Light it Up: Evaluating Versatile Autonomous Vehicle-Cyclist External Human Machine Interfaces

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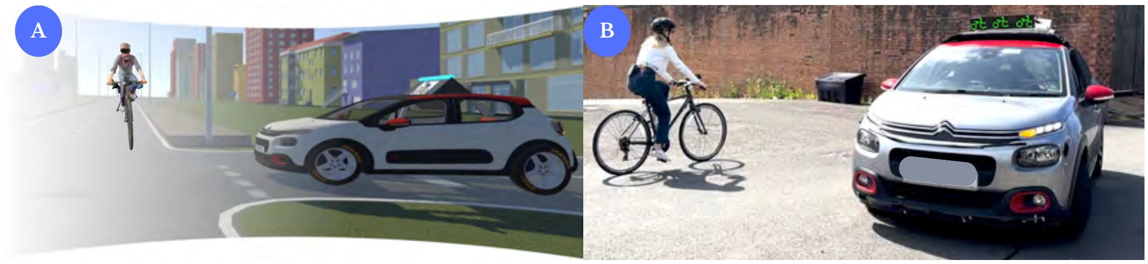

Fig. 1. Our two-stage eHMI evaluation. (A) Cyclist encounters an AV with an eHMI in a VR cycling simulator, (B) cyclist encounters an AV with an eHMI in a real-world setting.

The social cues drivers exchange with cyclists to negotiate space-sharing will disappear as autonomous vehicles (AVs) join our roads. External Human-Machine Interfaces (eHMIs) on vehicles are a possible replacement for drivers' social signals. How these should communicate with cyclists is unknown. We evaluated three eHMIs in two stages. First, we compared eHMI versatility, acceptability and usability in a VR cycling simulator ($N = 20$); cyclists preferred eHMIs appearing in their peripheral vision and using colour-coded signals communicating AV intent. Second, we refined the interfaces based on our findings and compared them outdoors ($N = 20$). Participants cycled around a moving car with real eHMIs. They preferred eHMIs using large surfaces surrounding the vehicle and animations to support colour changes. We conclude with novel guidelines for designers to develop versatile eHMIs based on first-hand AV-cyclist interaction experience. Our findings establish the factors that enable AVs to operate safely around cyclists across different traffic scenarios.

Additional Key Words and Phrases: Autonomous Vehicle-Cyclist Interaction, eHMI

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1 INTRODUCTION

Cyclists share the road with motorised vehicles, encountering them in various traffic scenarios during their commutes, such as intersections and roundabouts [3]. This exposes them to potential conflicts over road space, as cyclists and drivers seek to occupy the same space simultaneously [22]. These conflicts can pose significant dangers if not resolved. For instance, statistics from the UK indicate that over 60% of vehicle-cyclist collisions between 2015 and 2020 occurred at intersections and roundabouts [2]. Cyclists and drivers often rely on social communication cues like facial expressions and hand gestures to safely navigate through space-sharing conflicts [3]. Clear communication is crucial for cyclist safety on the road; there were over 4,000 vehicle-cyclist collisions in the UK between 2015 and 2020 because one of the road users failed to interpret the other's intentions correctly [2].

As autonomous vehicles (AVs) become a part of our roads [6], human drivers and the social cues they provide will disappear; cyclists and other road users will no longer be able to rely on current social interactions to safely negotiate the use of road space [19]. This could lead to more ambiguities and dangerous encounters. In response, the automotive industry and the AutomotiveUI[1] community have suggested external Human-Machine Interfaces (eHMIs) to replace these missing social cues [10]. eHMIs are *"displays of any modality placed on the vehicle's exterior"* [5]. Examples of eHMIs include LED light strips on the vehicle's bonnet or a speaker mounted on the roof. These have primarily been developed and evaluated for scenarios involving pedestrians encountering AVs at crossings, where the focus is on the vehicle's front [10]. However, cyclists present distinct requirements and challenges; they can be positioned anywhere around a vehicle and travel at higher speeds. Riders will encounter AVs in many traffic scenarios, including spontaneous ones like lane merging [3, 15, 18]. eHMIs designed for AV-cyclist interactions must be *versatile*, meaning they must function consistently across all traffic scenarios and provide clear communication with cyclists throughout their journeys.

AV-cyclist eHMI research has focused on gathering the requirements for these interfaces based on how cyclists and human drivers currently communicate [3, 4, 8], designing early concepts [5], and evaluating them in individual traffic scenarios [18]. To extend this, we conducted a two-stage evaluation of eHMIs in practice. Three versatile eHMIs were compared: a light ring around the vehicle, a rooftop emoji display, and on-road projections. These were tested across five traffic scenarios critical for interactions between human-driven vehicles and cyclists [3]: (1) Controlled Intersections, (2) Roundabouts, (3) Uncontrolled intersections, (4) Lane merging and (5) Bottlenecks. The first stage used a virtual reality (VR) cycling simulator with participants encountering AVs using eHMIs while navigating the five scenarios. Results indicated that cyclists preferred a colour-coded signalling system from the AV, with red indicating the AV will not yield and green that the AV will yield to the cyclist and give them right-of-way. A second iteration of each eHMI was developed based on this feedback and evaluated in Stage 2, a Wizard-of-Oz study conducted outdoors, with cyclists riding around a real moving car using actual eHMIs in the traffic scenarios. Cyclists preferred eHMIs using the entire vehicle body as a signalling platform rather than a single location, such as the roof, as they can infer the AV's message through quick glances.

