cpsc.ucalgary.ca

Lora Oehlberg
University of Calgary
Calgary, Canada
lora.oehlberg@ucalgary.ca

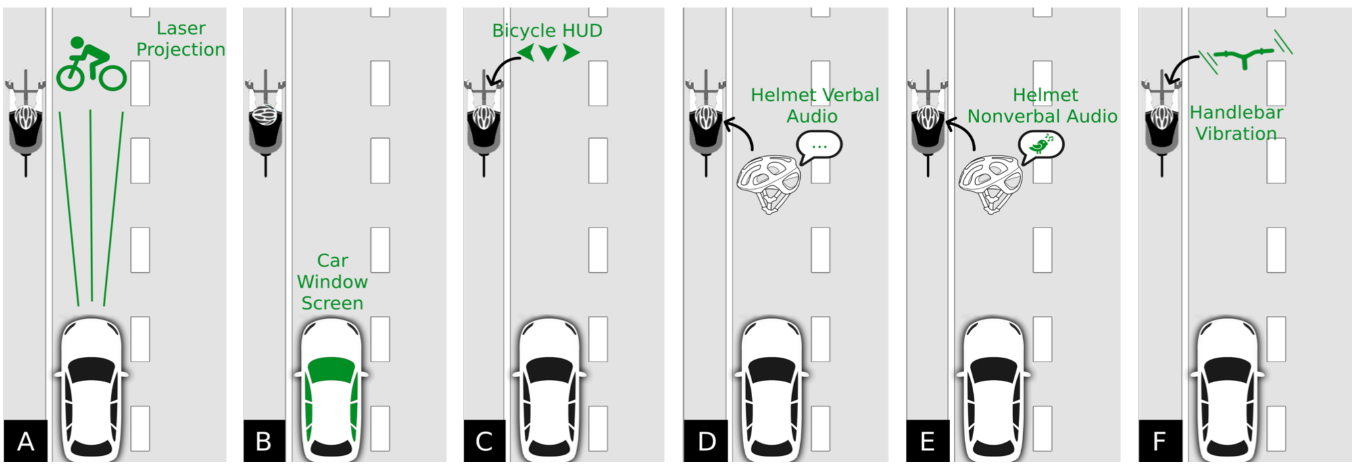

Figure 1. Interfaces implemented and tested in our virtual reality cycling simulator study: (A) Laser Projection, (B) Car Window Screen, (C) Bicycle Heads-Up Display (HUD), (D) Helmet Verbal Audio, (E) Helmet Nonverbal Audio, (F) Handlebar Vibration.

ABSTRACT
Autonomous vehicles (AVs) will redefine interactions between road users. Presently, cyclists and drivers communicate through implicit cues (vehicle motion) and explicit but imprecise signals (hand gestures, horns). Future AVs could consistently communicate awareness and intent and other feedback to cyclists based on their sensor data. We present an exploration of AV-cyclist interaction, starting with preliminary design studies which informed the implementation of an immersive VR AV-cyclist simulator, and the design and evaluation of a number of AV-cyclist interfaces. Our findings suggest that AV-cyclist interfaces can improve rider confidence in lane merging scenarios. We contribute an AV-cyclist immersive simulator, insights on trade-offs of various aspects of AV-cyclist interaction design including modalities, location, and complexity, and positive results suggesting improved rider confidence due to AV-cyclist interaction. While we are encouraged by the potential positive impact AV-cyclist interfaces can have on cyclist culture, we also emphasize the risks over-reliance can pose to cyclists.

Author Keywords
Autonomous vehicle-cyclist interaction; Interfaces for communicating intent and awareness

CCS Concepts
•**Human-centered computing** → *Empirical studies in HCI;*

INTRODUCTION
Communication between cyclists and vehicle drivers can be challenging [7, 24, 33]. Cyclists employ several techniques such as shoulder checking, hand-signaling, and ringing bells to communicate with other road users. In practice, these communication methods are limited. For example, a short over-the-shoulder glance from shoulder checking may not help a cyclist discern whether a vehicle driver is aware of them and intends to give them sufficient space, particularly if multiple vehicles are present [1]. Similarly, auditory communication can be masked by traffic noise, physically blocked from drivers by vehicle soundproofing, or have ambiguous meaning in the case

CHI '20, April 25–30, 2020, Honolulu, HI, USA.
2020 Association of Computing Machinery.
ACM ISBN 978-1-4503-6708-0/20/04 ...$15.00.
http://dx.doi.org/10.1145/3313831.3376884

of horns and bells. When cyclists indicate intent using hand signals, it is not always clear whether drivers have noticed the hand signal and are aware of its meaning.

In the near future, the introduction of autonomous vehicles (AV) may alleviate some of these problems. Awareness and intent are two key factors for AVs to communicate with other road users via interfaces [7, 8, 29]. Using the built-in sensing of AVs, vehicles can communicate their awareness and intent to cyclists (e.g., indicate that the vehicle is at a safe distance away from the cyclist), which in turn could help cyclists make better decisions about when to merge or overtake.

Companies such as Google and Uber have already tested semi-autonomous vehicles on city roads for several years [24, 28]. Surveys conducted in Pittsburgh, where semi-autonomous vehicles have been deployed, show that cyclists generally feel safer around autonomous vehicles than manually-driven vehicles [5]. Thus far, much of the academic and corporate interest has been directed towards the technological challenge of cyclist detection. For example, Waymo is implementing cyclist hand gesture recognition into its autonomous vehicles [12]. However, the actual interaction between cyclists and AVs is still an emerging research area [4, 9, 11].

To address some of the fundamental issues of AV-cyclist interaction research and design, we built a virtual reality cycling simulator, *ACS* (Autonomous Vehicle-Cyclist Simulator) (Figure 3). Using physical vehicles to explore AV interaction with cyclists could be dangerous, costly, and slow to iterate on prototype interfaces. ACS allows researchers to modularly prototype AV-cyclist interfaces in simulated traffic and examine cyclist behavior during different cycling tasks. Interfaces can also be toggled and evaluated in different combinations.

We primarily focus on one AV-cyclist road interaction scenario: cyclists merging into traffic. We used a lane merging scenario for two reasons. First, Kim et al. found that merging cyclists accounted for the majority of vehicle-cyclist accidents [14]. Second, lane merging requires cyclists to immediately process information and decide whether to act. Cyclists may choose to merge into traffic for a number of reasons, including avoiding lane obstructions or overtaking other road users. Cyclists in urban areas frequently encounter obstructions even in protected bike lanes [2]. However, due to differences in speed between cyclists and cars, it can be dangerous for cyclists to merge into traffic. We believe that AV-cyclist interfaces located on vehicles, bicycles, or road infrastructure could improve cyclist safety and confidence in this scenario.

To identify key communication elements for end-users (cyclists) in AV-cyclist interface design, we conducted user-centered design sessions with 10 participants. From these results, we prototyped 6 interfaces in our simulator and evaluated them with 18 participants. Both studies were conducted in Calgary, Canada, a city with limited on-street bicycling infrastructure [34]. We contribute: (1) an evaluation of using immersive cyclist simulators to help examine AV-cyclist interaction, (2) design considerations for interfaces that can be built to assist cyclists, and (3) an evaluation of those interfaces.

RELATED WORK

In this section, we first address previous studies on current cyclist behavior. Findings from these studies are important for determining key behaviors and signals in AV-cyclist interaction. We then discuss prior work on conceptual and prototype interfaces for autonomous vehicles that communicate with vulnerable road users. Lastly, we look at prior use of VR cycling simulators in research and identify important factors for immersion and data collection.