This research investigates the practical use of eHMIs with cyclists in simulated and outdoor environments. The two-stage evaluation focused on the versatility, acceptability and usability of eHMIs through measures of cyclist perception (questionnaires) and cycling behaviour (speed and shoulder checks). We used our findings to develop guidelines assisting designers in contributing versatile AV-cyclist eHMIs suitable for real-world use. We contribute:

- Two empirical evaluations (one in VR, one with an actual vehicle) investigating the versatility, acceptability and usability of two iterations of novel AV-cyclist eHMIs through cyclist perception and behaviour;
- A methodology to compare multiple eHMIs outdoors, around a moving vehicle, across different traffic scenarios;
- Novel design guidelines for versatile AV-cyclist eHMIs based on first-hand interaction experience;
- A proposed versatile AV-cyclist eHMI based on the guidelines.

[1]Automotive User Interfaces: auto-ui.org

2 RELATED WORK

Introducing self-driving vehicles without an approach to resolving space-sharing conflicts with cyclists (and other vulnerable road users, VRUs) could have significant safety implications as they encounter AVs across many different traffic scenarios with varying levels of traffic control [15]. This was highlighted in real-world studies by Pokorny et al. [28] and Pelikan [27], who observed autonomous shuttle bus-cyclist interactions and found that the absence of a human driver or an interface to communicate with the cyclist caused many issues in resolving space-sharing conflicts. The very cautious driving style of the buses made their intentions unclear, meaning that cyclists hesitated to pass them, resulting in cyclists being forced into oncoming traffic and the buses making hard stops. These findings offer real-world evidence that there needs to be some facilitator to communicate the AV's intent and maintain cyclist safety on the road. Hagenzieker et al. [16] compared cyclists' perceptions of AVs vs. human-driven vehicles by asking riders to judge photographs of vehicle-cyclist encounters. Participants were more confident that a human-driven vehicle was aware of them due to the availability of social cues; this suggests that there needs to be some form of explicit communication between an AV and a cyclist for these vehicles to replace human-driven ones. These foundational studies cemented the need for AV-cyclist interfaces and paved the way for research to explore their design space and requirements.

Both Berge et al. [8] (interview with cyclists) and Al-Taie et al. [4] (online survey) explored early requirements and potential placements of AV-cyclist interfaces. Cyclists wanted reassurance from AVs yielding to them when they have right-of-way; this is where most interactions happen with drivers. They preferred displays placed on the vehicle or environment rather than the bike or cyclist. There was great variability in cyclists' characteristics (e.g. experience or carried devices), and cyclists are already used to interfaces on the environment (e.g. traffic lights) or vehicle (e.g. directional indicators). This narrowed design space also corroborates with the emerging consensus that eHMIs are a promising solution to facilitating interaction between AVs and human road users [10, 17, 21]. However, in their literature review, Dey et al. [10] found that most eHMIs were designed and evaluated according to *pedestrian* needs, who encounter the front of vehicles at crossings [15]. There is no comprehensive evaluation of AV-cyclist eHMIs covering a range of traffic scenarios cyclists are likely to encounter in their journeys [7].

To begin addressing this gap, Al-Taie et al. [3] gathered the requirements for AV-cyclist interfaces (including eHMIs) through in-the-wild observations of driver-cyclist encounters in multiple traffic scenarios and a naturalistic study with cyclists wearing eye-trackers. Over 50% of encounters resulted in interaction, providing real-world evidence that AV-cyclist interaction must be facilitated in the future. Most interactions happened when cyclists had right-of-way, and drivers should have yielded to them. The road users also interacted differently between traffic scenarios, cementing *versatility* as a key issue that separates AV-cyclist interfaces from pedestrian ones and suggesting that evaluations of cyclist interfaces should cover multiple traffic scenarios, an approach we took in this paper. In a follow-up study, Al-Taie et al. [5] conducted design sessions with cyclists and AutomotiveUI experts to develop eHMIs around a real car. Each session resulted in two designs for a specific traffic scenario, e.g. a controlled intersection with traffic lights. The authors synthesised a taxonomy showing different eHMI features and contributed eHMI designs from this taxonomy. We evaluated these as a starting point in this paper. These were a *cyan light bar around the car* using animation patterns to communicate the AV's intent and awareness of cyclists, a *rooftop display* communicating through emoticons and an *on-road projection* showing riders the AV's intentions. See Section 3.2 for a detailed explanation of the eHMIs.

2.1 Evaluating AV-Cyclist eHMIs

Cycling interfaces, such as augmented reality (AR) headsets [32], vibrating helmets [31] or eHMIs [10], are commonly evaluated in simulated or controlled outdoor environments. Hou et al. [18] evaluated five AV-cyclist interfaces, two of which were eHMIs, in a VR simulator. Participants were tasked with cycling in the virtual world and merging lanes with an AV behind them across different interface conditions. They were asked about their confidence in performing the lane merging manoeuvre and the perceived usefulness of each interface. Shoulder checking and stopping behaviour (i.e. if the cyclist let the AV pass) were also measured. The authors found that having an AV-cyclist interface improved participant confidence and performance. eHMIs placed on specific car areas (e.g. windows or windscreen) did not perform well compared to ones using large surfaces, such as road projection, as they diverted cyclists' attention from the road. However, this work only explored lane merging, so the versatility of their designs is unknown. Our paper widened the scope and evaluated eHMIs in five scenarios with different characteristics [3]. A VR simulator also showed promise in examining these interfaces in a controlled setting without any practical, safety or environmental concerns, e.g. visibility issues for road projections [34]. It also helped the authors use SAE level 5 AVs without any human driver and easily switch between high-fidelity implementations of the interfaces. We took this approach in the first stage of our investigation. However, we followed it up with a real-world evaluation of the eHMIs to understand the practical limitations of implementing the eHMIs and allow for more natural cycling behaviour.

Matviienko et al. [25] developed an augmented reality (AR) cycling simulator deployed on a Hololens[2] to evaluate AV-cyclist interfaces that use AR. The authors only considered encounters at uncontrolled intersections, so how the interfaces performed beyond this scenario is unknown. They found that interfaces improved perceived safety and cycling performance as cyclists proceeded at the intersection with smaller gaps between them and the AV when an interface was used. The AR simulator helped trigger real cycling behaviours with participants cycling on a moving bicycle in physical space. We considered this approach. However, the field-of-view limitations of current AR headsets and the need to conduct the study in a dark indoor space motivated us to proceed with a two-stage investigation that used VR and outdoor space. A VR simulator allowed us to overcome any field-of-view and immersiveness issues in AR simulators without sacrificing any practical or environmental limitations on the eHMIs, and the outdoor study allowed participants to appreciate riding around real eHMIs mounted on a real car with greater ecological validity [34].

Existing research showed outdoor evaluations of cycling interfaces. However, these are rarely conducted around moving cars. Vo et al. [31] evaluated a vibrating helmet that warned cyclists about nearby obstacles such as cars. Participants cycled on an outdoor 20m long track. An experimenter controlled the helmet's cues remotely via Bluetooth. Participants were asked to state the direction and proximity of an obstacle based on the helmet's haptic cues. However, there were no real obstacles around the cyclist due to safety concerns; we used a real moving car in our investigation's second stage to trigger natural responses from cyclists, allowing us also to measure cycling behaviour such as speed changes and shoulder checks. Matviienko et al. [23] conducted a two-step study evaluating cues to assist child cyclists in navigation. These were first explored in a screen/projector-based cycling simulator, followed by a test track study outdoors. This motivated us to take a similar direction, but we took an iterative design approach; our interfaces were revised based on participant feedback from the simulator evaluation before moving to the real-world study.

Stage 2 of our investigation required us to convince participants that they were riding around a driverless car. We took Rothenbücher et al.'s [29] *Ghost driver* method. A human driver was hidden in a car seat costume to produce the illusion that the car was autonomous. This was helpful in Wizard of Oz studies investigating AV-pedestrian interaction.

[2]Hololens AR headset: microsoft.com/en-us/hololens

For example, Dey et al. [13] used *Ghost driver* to evaluate an eHMI in a real-world setting. A car with a cyan-coloured light-bar eHMI approached a real pedestrian crossing closed off from non-participants. The light bar used different animation patterns to indicate yielding, and participants indicated their willingness to cross using a slider. They found that eHMIs were key in resolving ambiguity in AV-pedestrian interaction; participants were more willing to cross when the car used an eHMI. We took a similar approach to Dey et al.'s [13] in the second stage of our investigation, but we compared multiple eHMIs with cyclists riding around and interacting with an 'autonomous' car in different scenarios, allowing us to gain, for the first time, insight into how cyclists interact with AV eHMIs in a real-world setting.

2.2 Summary and Research Questions

eHMIs are a promising solution to facilitate AV-cyclist interactions necessary to navigate future traffic [3–5, 8]. However, there is no thorough evaluation of these interfaces and how they can interact with riders across various scenarios with varying levels of traffic control [10]. Existing work has instead focused on requirements gathering [3, 5] and evaluating interfaces in a single traffic scenario [18]. Work with pedestrians has evaluated eHMIs in VR and real-world settings [10, 13] and shown them to be good methods. In this paper, we scale up these approaches to evaluate three eHMI designs across five traffic scenarios, where the AV communicates its yielding intent; previous work showed this is where interaction is needed [3, 5, 8]. We conducted a two-stage investigation using a VR cycling simulator and a Wizard-of-Oz outdoor evaluation with real eHMIs on a real car. We answer the following research questions:

RQ1 How versatile, acceptable and usable are *eHMIs* in terms of *cyclist perception*?
RQ2 How versatile, acceptable and usable are *eHMIs* in terms of *cycling behaviour*?

3 STAGE 1: EHMI EVALUATION IN A VR CYCLING SIMULATOR

Versatility is key for eHMIs to work effectively around cyclists [3]. However, previous work has presented prototype designs [5], but they have never been tested, so it is unknown how they perform across traffic scenarios. This study used a VR cycling simulator to evaluate three eHMI designs which participants encountered across five traffic scenarios, allowing us, for the first time, to test the versatility of AV-cyclist eHMIs and bring them closer to real-world use.

3.1 Participants

We recruited 20 participants (4 Female, 16 Male; Mean Age = 29, SD = 6.6) through social media advertising. Ten cycled at least once a week, two at least once a month, five multiple times a year, and three once a year or less. Two participants cycled in VR before. All had experience riding in [redacted], on which our simulator was based. Participants were compensated with a £10 Amazon voucher. The University ethics committee approved the study.