Cyclists on Today's Roads

People may or may not choose to cycle as a mode of transportation based on a range of factors. One of the major barriers to cycling is a fear of collisions, particularly due to perceptions that drivers behave dangerously when interacting with cyclists [33]. As a result, cyclists must not only be aware of road conditions, but also be vigilant of other vehicles that pose a risk to their safety. Trefzger et al. [32] analyzed and compared gaze behavior of cyclists and pedestrians in various traffic scenarios. Participants were asked to either cycle or walk through predefined routes while wearing eye trackers. The collected gaze data indicated that unlike pedestrians, cyclists focused heavily on the paths in front of them and generally paid minimal attention to any distractions to the sides. Trefzger et al. also found that cyclists performed shorter and less frequent "shoulder checks" – looking over their shoulder to check on traffic – than pedestrians following the same route, including at points along the route where researchers considered shoulder checking to be important, such as crosswalks.

Future AV interactions could change how cyclists and pedestrians behave on roads and interact with vehicles. Vissers et al. [35] provide a literature review on future interactions between autonomous vehicles and other road users. While pedestrians rely on human eye contact or gestures, cyclists are often relying on larger-scale, non-human indicators like vehicle motion to infer awareness or intent. Future autonomous vehicles are expected to mitigate unsafe vehicle behavior towards cyclists once sensors are refined [4, 24]. Many studies [8, 17, 29] aim to emulate human drivers' modes of communication with pedestrians and bridge the gap left by their absence; we believe that AV-cyclist interfaces could improve communication between cyclists and vehicles and offer safer road cycling conditions than today. We hypothesize that clearer AV-cyclist interfaces will improve cyclists' perception of safety by providing accurate information about vehicle awareness and intent.

There is also some indication from Trefzger et al. that the requirements for AV-cyclist interfaces will differ from AV-pedestrian interfaces [32], the latter of which has been the focus of recent research in HCI.

AVs and Vulnerable Road Users

Mahadevan et al. [18] proposed a number of interfaces for AV-pedestrian interaction. To examine the impact of these interfaces on pedestrian crossing behavior, Mahadevan et al. created an immersive VR-based simulation varying vehicle autonomy, interfaces, and pedestrian group behavior [17]. Their findings indicated that AVs with explicit communication interfaces impacted pedestrians' crossing strategy. Merat et al. [21] discovered from a survey of pedestrians and cyclists that most vulnerable road users wanted future AVs to explicitly confirm awareness of them through visual or auditory signals.

Researchers have also evaluated cyclist perception of AVs through qualitative observation. Hagenzieker et al. [11] explored how cyclists expect autonomous vehicles to behave in contrast to manually-driven cars through a photo experiment. Participants were presented with a series of photos involving a cyclist interacting with either an autonomous or manually-driven car. They were then asked how confident they were that the cyclist would be noticed by the vehicle and given right of way. Consistent with prior pedestrian AV trust studies [35], Hagenzieker et al. found that trust in autonomous vehicles was overall lower than trust in manually driven vehicles.

Dey et al. [9] presented six AV interface concepts to communicate with vulnerable road users including cyclists and pedestrians. The concepts were designed with the stated goals of being scaleable, versatile, and unambiguous though they have not been prototyped or validated in user studies. One aspect of these designs is that they did not differentiate between AV-cyclist interaction and AV-pedestrian interaction as distinct design problems requiring separate approaches.

We aim to build on these projects by testing the use of explicit interfaces for AV-cyclist interaction. Unlike Dey et al. [9], we aim to distinguish some of the unique challenges involved in AV-cyclist interaction and evaluate interfaces designed to address these problems. Similar to Mahadevan et al. [17] we also built a VR simulator to examine the suitability of interfaces for AV-cyclist interactions.

Indoor Bicycling Simulators in Research

Indoor biking simulators have been used for a wide range of research applications such as evaluating infrastructure design [15, 30], cyclist interface prototyping [19], and studying vehicle-cyclist interactions [15]. Most simulators use either large screens [13, 19] or virtual reality goggles [15, 26] to increase immersion.

Nazemi et al. [26] conducted a study with the aim of validating cycling simulators as tools for studying cyclist behavior in depth. They created several simulation environments intended to test cyclist's perceived safety by varying several elements of the simulated environment. The use of a simulator involving traffic environments can be found in the study by Kwigizile et al. [15] who asked participants to navigate several road scenarios involving different arrangements of pedestrians and vehicles. Both studies found that cyclists behaved similarly in VR as they would in reality and that changes in simulated environments prompted realistic behavioral responses.

Meanwhile, interaction designers have used these simulators to help test possible new interactions for cyclists. Matviienko et al. [19] used multimodal feedback in a wide-screen indoor bicycling simulator to explore cues that could be used to communicate with child cyclists. They designed and implemented visual, auditory, and haptic navigational aids situated on either the handlebar or helmet. They found that each modality played a useful role in helping participants navigate a simple route designed for new cyclists. We are interested in extending the application of these modalities to AV-cyclist interaction.

Overall, while research exploring AV-cyclist interface design in particular is relatively rare, there is growing interest in cyclist interactions. Our paper builds upon these prior works by first examining what cyclists themselves might prioritize in AV-cyclist interface design. We then introduce *ACS*, a VR prototyping tool for creating immersive cycling simulations of mixed and homogeneous traffic to evaluate AV-cyclist interfaces. To our knowledge, ACS is the first cycling simulator to focus on interface design and testing for AV-cyclist interaction.

CONCEPTUALIZING AV-CYCLIST INTERFACES

We conducted a preliminary design study to understand what modes of communication people expect from AVs when cycling and how interfaces could address those expectations. By receiving input from future end-users – current and potential cyclists– we can develop ideas for preliminary interfaces that improve the road experience for a broad range of cyclists.

Participants

We recruited ten participants (4 male and 6 female) between the ages of 18 and 45. Six of the participants had substantial previous experience designing user interfaces while the other four participants were experienced road cyclists.

Procedure

Each participant took part in an individual design session. We adapted the PICTIVE [25] participatory design method, and asked participants to sketch interface prototypes for AV-cyclist communication (Figure 2). We chose to base our activity off of PICTIVE because it helps participants visualize the scenarios that they are designing for and offers an easy way to express ideas visually through labels.

We presented participants with initial sketches of our base scenario: a cyclist on a road shoulder with a vehicle in the next lane. The sketches offered a front and back perspectives of the scene. We asked participants to generate interfaces that helped the vehicle communicate awareness and intent. Participants were given 30 minutes to design three interfaces by drawing on the sketch and using labels. We encouraged participants to describe their thought process while creating the sketches.

Participants were initially provided with some basic labels for each modality, such as “display”, “speaker”, and “haptic feedback”. Participants were also free to create their own labels or combine labels in order to describe more complex sequences. Labels could be placed anywhere on the sketch corresponding to where the interface component would appear in the real world, including road infrastructure or bicycles.

We then provided participants with 30 minutes for discussion and reflection. After completing three designs, each participant then ranked their interfaces based on safety and practicality for ten scenarios where the vehicle had to communicate to the cyclist. Each scenario introduced specific factors such as whether the cyclist had shoulder checked (affecting cyclist visibility of some interfaces), or if the vehicle would be able to stop in time if the cyclist merged at that moment. After ranking the interfaces, participants were also given the opportunity to reflect on and suggest changes to their interfaces.

Figure 2. Example sketch from a design session participant: a projection-based interface that provides color-coded cues in front of a cyclist on whether it is safe for them to merge into the adjacent lane.

Results

Our ten participants created 32 interfaces designs in total, with two participants presenting four interfaces instead of three. All sketches incorporated either visual, auditory, or haptic feedback; 12 designs were multimodal. In total, 29 designs utilized visual communication in some way, while 13 designs had auditory communication and seven had haptic feedback. The most frequently used component overall was speakers, which featured in all interfaces using auditory feedback. However, only two audio interface designs were unimodal, as most participants identified hearing impairment as a potential risk.