3.2 Apparatus

The study used a Virtual Reality (VR) cycling simulator (see Figure 2) composed of a Giant Escape 3 size medium hybrid bicycle [3] mounted on a Wahoo Kickr Snap smart trainer[4]. Similar to Hou et al. [18]'s simulator, the wheel-on trainer allowed cyclists to use the bike's back brake in the virtual environment without any alterations to the bike. A Coospo Bluetooth speed sensor [5] attached to the back wheel hub controlled speed in the virtual environment. We used a Meta

[3]Giant Escape 3 bicycle: giant-bicycles.com/gb/escape-3
[4]Wahoo kickr snap: wahoofitness.com/devices/indoor-cycling/bike-trainers/kickr-snap-buy
[5]Coospo speed sensor: coospo.com/products/coospo-bk467-cadence-speed-sensor-dual-mode-2pcs

Fig. 2. The VR cycling simulator: (A) Meta Quest Pro headset; (B) the headset's left controller mounted on the handlebars for steering; (C) a fan simulating headwind; (D) a wheel-on indoor bicycle trainer and (E), a Bluetooth speed sensor attached to the rear hub.

Quest Pro headset[6] to display the virtual world and measure gaze behaviour (using its eye-tracker) during the study. Like Hou et al. [18]'s setup, the headset's left controller was attached to the handlebar centre to translate turn angles into the virtual world according to the controller rotation. The virtual environment was developed using Unity3D 2021.3.29f1; the EasyRoads3D package[7] was used due to its realistic textures and UK-like road infrastructure assets. A fan was placed 60cm in front of the participant to combat simulator sickness and increase immersion by simulating headwind [24]. An iPad was used to complete post-condition surveys hosted on Qualtrics[8].

3.3 Implementing the eHMIs

We used three eHMIs proposed by Al-Taie et al. [5] from their taxonomy of eHMI features, but which had not been evaluated. They were implemented in the simulator and placed on a 3D model of a 2019 Citroen C3. The eHMIs used different visual cues to present different types of information to riders, avoiding potential real-world issues with cyclists wearing headphones or masking other sounds in the environment (e.g. sirens). They work as follows:

- *Safe Zone:* Red/green road projections around the AV. Red means the AV has seen the cyclist but is not yielding, and green means the AV has seen the cyclist and will yield. A bonnet display shows a stop traffic sign matching the red projection and a proceed sign (white arrow in a blue background) synchronised with green ones;
- *Emoji-Car:* Roof display with a cyan lightbar at the top, communicating AV state (autonomous with sensors functioning correctly). The eHMI displays *cyclist* or *lightning* emojis on the front/sides/back. The *cyclist* icon means the AV has detected the rider and will yield, and *lightning* the AV has seen the rider but will not yield. The eHMI displays a blinking arrow on the front synchronised with the AV's direction indicator;
- *LightRing:* Always-on cyan light around the AV communicates AV state. The lights closest to the cyclist turn navy blue once the rider has been detected, and the blue segment grows wider around the AV as the cyclist moves closer. Yielding intent is shown by animating the lights in repeated segments: cyan lights stroke apart

[6]Meta Quest Pro: meta.com/gb/quest/quest-pro/
[7]EasyRoads3D: easyroads3d.com
[8]Qualtrics online survey platform: qualtrics.com

Fig. 3. The eHMI conditions: (A.1) Safe Zone yielding to the cyclist and (A.2) not yielding. (B.1) Emoji-Car shows a blinking arrow synchronised with the directional indicator, (B.2) a cyclist emoji to yield, and (B.3) lightning emoji communicating not yielding. (C.1) LightRing communicating AV state, (C.2) not yielding through 'stroking-apart' animation, (C.3) yielding by stroking toward each other and (C.4) echoing a directional indicator.

from the front centre (on the front bumper) when the car accelerates and move toward the front centre when decelerating. The eHMI also echoes directional indicators with the lights on the relevant side blinking in amber;

- *No eHMI:* Baseline condition where no eHMI display was attached to the car.

The eHMIs communicate different messages (e.g. awareness of the cyclist or autonomous mode) using different cues, such as emojis or animation. This allowed us to compare *complete* designs catered to cyclists' expectations and needs and give valuable insights into the types of colour schemes, symbols, and animations versatile AV-cyclist eHMIs should use. The eHMIs started reacting to the cyclist when they were 20 meters away; this distance was determined through trial and error in eight pilot tests.

3.4 Study Design

This within-subjects study had two independent variables: *Scenario* and *eHMI*. Participants used the VR simulator to interact with an SAE level 5 AV using each *eHMI* across five traffic *Scenarios*: (1) *Controlled Intersection*, (2) *Roundabout*, (3) *Uncontrolled Intersection*, (4) *Lane Merging* and (5) *Bottleneck* (road users moving toward each other in a narrow lane). These were identified as hubs for human driver-cyclist communication [3]. Each scenario has different characteristics, e.g. traffic lights or AV position, allowing us to investigate eHMI *versatility*. Scenarios were grouped into *tracks*; four were developed, one for each *eHMI* condition. We focused on scenarios where the AV yields to the cyclist, so each track was a straight 1KM two-lane road. Riders cycled on the left lane and had right of way in intersections and roundabouts. Tracks contained each of the five scenarios where the AV yielded, plus two additional ones where the AV did not yield. These were excluded from analysis and used to ensure cyclists paid attention and did not assume the car would always give way. Tracks had a random *Scenario* order. Participants navigated the seven scenarios, placed 100m apart, until the track's end. All AVs in one track had the same eHMI. The eHMI sequence was counterbalanced using a Latin square.