Laser projections were the second most common interface element (12 designs). Laser projections were also the most popular unimodal cue implementation, with nine designs featuring no other cues. Of the designs that incorporated haptic feedback, six out of seven involved vibrating parts of the bicycle, most often the handlebar, and one suggested vibrating the cyclist's phone.

Most interfaces that were designed were relatively simple to understand and use. Only three of the visual interface designs and one audio interface design used complex encoded cues that cyclists would need to learn beforehand. The remaining visual and auditory interfaces presented likely familiar cues: red and green to represent "stop" or "go", simple icons such as common stop symbols, outlines of bicycles, or numbers and units indicating measures such as distance to the approaching vehicle. Almost all audio interfaces used either simple phrases or car honks. The overall simplicity of cues was often attributed to the current state of city road cycling: *"I won't be able to process anything complicated as well because there is a lot of noise and when I look away it has to be quick"* (P4).

Locations of cues also varied significantly. 15 of the interfaces presented involved at least one component located outside of the vehicle. Ten of those designs had elements situated on the bicycle and five had elements placed on road infrastructure. During discussion, six participants identified that interfaces located on the bicycle would require both bicycles and cars to adopt a common system for wireless communication. Similarly, participants also commented that interfaces located on the road would require changes to road infrastructure. While this deterred two participants completely from placing interfaces on entities other than vehicles, the remaining eight participants still used the design space of placing interfaces on roads or bicycles for at least one design.

INTERFACE PROTOTYPES

Incorporating some of the ideas presented in our design study, we prototyped interface designs in *ACS*. The majority (29/32) of participants' design ideas were visual; thus, we chose to implement and test more visual designs (3/6) than other modalities. When designing interfaces, we modified ideas from the design study, and intentionally selected a set that included different modalities and interface placements. While some of the designs featured combinations of several interface elements working in relatively complex sequences, it is beyond the scope of this paper to exhaustively implement every possible permutation. We instead chose to identify the most prevalent elements across the design set and implement these modularly in the simulation. Furthermore, we chose to consolidate functionally similar cues that differed in their use of specific symbols or language. For example, 10 out of 13 proposed auditory cues were intended to play a message only when the cyclist began a merge or approached an obstacle. Because the primary difference was the symbolic language of the message and not the message itself, we instead reduce these interfaces to two variants: vocal and non-vocal auditory notifications.

Four of the six VR-implemented interfaces (laser projections, verbal audio, nonverbal audio, and handlebar haptics) were proposed by participants. The remaining two designs (helmet HUD and vehicle windshield display) were also adapted from participants' ideas, but underwent changes in location after preliminary testing in order to improve visibility. Overall, out of the seven most common interface concepts from the study, only LEDs were excluded due to general overlap with screen displays with regards to proposed functionality.

Visual Interfaces

We implemented three different visual interfaces– laser projections, vehicle screens and bicycle HUDs (see Figure 1)– to evaluate the impact of placement and different visual symbols. Interfaces become active on vehicles once the vehicle notices a cyclist. In our simulation, vehicles notice cyclists when within 100 meters behind them, and while there are no significant obstructions blocking line of sight.

In our laser projections interface (see Figure 1), vehicles projected symbols in two different states onto the road in front of the cyclist . Cyclists do not have to shoulder check to see the projection but it is slightly to their side because it is on the road. In one state, a green bicycle silhouette indicates that it is safe for the cyclist to merge onto the vehicle's lane; in the other state, a red outline of a hand indicates it is still unsafe.

In our screen-based cues (see Figure 1), the vehicle uses the entire windshield of the vehicle as a display representing one of two states. When green it indicates that the cyclist can merge onto the lane and when red it indicates that it is unsafe to merge. Cyclists will have to shoulder check to view the screen when the vehicle is behind them.

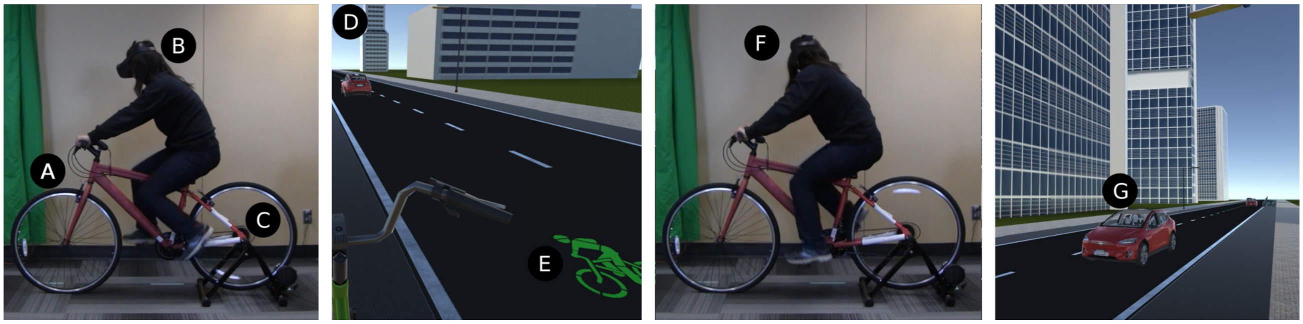

Figure 3. In the ACS Experimental Setup, a cyclist rides a (A) bicycle equipped with a sensor on its rear hub and wears a (B) VR Headset. The bicycle is stabilized on an (C) Indoor Bike Trainer. Inside the (D) Simulator View, the cyclist is alerted to an oncoming vehicle thanks to a (E) Laser Projection Interface. When a cyclist looks over their shoulder during a (F) shoulder check, they can see an oncoming (G) autonomous vehicle

In the heads-up display interface (see Figure 1), the vehicle communicates with systems on the bicycle to displayed information on a bicycle heads-up display (HUD) located above the handlebars. Arrows and distance indicators help the cyclist keep track of nearby vehicles in each lane and change color from green to red in order to indicate it is unsafe to merge. Similar to the laser projection interface, shoulder checking is not required to see the interface itself.

Audio Interfaces

When an audio interface vehicle sees a cyclist initiating or imminently merging, such as when the cyclist turns towards traffic or is within 10 to 20 meters of an obstacle, the cyclist will hear an audio cue. This cue will repeat until the cyclist has stopped merging, passed the obstacle, or finished merging into the lane.

We implemented two types of audio cues: verbal and nonverbal (see Figure 1). Both indicate one of two states: either it is safe to merge, or it is unsafe to merge. The verbal cues use simple statements (*"Don't merge", "You may merge"*). For nonverbal cues, we chose to use a car horn honk to signal an unsafe merge, similar to how human drivers might alert a cyclist. To indicate safe merging, we used a non-verbal "cuckoo" sound similar to those used in accessible pedestrian crosswalk signals around the world [31].

One deviation from the audio cue ideas provided in the design study was the location of the speaker. Because the audio cues are targeted towards a specific cyclist, and the distances between vehicle and cyclist may vary, the auditory cues play from the cyclist's helmet (the participant's VR headset) instead of playing from vehicles. Otherwise, cyclists may have difficulty differentiating or hearing the audio signals.

Haptic Interfaces

Vehicles with haptic interfaces provide vibrations in the cyclist's handlebars when it is safe to merge (see Figure 1). In the simulation, we triggered a vibration on the handlebar-mounted VR controllers while it is touching the participant's hand. To help cyclists distinguish these vibrations from normal vibrations from bicycle motion, the haptic cue is a high-frequency vibration that lasts for two seconds. We do not provide haptic cues when it is unsafe, to avoid requiring cyclists to recognize and interpret unique vibration patterns.

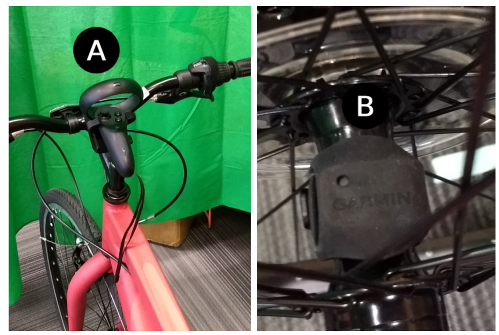

Figure 4. Physical sensors attached to the bike: (A) Handlebar-Mounted VR Controller for Steering, (B) Garmin Speed Sensor 2

DESIGN OF ACS

We implemented the prototypes on *ACS*, a VR cycling simulator for designing and evaluating AV-cyclist interfaces. We developed ACS using Unity 3D for the Oculus Quest headset.

Simulation Platform

We used an Oculus Quest VR headset because of its lack of tethering wires, which offers a greater degree of immersion at the cost of some graphical fidelity. We chose to simulate the bicycle using a physical bicycle (2016 Hyper Bicycles 700C Spinfit), an adult-sized city bike. To ensure that participants are stable and keep their balance, we used an indoor bike trainer to secure the bicycle.

Because the cyclist is occupied with cycling during the simulation, the researcher manually transitions to the next trial after each trial using the right controller of the Oculus Quest. The other controller is mounted on the handlebar of the bicycle (see Figure 4). As the cyclist turns the handlebars of the bike, the simulation checks the rotation of the left controller and reflects these movements in the virtual simulation on the virtual bike. The cyclist controls their bicycle speed in the simulator by pedalling. We mounted a Garmin Speed Sensor 2 on the rear hub, which monitors and transmits wheel rotations to the Oculus Quest, allowing us to calculate speed. Cyclists use the mechanical brakes on the bike to slow down the rotation of the rear wheel, which correspondingly slows down their bike in the simulation. Figure 4 shows the controller placement and speed sensor and Figure 3 shows the simulator in use.

Simulation Environment and Traffic

The environment of *ACS* is a one way, two-lane, city road with shoulders for the cyclist to ride on (see Figure 3). These conditions are designed to reflect road infrastructure in Calgary, Canada, an automobile dependent city with lower bicycle traffic share and less on-street cycling infrastructure than nearly every other major Canadian city [34]. The simulation has ambient wind noise and light traffic sounds at levels that still allow auditory cues from vehicles to be audible. Traffic characteristics are manipulated by the researcher through button inputs to the right controller of the Oculus Quest headset. The autonomy level of traffic in the simulation can be set to either homogeneous or mixed; each individual AV interface can be toggled on or off.

To ensure that the vehicle model does not affect cyclist decisions between interactions, all AVs in the simulation are identical models of a red electric car. In *ACS*, vehicle driving behavior is identical across all vehicles. The primary factor that is manipulated between are the AV-cyclist interfaces. Consequently, we can better evaluate the impact of each interface. All cars have a default speed of approximately 14m/s (50 km/h) to represent city traffic. Based on data collected on city cycling speed [3, 10] as well as our own observations in the simulator, we anticipate cyclist speed to range from 4 m/s (14.4 km/h) to 6 m/s (21.6 km/h). When a vehicle is within 20 meters behind the cyclist and detects that the cyclist is turning into traffic, the AV decelerates until it roughly matches the speed of the cyclist. If the cyclist is stopped or if a collision is imminent, cars will come to a full stop. AVs begin accelerating back to default speed once the cyclist is no longer in the way.

To prompt merging behavior, obstructions will periodically appear on the lane shoulders. An overview of obstruction frequency and rate in Manhattan, New York City, is provided by Basch et al. [2]. However obstructions are only categorized in broad categories with no specific breakdown. To our knowledge, that study is the only work thus far to document obstructions encountered by cyclists in urban areas. Miyadai et al. [23] evaluated cyclist behavior and swerve width when avoiding obstacles and found that results were approximately the same across different types of stationary obstacles. However, to ensure consistency, all spawned obstacles are identical. We chose parked mopeds as our obstacle, as it is clear that the mopeds will not move without a rider. We chose not to use parked cars as an obstacle due to the perceived risk of door collisions that cyclists may have [16].

When the cyclist is 30 meters away from the obstacle in front of them, a vehicle spawns at either 24, 48, or 72 meters behind the cyclist depending on the trial. We identified these parameters through trial-and-error during pilot testing. We found that these spawn distances meaningfully vary the amount of time the cyclist has to decide when to merge. At 30 meters from an obstacle, the cyclist is close enough to begin considering how to merge into traffic, but far enough that they will not immediately merge.

The simulation scenario allows us to observe how cyclists behave when merging onto traffic from road shoulders or bike lanes. There is no generally agreed-upon standard for the longitudinal distance cyclists should maintain from nearby vehicles when merging, or vice-versa. We choose a longitudinal distance of 20 meters as the point where vehicles with interfaces communicate that merging is no longer safe. We chose this distance because the vehicle is clearly visible to the cyclist during a shoulder check, but is still far enough away to allow for a reasonably safe merge if the cyclist chooses to merge late. Because our study focuses on how AV interfaces impact merging strategy, our control scenario were cars with no explicit AV-cyclist interface.

Because AV-cyclist interactions have been rarely explored in naturalistic and simulated environments in literature, our initial exploration focuses primarily on cyclist interactions with AV-only traffic. We disabled manually-driven vehicle traffic in the simulation for our study.

STUDY

We tested our six implemented AV-cyclist prototype interfaces using our simulator. Our goal was to observe how cyclists adjusted their behavior in response to different cue modalities and interface locations in merging scenarios. In particular, we wanted to identify trade-offs between various factors of AV-cyclist interface design, such as modality (audio, visual, haptic), cue location, and complexity. We provide details about our procedure and data collection process below.

Participants

We recruited 18 participants (8 male and 10 female) with ages ranging from 18 to 55 through social media and word of mouth. Similar to the design study, participant cycling experience ranged from infrequent cyclists to experienced hobbyists. 15 of the participants had previously experienced VR but none had experience cycling in VR prior to the study. We did not require participants to be experienced cyclists, but they did need to know how to ride a bicycle.

Study Procedure

The study began with a pre-study questionnaire to collect participants' cycling experience and demographic information.

Our participants cycled in our virtual city road environment for 30 minutes. We asked participants to stay on the left shoulder of the simulation road, and to only merge when necessary to avoid obstacles in front of them. Before beginning the study task, we described the interfaces to participants and showed pictures of the various states of each visual interface. The simulation ran continuously between trials, allowing the participant to continue cycling.

Each trial began when the participant was 30 meters away from an obstacle; a researcher verbally told participants which interface they would be encountering before each trial. At the beginning of each trial, an autonomous vehicle spawned either at 24, 48, or 72 meters behind the participant in the closest road lane. We tested each spawn distance once for each of the 6 interfaces as well as for a baseline condition with no interface where shoulder checking is necessary to visually confirm if merging is safe; this resulted in 21 trials in total per participant. When merging, participants could choose their actions: either let the nearby vehicle pass first before merging into the adjacent lane, or merge in front the oncoming vehicle. Each interface signaled participants not to merge once the vehicle was within 20 meters behind them. Consequently, vehicles that spawned 24 meters behind participants signalled participants not to merge almost immediately. By contrast, vehicles that spawned 72 meters behind almost always allowed participants to merge in time, unless the participant chose to slow down significantly or stop. Vehicles that spawned at 48 meters behind participants were more ambiguous and gave participants more choice on whether to wait for vehicles to pass or merge in front of them.