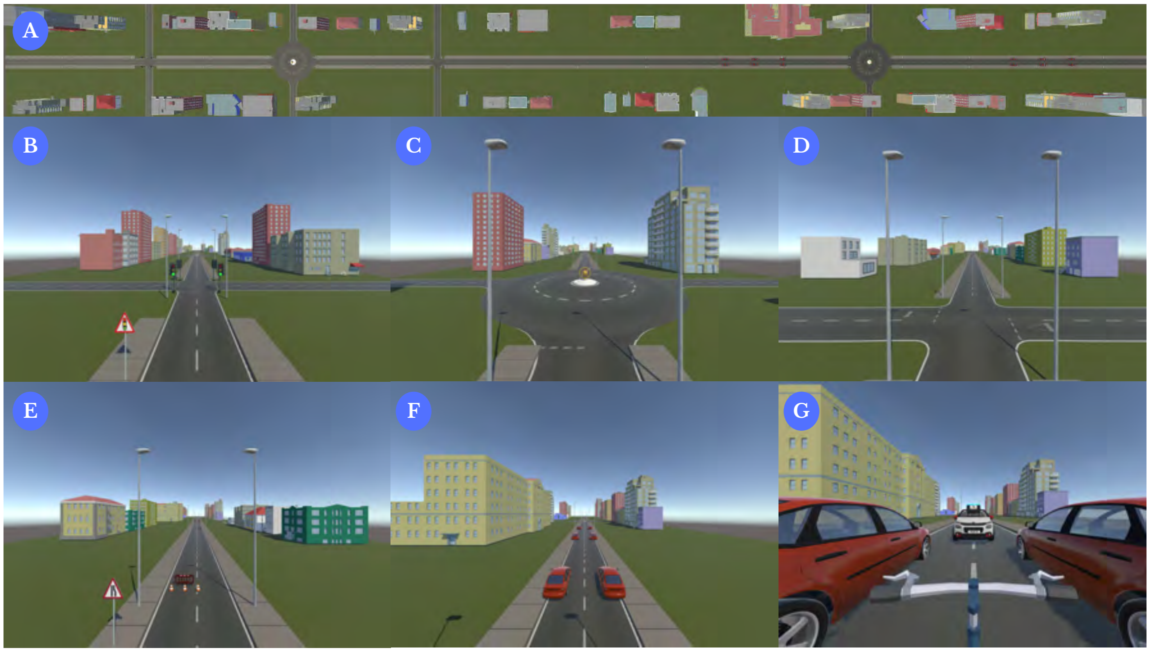

Fig. 4. (A) Birdseye view of a track and the traffic Scenarios: (B) Controlled Intersection, (C) Roundabout, (D) Uncontrolled Intersection, (E) Lane Merging and (F) Bottleneck. (G) Shows a cyclist encountering an AV with the Emoji-Car eHMI in a bottleneck.

Scenarios were modelled after video footage of cycling in [Redacted] [3] (see Figure 4). UK road markings and traffic signs were used. *Lane Merging* had obstacles requiring cyclists to enter from the right lane and exit from the left while overtaking the AV behind them. *Bottleneck* had parked cars on both sides; participants cycled in a narrow lane with the AV approaching them. One road user had to steer away. At intersections and roundabouts, the AV accelerated to 30mph (standard UK speed in urban areas) when it was 50 meters from the cyclist and stopped 50cm behind the give-way line if yielding. It accelerated to 25mph in *Lane Merging* and decelerated to 10mph when yielding. The AV drove at 15mph in *Bottleneck*, steered to the left (between two parked cars) and stopped when yielding. The vehicle maintained speed when not yielding in all scenarios. *Controlled Intersection* had red lights for 30 seconds in the non-yielding condition. AVs used directional indicators in *Roundabout* and *Bottleneck* to indicate turning. We collected the following:

- *Post-scenario questionnaire.* To measure the versatility aspect of RQ1, NASA TLX indicated each interaction's workload, and five-point Likert scale (strongly disagree-strongly agree) questions asked: *The AV was aware of my presence* and *I was confident in the AV's next manoeuvre*. These were derived from work showing that AV awareness and intent are key for AV-cyclist interaction [5, 22].
- *Cycling behaviour.* We addressed RQ2 by logging speed (meters per second) and shoulder checks (Unity camera (head) Y-axis rotation> 45°; determined through pilot tests with eight participants) every second. We collected gaze data: number of times a participant fixated on an *area of interest* (AOI); these cover vehicle (e.g. windscreen) and traffic control features (e.g. traffic lights, see Figure 6).

- *Post-track questionnaire.* We measured the acceptability aspect of RQ1 using the Car Technology Acceptance Model (CTAM) [26] and the usability aspect with the User Experience Questionnaire - Short Version (UEQ-S) [30]. These were previously used to evaluate cycling interfaces and pedestrian eHMIs [12, 33].
- *Qualitative data.* Post-study semi-structured interviews to contextualise the findings. Participants discussed and ranked each eHMI. They highlighted any points for improvement. Participants also discussed the different scenarios and identified ones that they felt needed/did not need eHMIs.