We streamed the simulation to a nearby display to help the researcher provide the participants with instructions and initiate each new trial. During each trial, the researcher recorded whether or not the cyclist shoulder checked and whether or not they chose to allow nearby vehicles to pass first before merging. After each trial, the researcher verbally asked participants to rate on a 1 (low) to 5 (high) scale (a) their level of confidence in their merging decision ("How confident were you in your decision?") and (b) how helpful they found the interface to be for their decision ("How helpful was the interface towards your merging decision?"). In the baseline condition (no interface), we asked participants to assess how helpful observing vehicle motion was in making merging decisions.

To partially balance the effect of interface order, we created a 3x3 Latin square based on interface modality order (visual-auditory-haptic, haptic-auditory-visual, and auditory-haptic-visual), randomizing the order of the interfaces within each modality. Consequently, we could order conditions such that participants experienced all interfaces within each modality as a sequence so as to more easily compare interfaces within a modality. A 6x6 Latin square was considered, but then some participants would experience the same modalities back-to-back, while others would not. With 18 participants, 6 participants were assigned to each order. We randomized the order of interfaces within each modality and the order of vehicle spawn distances for each interface. We recorded the study by placing a camera on a nearby desk, and by capturing the view from within the simulation.

After completing the primary study task, participants then completed two post-study questionnaires. The first questionnaire asked participants to rank the interfaces and the baseline in order of helpfulness, and to rationalize their rankings. In the second questionnaire, we asked participants about their overall experience and thoughts regarding the simulation.

Analysis

In our analysis, we assessed participant merging behavior, confidence, and perceived interface helpfulness for all trials performed, yielding 378 (18 x 21) merges in total. We classified participant behavior in each trial based on whether or not they shoulder checked, and whether they merged in front of vehicles or waited for all nearby vehicles to pass before merging. We also recorded and analyzed responses to the pre-study and post-study questionnaires.

FINDINGS

We summarize the key findings from our study and the pre-study and post-study questionnaires. Important findings from our study include the confidence effect of interfaces when compared to the baseline as well as behavioral effects of interfaces. We also discuss how participants ranked interfaces in terms of perceived helpfulness when merging. Behavioral adjustments that cyclists made in response to interfaces are another focus. Shoulder checking behavior in particular was significantly affected by some interfaces. Prior to performing ANOVA analyses, we used histograms of our results to affirm that our data was normally distributed.

Confidence Scores

We performed a one-way ANOVA with 7 levels on our participants' merging confidence and found a statistically significant interface effect on confidence ($F(6, 102) = 7.491$, $p < 0.001$). This indicates that participants had significantly higher confidence when merging with the aid of an interface than without. The laser projection and HUD in particular ranked higher than the baseline (Bonferronis adjusted $p < 0.001$ for both).

Interface Usefulness Scores

We performed a one-way ANOVA of 7 levels on participants' perceived interface usefulness and found that participants considered interfaces to be more useful than the baseline, which was merging based just on vehicle motion ($F(6, 102) = 12.299$, $p < 0.001$). In this case, the laser projection and HUD again achieved statistically significant higher ratings in comparison to the baseline (Bonferronis adjusted $p < 0.003$ and $p < 0.031$, respectively). In contrast, the vehicle windshield display was the only interface to receive a lower mean rating than the baseline, although this differences was not statistically significant. Twelve of eighteen participants indicated some degree of preference for one auditory cue over the other: 8 participants preferred verbal cues while 4 preferred nonverbal cues.

Shoulder Checking Behavior

All participants shoulder checked for every trial in the baseline case (no interface) and for every trial with the windshield display; both required shoulder checks to assess vehicles behavior or the interface itself. In contrast, in the 270 trials involving the five interfaces that do not explicitly require shoulder checking (laser projection, bicycle HUD, verbal audio cue, nonverbal audio cue, haptic cue), participants only shoulder checked 29 times. From this we learned that participants relied on interface cues instead of visual interpretations of vehicle behavior to make merging decisions.

Stopping and Waiting Behavior

To determine if vehicle spawn distances or interfaces affected whether participants stopped and waited to let nearby vehicles pass before merging, we performed a two-way ANOVA on stopping behavior. We encoded data such that zeros represented trials where participants did not stop and ones represented trials where participants did stop. We found no statistically significant distance by interface interaction effect ($F(12, 204) = 1.11$, $p = 0.353$). We did find a statistically significant distance effect with ($F(2, 34) = 4.362$, $p = 0.021$), but there is no statistically significant interface effect ($F(6, 102) = 0.907$, $p = 0.497$). Pairwise comparisons reveal that participants stopped and waited more often when vehicles spawned 24 meters behind them than when vehicles spawned 72 meters behind (Bonferroni adjusted $p = 0.039$). Notably, participants stopped and waited 12 out of 18 times when interacting with nonverbal auditory cues, and only stopped and waited six times with verbal auditory cues.

Post-Study Interface Rankings

When participants were asked to rank the interfaces as well as the baseline case, the bicycle HUD received 8 out of 18 votes for first place while the laser projection received 6 out of 18 votes for first place. The baseline case ranked last overall, receiving 9 out of 18 votes for last place. The least popular explicit interface was the windshield display, which was the lowest ranked interface for 11 participants.

DISCUSSION

Our findings suggest that explicit interfaces improved participant's confidence and were considered helpful. In this section, we discuss potential implications from our findings for future AV-Cyclist interface design and cycling culture in AV traffic.

Using VR Cycling Simulators for Interface Prototyping

14 out of 18 participants indicated that the decisions they made in the simulator would be similar to their real life decisions. The remaining four indicated that their difference in behavior was due to the lack of risk in the simulation. We were able to observe cyclist behavior using the simulator; however, we did not evaluate whether the simulator accurately simulated real-life cycling behaviour. While it is difficult to evaluate how these changes may exactly map to real life, we think there are still many observations that can be made about potential factors for interface designers to address.

Perhaps the most significant benefit of simulators remain in their use to replicate and scale studies. New interfaces and environmental conditions can be easily introduced within the simulation. Modifying the environment in simulations or adding new testing variables may require just some changes to code, as opposed to real world prototyping where hardware and scalability are more substantial limiting factors.

Interfaces and Cycling Culture

We found no significant interface effect on stopping behavior in the simulator. These results are not surprising as each interface provided a condensed form of shoulder checking without requiring the cyclist to physically look behind them. However, shoulder checking and interpreting vehicle motion to make merging decisions is not inherently unsafe. Present day cyclists observe and gauge the state of traffic themselves to decide whether to merge or not merge; drivers are expected to be attentive and aware of their surroundings, including other road users. Overall, collision rates for cyclists on roads are low, although concerns about safety deter many from cycling [6, 28, 33]. In cases where the responsibilities and expectations placed on drivers are not met, cyclists can feel endangered. The introduction of interfaces allows for greater certainty around vehicle-cyclist interaction, as reflected in the overall increase in confidence expressed by our participants when interacting with interfaces. All 18 participants felt that interfaces presented more awareness and intent information than the baseline. 15 participants stated they would cycle more around traffic and 16 responded that they would cycle more in general if they felt safer cycling around traffic.

Thus, we believe that the increase in cyclist confidence that interfaces provide may reduce risk concerns and lower the barrier to cycling. AV-cyclist interfaces could actually promote cycling as a safer mode of transportation. However, we also want to emphasize that it is uncertain whether this perceived increase in safety corresponds to an actual difference in safety when on the road with AVs.

Merging Against the Machine

We were surprised by the frequency at which some participants still merged immediately after interfaces began signalling that merging was unsafe. This behavior was not ubiquitous, as there was still a statistically significant distance effect on merging and stopping behavior. For the most part, when participants defied interfaces, they did so right after the state switched – *"I thought it would be safe right when it changed since the car was still far"* (P11). In these cases, participants still relied on the interface to make their decisions, even if it was to act against the explicit message. Interfaces that convey a more continuous measure of environmental information may help alleviate the risks of such behaviors. The bicycle HUD, the only non-discrete interface, was the best received interface overall because participants felt they were able to gauge the distance measurement themselves and make an independent decision of whether they felt comfortable merging.

Interface Complexity

16 out of 18 participants stated that the lack of human drivers in the autonomous vehicles was not important to their merging decisions and that they mainly focused on vehicle positioning. However, the fact that the baseline was rated lowest in cyclist confidence demonstrates that vehicle motion was not sufficient to assure cyclists that their decision to merge was safe. We think this is due to the ambiguity of whether non-autonomous or non-interface vehicles are aware of cyclists and intent.

Consequently, we believe our approach of simple cues that communicate basic positioning information or binary 'safe or unsafe' merging conditions is worth further exploration. These interfaces reduce potential information overload, particularly when cyclists have limited time to make decisions and could easily be overwhelmed by complex cues [20]. Concise cues could help reduce hesitation during important moments. Limited visibility of vehicles, the brevity of shoulder checking, or external factors such as environmental noise further limit the effectiveness of complex cues. However, during abnormal or unexpected circumstances there may be a need to incorporate more nuanced cues.

Interface Locations

Each potential interface location had trade-offs. Several were evident in our study conditions; more are evident when considering real-world implementations of interfaces.

Bicycle-based interfaces would require wireless communication between the vehicle and the interface. Unless a communication standard is established across all vehicles and bicycles, wireless communication will not be reliable. To avoid this, bicycles could also incorporate vehicle detection; but, this would require the bicycle to include a complex suite of sensors.

Haptic interfaces would be particularly challenging to locate on the bicycle. Only four participants considered haptic interfaces to be helpful; for many others, vibrations from bicycle motion introduced confusion regardless of the relative strength of the interface's haptic vibration. While there are some examples of haptic cues for cycling navigation purposes [19], they may not be practical for AV-cyclist communication.

For auditory cues, it may also be practical to only play sound from vehicles when close to cyclists to reduce the need for wireless communication. However, the presence of multiple cyclists or vehicles could muddle messages intended for specific cyclists, bringing the scalability of such cues into question. Other factors could reduce the effectiveness of auditory cues in real world implementations, such as louder environmental noise. However, auditory cues could still be valuable for visually impaired cyclists or distracted cyclists. Alternately, autonomous vehicles could be equipped with loud horns similar to those present in manually-driven vehicles, which are easily audible but still an imprecise form of communication.

Visual interfaces located on vehicles benefit from being directly implementable on vehicles, but tested very poorly with our participants. The vehicle windshield display was the only explicit interface to receive lower helpfulness rankings than the baseline of interpreting vehicle motion. Ten participants considered visual interfaces situated on autonomous vehicles to be unnecessary, mostly due to the need to shoulder check. Participant 8 said *"interfaces on cars are redundant information to the position of the car"*. While placing more complex cues on vehicles could provide additional information, visibility becomes a concern depending on distance. For example, despite the large surface area of the windshield display interface, its binary color-coded cues, and high level of detail of the in-simulation vehicle models, participants still rated the readability of that interface as poor during brief shoulder checks unless the vehicle was immediately behind them. Smaller or more detailed interfaces will likely be even more difficult to decipher, even at close distances. Other factors in real life such as sunlight and visual clutter from the environment might further reduce visibility.

Meanwhile, the laser projection interface avoided some of the real-world complications from wireless communication and low visibility during a shoulder check. While the cue itself is located on the road in front of the cyclist, the device would still be housed on the vehicle. However, visibility could still be a potential issue in the real world, particularly in bright conditions. Obstructions, poor weather, and road surface quality could also obscure projections. Physical constraints could also limit the distance that images can be projected by vehicles.

Considering these trade offs, we believe single-modality, single-location interfaces will not be sufficient for cyclists. Compared to pedestrians, cyclists move faster and only have intermittent view of vehicles when travelling in the same direction [32]. When an interface fails to convey important information to a cyclist, having a redundant cue to offset risk can be crucial, particularly if cyclists expect some form of cue.

Blind Trust in Interfaces

Shoulder checking is a vital action when changing lanes while cycling with traffic. Some city guidelines advise that cyclists shoulder check before initiating a merge and do so again before turning into the lane [27].

With the exception of the vehicle windshield display, most of the interfaces evaluated in our study conveyed information sufficient to make a merging decision without shoulder checking. However, the intention of these interfaces was not to supplant shoulder checking entirely. Our findings indicate that most participants stopped shoulder checking almost entirely once those interfaces were present, developing a blind trust. We believe that the lack of risk in the simulation environment is a contributing factor, as expressed by several participants: *"I would never be trusting a HUD with absolute certainty. There are too many risks associated with trusting a gadget that can easily go wrong"* (P8). However, we think that there may still be potential implications for future interface design.

When asked if they trusted the simulation vehicles to give them space when an interface was not present, only 4 out of 18 participants responded yes. However, when asked if they trusted the simulation vehicles when an interface was present, 17 participants said yes. These results indicate that despite the safety of the simulated environment, interfaces were still required for AVs to gain the trust of participants.

When asked how the introduction of interfaces affected the responsibility distribution between vehicles and cyclists, 12 out of 18 participants believed that cyclist responsibility was reduced. Over time, cyclists could blindly trust and become dependent on interfaces, which may introduce danger if the AV's sensors are malfunctioning or not necessarily accurate. Interface designers will need to carefully consider and test how interfaces influence cyclist perception of risk and how to dissuade cyclists from taking unnecessary risks.

Prior research has expressed concerns over unpredictable future behavior once vulnerable road users realize that risk-adverse autonomous vehicles will reliably stop and yield for them [22, 35]. We think certain AV-cyclist interfaces may exacerbate these issues by further diminishing cyclists' desire to verify they are safe with their own eyes before acting.

Importantly, our findings demonstrate that due to cyclist over-reliance, interfaces that did not require shoulder checking are likely unsuitable for mixed traffic or even in homogeneous AV traffic with varying interfaces. Cyclists will not be able to rely on any specific modalities or cues in the traffic merging scenario unless certain interfaces and standards are adopted for autonomous vehicles industry-wide.

Should AV-Cyclist Interfaces be used when Merging?

Our work demonstrates that while AV interfaces have promise in improving cyclist confidence when merging, these interfaces could still prove redundant or detrimental due to over-reliance. Unlike pedestrian street crossings, merging cyclists only have intermittent over-the-shoulder views of traffic behind them to verify safety, and may be less likely to confirm with their own eyes with increasing dependence on interfaces. Audio and haptic interfaces could also be masked by environmental noise or vibration from bicycle movement. However, if these issues can be addressed, AV-cyclist interfaces could actually encourage more of the general population to cycle in an autonomous vehicle future. Interfaces bridged much of the lack of trust that many of the participants expressed towards baseline AVs.

Extensive further development and testing is needed to make a final conclusion about the value of AV-cyclist interfaces. However, our contributions offer a starting point for future work that explore alternate interface designs and additional scenarios. For example, cyclists turning at an intersection may experience many of the same environmental factors and rules, including speed discrepancies, the need to shoulder check, and limited visibility of vehicles not directly in front of the cyclist.