3.5 Procedure

Each participant answered a survey on their demographics and cycling experience. The experimenter then briefed them about the study and showed them videos of the eHMIs, familiarising them with the signals before the study. They were then familiar with the simulator; they ensured they were comfortable with the bike gear and saddle height by riding for three minutes with no headset. Each participant practised between 7 and 15 minutes of virtual cycling in a car park-like environment before starting the experiment. A start menu was shown in VR before each track, and the experimenter informed the participant which track and eHMI to select using the right headset controller based on the Latin square. The experimenter then reminded the participant of the eHMI signals' meaning and turned on the fan. The participant started cycling and navigated through the scenarios until reaching the track end. The VR app paused after each scenario, and the experimenter read out questions from the *post-scenario questionnaire*; the participant verbally answered and unpaused the app using the headset controller. After each track, the participant took off the headset and had a break while answering the *post-track questionnaire* on a tablet. This was done four times until they encountered all eHMI conditions. A semi-structured interview followed the experiment. The study took approximately 90 minutes.

3.6 Results

We answer the RQs by reporting cyclist perceptions and behaviours toward each interaction. We also examine how visual attention changes with *eHMI* through eye-tracking and show how acceptable and usable each eHMI was.

3.6.1 *Post-Scenario Questionnaire.*

The data did not have a normal distribution (via the Shapiro-Wilk test), so we conducted an Aligned-Rank Transform (ART) two-way ANOVA [35] exploring the effects of *Scenario* and *eHMI* on our outcomes. *Post hoc* tests between *Scenario* and *eHMI* pairs were conducted using the ART-C method [14].

NASA-TLX Overall Workload. Figure 5 shows the mean results. We found a significant main effect for *Scenario*, with a small effect size (F(4, 349.68) = 4.92, $P < .001$; $\eta^2 = 0.05$) and a significant main effect for *eHMI* with a large effect size (F(3, 349.78) = 23.49, $P < .001$; $\eta^2 = 0.17$). There was no interaction (F(12, 349.77) = 0.96, $P = .486$). Comparing *Scenarios* showed that *Controlled Intersection* had a lower workload than *Lane Merging* ($P = .005$) and *Bottleneck* ($P < .005$). For *eHMI* pairs, *Safe Zone* had a lower workload than *Emoji-Car* ($P < .001$), *LightRing* ($P < .001$) and *No eHMI* ($P < .001$). *Emoji-Car* had a lower workload than *No eHMI* ($P < .05$). NASA-TLX subscale results follow a similar trend to the overall ones: *Controlled Intersection* was the least demanding *Scenario* to navigate. *Safe Zone* outperformed the other conditions in all subscales. No interaction was found between *Scenario* and *eHMI* for all subscales. The detailed findings can be found as supplementary material.

Confidence in AV Awareness. We found a significant main effect of *Scenario*, with a small effect size (F(4, 349.95) = 2.64, $P = .034$; $\eta^2 = 0.03$) and a significant main effect of *eHMI*, with a large effect size (F(3, 350.19) = 32.48, $P < .001$; η^2 = 0.22). There was no interaction (F(12, 350.11) = 0.93, $P = .518$). Comparing *Scenarios* showed no significant results.

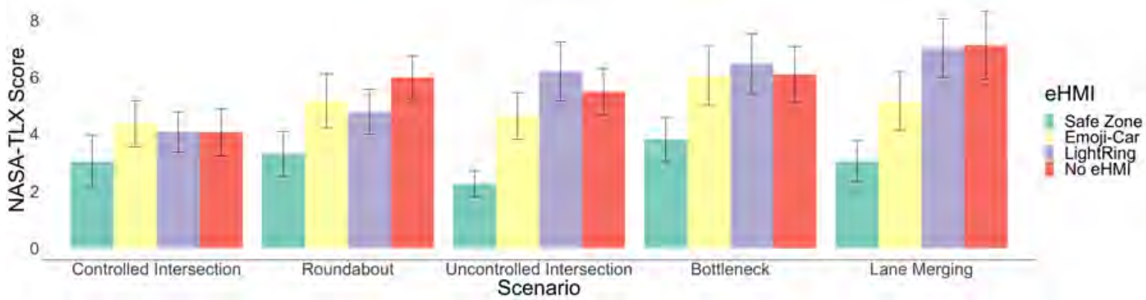

Fig. 5. Mean overall NASA TLX workload per Scenario and eHMI in Stage 1.

Comparing *eHMIs* showed cyclists were less confident with *No eHMI* than *Safe Zone* ($P < .001$), *Emoji-Car* ($P < .001$) and *LightRing* ($P < .001$), and less confident around *LightRing* than *Safe Zone* ($P < .001$) and *Emoji-Car* ($P < .01$).

Confidence in AV Intent. We found a significant main effect of *Scenario*, with a small effect size (F(4, 350.03) = 3.79, $P < .005$; $\eta^2 = 0.04$), and a significant main effect of *eHMI* with a large effect size (F(3, 350.38) = 36.17, $P < .001$; $\eta^2 = 0.24$). There was no interaction (F(12, 350.23) = 0.83, $P = .620$). Comparing *Scenarios* showed participants were more confident in *Bottleneck* than *Lane Merging* ($P < .05$). Comparing *eHMIs* showed participants were unsure of AV intent with *No eHMI* than *Safe Zone* ($P < .001$), *Emoji-Car* ($P < .001$) and *LightRing* ($P < .01$). They were more confident around *Safe Zone* than *Emoji-Car* ($P < .001$) and *Lightring* ($P < .001$), and around *Emoji-Car* than *LightRing* ($P < .05$).

3.6.2 Cycling Behaviour. Data did not have a normal distribution, so we did a two-way ANOVA of Aligned-Rank Transformed data exploring effects of *Scenario* and *eHMI* on cycling behaviour, with *post hoc* comparisons using ART-C.

Cycling Speed. We found a significant main effect of *Scenario* with a large effect size (F(4, 361) = 19.33, $P < .001$; $\eta^2 = 0.18$), and a significant main effect of *eHMI* with a medium effect size (F(3, 361) = 11.92, $P < .001$; $\eta^2 = 0.09$). There was no interaction (F(12, 361) = 0.64, $P = .807$). Comparing *Scenarios* showed participants cycled faster in *Controlled Intersection* than *Roundabout* ($P < .05$), *Uncontrolled Intersection* ($P < .05$) and *Bottleneck* ($P < .001$). They were slower in *Bottleneck* than *Roundabout* ($P < .001$), *Uncontrolled Intersection* ($P < .001$) and *Lane Merging* ($P < .001$). Comparing *eHMIs* showed participants cycled faster around *Safe Zone* than *LightRing* ($P < .001$) and *No eHMI* ($P < .005$).

Shoulder Checking. Data were binary (1 if a shoulder check was conducted, 0 if not); we analysed the mean number of shoulder checks for each eHMI in each scenario. We found a significant main effect of *Scenario* with a medium effect size (F(4, 361) = 9.53, $P > .001$; $\eta^2 = 0.10$) and a significant main effect of *eHMI* with a small effect size (F(3,361) = 3.94, $P < .01$; $\eta^2 = 0.03$). There was no interaction (F(12, 361) = 1.7, $P = .064$). Comparing *Scenarios* showed shoulder checks were less likely in *Uncontrolled Intersection* than *Controlled Intersection* ($P < .05$), *Roundabout* ($P < .005$) and *Bottleneck* ($P < .001$). They were more likely in *Bottleneck* than *Controlled Intersection* ($P < .05$) and *Lane Merging* ($P < .005$). Comparing *eHMIs* showed they were more likely around *Emoji-Car* than *Safe Zone* ($P < .01$).

3.6.3 Eye-Tracking. Figure 6 visualises the effect of *eHMI* on participant gaze behaviours. We conducted a Chi-square test of independence to investigate the relationship between *eHMI* and *fixation counts*. *Post hoc* tests were performed using a Chi-Square test of independence with a Bonferroni correction. We found a significant association between the variables (χ^2(36, 10970) = 2187.8, $P < .001$). *Post hoc* comparisons showed that participants relied more on traffic control

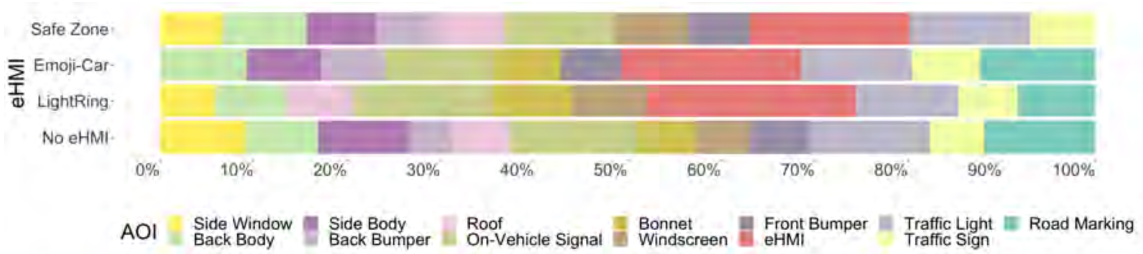

Fig. 6. Cyclists' gaze fixations as a % of trial time visualised on a heatmap for each eHMI condition.

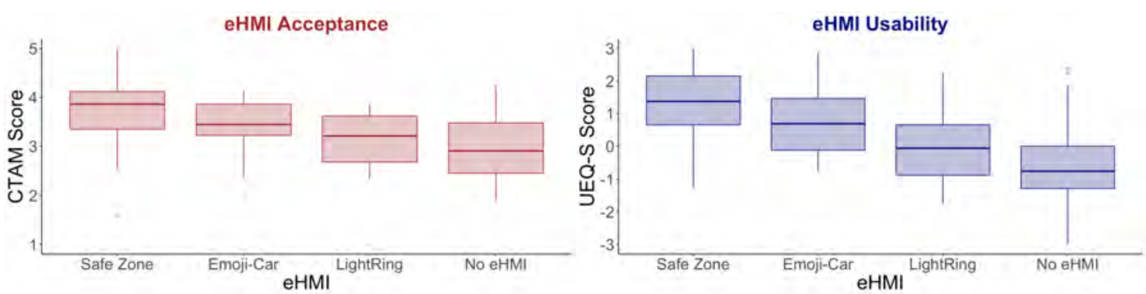

Fig. 7. Post-track survey results in Stage 1.

with *No eHMI* as they fixated on traffic signs/lights and road markings more often than with *Safe Zone* ($P < .001$), *Emoji-Car* ($P < .001$) and *LightRing* ($P < .001$). They also showed the *Safe Zone* required less attention (less fixations on the eHMI display) than *Emoji-Car* ($P < .001$) and *LightRing* ($P < .001$).

3.6.4 Post-Track Questionnaire. Figure 7 shows the mean scale ratings. A Friedman's test was conducted to investigate the impact of *eHMI* on the results. Pairwise *post hoc* comparisons were conducted using the Nemenyi test.