AV-Cyclist Interfaces versus AV-Pedestrian Interfaces

Because of the shared environments and platforms between AV-cyclist and AV-pedestrian interaction, we think it is important to deliberate the possibility of simply using the same interfaces for both scenarios. In AV-pedestrian street crossing interactions, both parties are slow moving and able to maintain visual contact. For AV-cyclist interactions in a merging scenario, both parties are fast moving and vehicles are behind the cyclist's line of sight [32]. Due to these differing behaviors and requirements, it is unsurprising that results for conceptually similar interfaces often varied significantly between our study and AV-pedestrian studies. For example, Mahadevan et al. [17] assessed AV-pedestrian interfaces in a virtual reality pedestrian simulation, testing several interfaces with similar locations and modalities as our interfaces (visual interfaces on the vehicle, auditory cues). The authors concluded verbal audio and color-coded visual interfaces situated on vehicles to be most effective in the context of their simulation. In our findings, neither the visual interface (car window screen) on the vehicle nor both auditory cues yielded cyclist behavior that was statistically different from the baseline condition. Both interfaces also received low results in confidence and usefulness rankings from participants. These disparities highlight how designers need to consider critical interaction behaviors that are specific to the needs of certain road users.

LIMITATIONS

Our work serves as an initial look into using virtual reality cycling simulators to assist the AV-cyclist interface design process. However, there are several limitations that should be considered. The participant sample size for both studies was small, and the scenario of cyclists merging into traffic is just one of many complex interactions that cyclists have with vehicles. Vehicles in the simulation maintained similar speeds and reacted in consistently similar ways to cyclist behavior; in reality, with a range of autonomous vehicles on the road, there may be much more variance in how AVs react. Additional real-world traffic elements were also missing from our simulation, such as pedestrians and other cyclists.

There are some technical limitations related to the use of virtual reality headsets, such as limited field of view and audio spatialization. Our choice of the Oculus Quest headset for immersion resulted in some reduced graphical fidelity and draw distances as compared to non-portable VR headsets. However, apart from the lack of risk in the simulation, most participants found the simulation and setup to be a fairly convincing representation of a cyclist traffic merging scenario.

CONCLUSION AND FUTURE WORK

As autonomous vehicles begin to populate roads, new autonomous driving system interfaces have the opportunity to better communicate awareness and intent in lieu of a human driver. In addition to leveraging precise sensor data to improve safety for other road users, interfaces can also communicate feedback from the sensor data to other road users.

However, there are a range of ways that vehicles can explicitly communicate in a given situation. Vehicle designers must determine the effectiveness of various cues and modalities, taking into account a spectrum of road users with different requirements such as vehicles, pedestrians, or cyclists. Our paper details the use of a VR cycling simulator to prototype and test various interfaces for AV-cyclist interaction. Due to the challenges present in conducting studies to evaluate such interfaces in real life, we believe that VR cycling simulators are useful tools to reduce cost and safety risks.

We performed a user-centered design study to develop a series of interface designs for AV-cyclist interaction while merging. We implemented six prevalent concepts from the design study in the simulation and conducted a user study to observe the behavioral effects of each interface. Our simulator study demonstrated that interfaces had a positive effect on cyclist confidence when interacting with AVs and assisted with merging decisions. Improving confidence on the road may reduce barriers to cycling, as one of the current barriers to cycling is a perceived lack of safety from vehicle traffic.

Over reliance on interfaces can also pose significant danger to cyclists, who may shoulder check less, especially in mixed traffic. The unique dangers that over dependence on interfaces present may be important considerations for designers.

As this is an initial exploration into AV-cyclist interactions, there are many possible directions for future work. We would like to explore a larger and more complex subset of potential AV-cyclist interactions, including behavior at intersections. Future research could look at how cyclist respond to a more heterogeneous mix of traffic that includes vehicles with varying levels of autonomy or multiple types of AV interfaces. Furthermore, we would like to test our prototypes when operating with multiple vehicles and road users of different types. Multiple participants could act as either pedestrians or cyclists and interact with AVs in a VR simulation. We expect the scalability of some of our interfaces to be questioned, with modifications required to allow cues to more specifically identify the sender and recipients while avoiding cognitive overload. We would also like to evaluate the effectiveness of multimodal interfaces now that we have performed an initial exploration of several individual modalities.

As autonomous-vehicle cyclist interactions become more prevalent on the road, we expect the presence of AV interfaces to improve the conditions and appeal of road cycling. Our work demonstrates the benefits of using VR cycling simulators as a design and testing platform, and also grants some preliminary insight into potential interfaces and modalities.

Acknowledgements

We would like to thank Dr. Tak Fung for his expertise and support in statistical analysis and reporting. Support and funding thanks to the Natural Sciences and Engineering Research Council of Canada (NSERC) RGPAS-2019-00077, RGPIN-2013-312218, RGPIN-2018-05950, and RGPIN-2016-04540.

REFERENCES

[1] Peter Apasnore, Karim Ismail, and Ali Kassim. 2017. Bicycle-vehicle interactions at mid-sections of mixed traffic streets: Examining passing distance and bicycle comfort perception. *Accident Analysis and Prevention* 106 (sep 2017), 141–148. DOI: http://dx.doi.org/10.1016/j.aap.2017.05.003

[2] Corey H. Basch, Danna Ethan, and Charles E. Basch. 2019. Bike Lane Obstructions in Manhattan, New York City: Implications for Bicyclist Safety. *Journal of Community Health* 44, 2 (apr 2019), 396–399. DOI: http://dx.doi.org/10.1007/s10900-018-00596-4

[3] Silvia Bernardi and Federico Rupi. 2015. An analysis of bicycle travel speed and disturbances on off-street and on-street facilities. *Transportation Research Procedia* 5 (2015), 82–94. DOI: http://dx.doi.org/10.1016/j.trpro.2015.01.004

[4] Bryan Botello, Ralph Buehler, Steve Hankey, Andrew Mondschein, and Zhiqiu Jiang. 2019. Planning for walking and cycling in an autonomous-vehicle future. *Transportation Research Interdisciplinary Perspectives* 1 (jun 2019), 100012. DOI: http://dx.doi.org/10.1016/j.trip.2019.100012

[5] Eric Broer, BikePGHm, and Alexandria Shewczyk. 2019. AV Survey Results 2019. (2019). https://www.bikepgh.org/our-work/advocacy/save/av-survey-results-2019/

[6] Chris Cavacuiti. 2009. *An Overview of Cycling Research: Selected Facts, Statistics, Citations and Quotations*. Technical Report. 1–69 pages. www.sharetheroad.ca

[7] Christine Chaloupka-Risser and Elisabeth Füssl. 2017. The importance of communication between cyclists and other traffic participants and its potential in reducing traffic safety-critical events. *Transactions on Transport Sciences* 8, 1 (apr 2017), 24–30. DOI: http://dx.doi.org/10.5507/tots.2017.004

[8] Shuchisnigdha Deb, Lesley J. Strawderman, and Daniel W. Carruth. 2018. Investigating pedestrian suggestions for external features on fully autonomous vehicles: A virtual reality experiment. *Transportation Research Part F: Traffic Psychology and Behaviour* 59 (nov 2018), 135–149. DOI: http://dx.doi.org/10.1016/j.trf.2018.08.016

[9] Debargha Dey, Marieke Martens, Chao Wang, Felix Ros, and Jacques Terken. 2018. Interface concepts for intent communication from autonomous vehicles to vulnerable road users. In *Adjunct Proceedings - 10th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications, AutomotiveUI 2018*. Association for Computing Machinery, Inc, 82–86. DOI: http://dx.doi.org/10.1145/3239092.3265946

[10] Jennifer Dill and John Gliebe. 2008. *Understanding and Measuring Bicycling Behavior: A Focus on Travel Time and Route choice*. Technical Report December. 1–74 pages. DOI:http://dx.doi.org/OTREC-RR-08-03

[11] Marjan P. Hagenzieker, Sander van der Kint, Luuk Vissers, Ingrid N.L.G. van Schagen, Jonathan de Bruin, Paul van Gent, and Jacques J.F. Commandeur. 2019. Interactions between cyclists and automated vehicles: Results of a photo experiment *. *Journal of Transportation Safety and Security* (2019). DOI: http://dx.doi.org/10.1080/19439962.2019.1591556

[12] Henrik KretzschmarJiajun Zhu. 2014. Cyclist hand signal detection by an autonomous vehicle. (2014). https://patents.google.com/patent/US9014905B1/en

[13] R. Herpers, W. Heiden, M. Kutz, D. Scherfgen, U. Hartmann, J. Bongartz, and O. Schulzyk. 2008. FIVIS bicycle simulator - An immersiv game platform for physical activities. In *ACM Future Play 2008 International Academic Conference on the Future of Game Design and Technology, Future Play: Research, Play, Share*. 244–247. DOI: http://dx.doi.org/10.1145/1496984.1497035

[14] Joon Ki Kim, Sungyop Kim, Gudmundur F. Ulfarsson, and Luis A. Porrello. 2007. Bicyclist injury severities in bicycle-motor vehicle accidents. *Accident Analysis and Prevention* 39, 2 (mar 2007), 238–251. DOI: http://dx.doi.org/10.1016/j.aap.2006.07.002

[15] Valerian Kwigizile, Jun-seok Oh, Pavel Ikonomov, Raed Hasan, Cole G Villalobos, Aous Hammad Kurdi, and Anil Shaw. 2017. *Real Time Bicycle Simulation Study of Bicyclists ' Behaviors and their Implication on Safety FINAL REPORT*. Technical Report. https://rosap.ntl.bts.gov/view/dot/34885

[16] Brendan M. Lawrence, Jennifer A. Oxley, David B. Logan, and Mark R. Stevenson. 2018. Cyclist exposure to the risk of car door collisions in mixed function activity centers: A study in Melbourne, Australia. *Traffic Injury Prevention* 19 (feb 2018), S164–S168. DOI: http://dx.doi.org/10.1080/15389588.2017.1380306

[17] Karthik Mahadevan, Elaheh Sanoubari, Sowmya Somanath, James E. Young, and Ehud Sharlin. 2019. AV-Pedestrian Interaction Design Using a Pedestrian Mixed Traffic Simulator. Association for Computing Machinery (ACM), 475–486. DOI: http://dx.doi.org/10.1145/3322276.3322328

[18] Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. 2018. Communicating awareness and intent in autonomous vehicle-pedestrian interaction. In *Conference on Human Factors in Computing Systems - Proceedings*, Vol. 2018-April. Association for Computing Machinery. DOI: http://dx.doi.org/10.1145/3173574.3174003

[19] Andrii Matviienko, Swamy Ananthanarayan, Shadan Sadeghian Borojeni, Yannick Feld, Wilko Heuten, and Susanne Boll. 2018. Augmenting bicycles and helmets with multimodal warnings for children. In *MobileHCI 2018 - Beyond Mobile: The Next 20 Years - 20th International Conference on Human-Computer Interaction with Mobile Devices and Services, Conference Proceedings*. Association for Computing Machinery, Inc. DOI: http://dx.doi.org/10.1145/3229434.3229479

[20] Peter Melinat, Tolja Kreuzkam, and Dirk Stamer. 2014. Information Overload : A Systematic Literature Review Theoretical Background : Information Overload. *International Conference on Business Informatics Research* (2014), 72–86. DOI: http://dx.doi.org/10.13140/2.1.4293.7606

[21] Natasha Merat, Tyron Louw, Ruth Madigan, Marc Wilbrink, and Anna Schieben. 2018. What externally presented information do VRUs require when interacting with fully Automated Road Transport Systems in shared space? *Accident Analysis and Prevention* 118 (sep 2018), 244–252. DOI: http://dx.doi.org/10.1016/j.aap.2018.03.018

[22] Adam Millard-Ball. 2018. Pedestrians, Autonomous Vehicles, and Cities. *Journal of Planning Education and Research* 38, 1 (mar 2018), 6–12. DOI: http://dx.doi.org/10.1177/0739456X16675674

[23] Masayuki Miyadai, Teruo Uetake, and Masahiro Shimoda. 2012. How does a cyclist avoid obstacles? *Journal of human ergology* 41 (12 2012), 95–100.

[24] Lars Möller, Malte Risto, and Colleen Emmenegger. 2016. The social behavior of autonomous vehicles. In *UbiComp 2016 Adjunct - Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. Association for Computing Machinery, Inc, 686–689. DOI: http://dx.doi.org/10.1145/2968219.2968561

[25] Michael J. Muller. 1991. PICTIVE - An exploration in participatory design. *Conference on Human Factors in Computing Systems - Proceedings* (1991), 225–231. DOI:http://dx.doi.org/10.1145/108844.108896

[26] Mohsen Nazemi, Michael A.B. van Eggermond, Alexander Erath, and Kay W. Axhausen. 2019. Studying cyclists' behavior in a non-naturalistic experiment utilizing cycling simulator with immersive virtual reality. *TRB Annual Meeting Online* (2019), 19–02954. DOI: http://dx.doi.org/10.3929/ETHZ-B-000297131

[27] Ontario Ministry of Transportation. 2015. *Cycling Skills: Ontario's Guide to Safe Cycling*. Technical Report. 1–40 pages. www.mto.gov.on.ca

[28] Praveena Penmetsa, Emmanuel Kofi Adanu, Dustin Wood, Teng Wang, and Steven L. Jones. 2019. Perceptions and expectations of autonomous vehicles âĂŞ A snapshot of vulnerable road user opinion. *Technological Forecasting and Social Change* 143 (jun 2019), 9–13. DOI: http://dx.doi.org/10.1016/j.techfore.2019.02.010

[29] Amir Rasouli and John K. Tsotsos. 2019. Autonomous Vehicles That Interact With Pedestrians: A Survey of Theory and Practice. *IEEE Transactions on Intelligent Transportation Systems* (mar 2019), 1–19. DOI: http://dx.doi.org/10.1109/tits.2019.2901817

[30] Carlos Sun and Zhu Qing. 2018. Design and Construction of a Virtual Bicycle Simulator for Evaluating Sustainable Facilities Design. *Advances in Civil Engineering* 2018 (2018). DOI: http://dx.doi.org/10.1155/2018/5735820

[31] A. Y.J. Szeto, N. C. Valerio, and R. E. Novak. 1991. Audible pedestrian traffic signals: Part 3. Detectability. *Journal of Rehabilitation Research and Development* 28, 2 (1991), 71–78. DOI: http://dx.doi.org/10.1682/JRRD.1991.04.0065

[32] Mathias Trefzger, Tanja Blascheck, Michael Raschke, Sarah Hausmann, and Thomas Schlegel. 2018. A visual comparison of gaze behavior from pedestrians and cyclists. In *Eye Tracking Research and Applications Symposium (ETRA)*. Association for Computing Machinery. DOI: http://dx.doi.org/10.1145/3204493.3204553

[33] Sergio A. Useche, Luis Montoro, Jaime Sanmartin, and Francisco Alonso. 2019. Healthy but risky: A descriptive study on cyclists' encouraging and discouraging factors for using bicycles, habits and safety outcomes. *Transportation Research Part F: Traffic Psychology and Behaviour* 62 (apr 2019), 587–598. DOI:http://dx.doi.org/10.1016/j.trf.2019.02.014

[34] Nithya Vijayakumar and Cherise Burda. 2015. *Cycle Cities Supporting cycling in Canadian cities*. Technical Report.

[35] Luuk Vissers, Sander Van Der Kint, Ingrid Van Schagen, and Marjan P Hagenzieker. 2017. Safe interaction between. January (2017). DOI: http://dx.doi.org/10.13140/RG.2.2.23988.86408