CTAM Overall Score. We found significant differences among the *eHMI* conditions (χ^2 = 19.675, df = 3, $P < .001$; η^2 = 0.2194). Comparing *eHMIs* showed *Safe Zone* was more acceptable than *LightRing* ($P < .005$) and *No eHMI* ($P < .001$). Subscale results can be found as supplementary material. They followed a similar trend to the overall score: *Safe Zone* was the most acceptable *eHMI*, except for *Perceived Safety* where we did not find a significant difference between the *eHMI* conditions (χ^2 = 2.882, df = 3, P = .41017; η^2 = -0.0016).

UEQ-S. We found significant differences among the eHMI conditions (χ^2 = 29.793, df = 3, $P < .001$; η^2 = 0.3525). Comparing *eHMIs* showed *Safe Zone* was more usable than *LightRing* ($P < .005$) and *No eHMI* ($P < .001$), while *Emoji-Car* was more usable than *No eHMI* ($P < .005$). We found significant differences for *Pragmatic Qualities* (χ^2 = 27.454, df = 3, $P < .001$; η^2 = 0.3218). *Post hoc* tests showed that *Safe Zone* had greater pragmatic qualities than *LightRing* ($P < .001$) and *No eHMI* ($P < .01$), and *Emoji-Car* had greater qualities than *LightRing* ($P < .01$). Analysing *Hedonic Qualities* also showed significant differences (χ^2 = 25.569, df = 3, $P < .001$; η^2 = 0.297). *Post hoc* tests revealed that *No eHMI* had lower hedonic qualities than *Safe Zone* ($P < .001$), *Emoji-Car* ($P < .005$) and *LightRing* ($P < .01$).

3.6.5 Qualitative Results. We report themes based on the post-study interviews and participant rankings of the eHMIs, visualised in Figure 8. We conducted an inductive, data-driven, thematic analysis [9] of the post-study interview

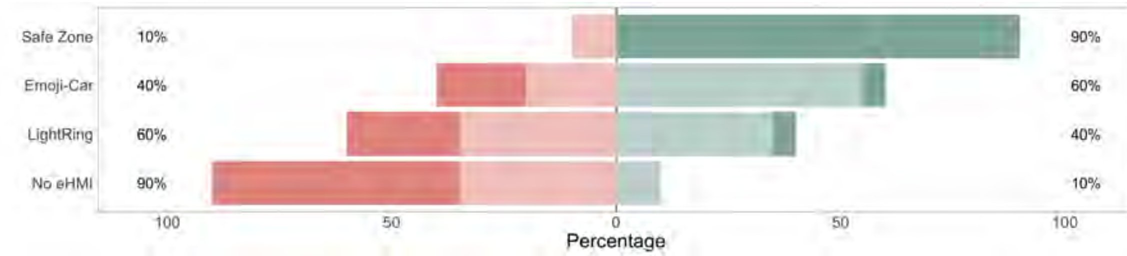

Fig. 8. Participant rankings of eHMI conditions in Stage 1. Red (worst) to dark green (best).

transcripts (auto-transcribed by otter.ai[9] and corrected by an author). Transcripts were imported into NVivo[10]. One author extracted 42 unique codes from the data. Two authors sorted these into three themes based on code similarity. This was iterative; disagreements were discussed, and codes were remapped until resolved. Themes with two or more overlapping codes were reassessed and combined when necessary.

Theme 1: Animation is insufficient. Participants could not easily distinguish between *LightRing*'s animated cyan lights communicating yielding. They suggested that other features accompany animations to make signals easier to process. For example, P16 said, *"LightRing would be my favourite if it used Safe Zone's colours"*, and P19 said, *"Sort out the strobing and have an unambiguous signal that knows where I am, and here's what the vehicle intends"*.

Theme 2: Traffic colours are easily learned. Cyclists were comfortable with *Safe Zone*'s colour scheme as it re-used red and green, which they were familiar with. For example, P14 said, *"I would go with conventional colours [...] They are easy to understand. I felt safer"*. They felt that the colours were distinguishable and unambiguous. For example, P2 said, *"Red and green super, super intuitive. I understood very quickly what was going on"*.

Theme 3: Symbols must be distinguishable from a distance. Participants could not differentiate between the emojis in *Emoji-Car* as both the cyclist and lightning icons used yellow, especially from a distance, and this required more effort to process than signals from *Safe Zone*. For example, P21 said *"I actually spent more time trying to identify the emoji."* and P13 said, *"Interpreting emojis from far caused a lot of ambiguity"*.

3.7 Discussion and Design Changes

We answered RQ1 and RQ2, and found consistent results on the impact of eHMIs across cyclist perceptions and behaviours: *Safe Zone* was the most positively evaluated eHMI. All designs demonstrated versatility, as there were no interactions between the *Scenario* and *eHMI* conditions in any *post-scenario* or *cycling behaviour* measure. eHMIs were based on Al-Taie et al.'s [5] taxonomy; our findings provide a degree of validation for their approach. Our analysis revealed areas for eHMI improvement, and so we revised each concept to accommodate these (see Figure 9). We adopted a red (not yielding)/green (yielding) colour scheme in these revised designs to communicate AV intent, which our initial results showed was easy to learn and distinguish. However, we recognised the potential challenge for colour-blind riders to differentiate between them. Therefore, we incorporated animations, patterns, or symbols into our designs to enhance accessibility, drawing inspiration from how traffic lights use light positions (red-top and green-bottom) and animations (flashing amber lights) to convey meaning. Regarding the *Scenarios*, *Controlled Intersections* required a lower

[9]Otter.AI transcription software: otter.ai
[10]NVivo qualitative analysis software: lumivero.com/products/nvivo/

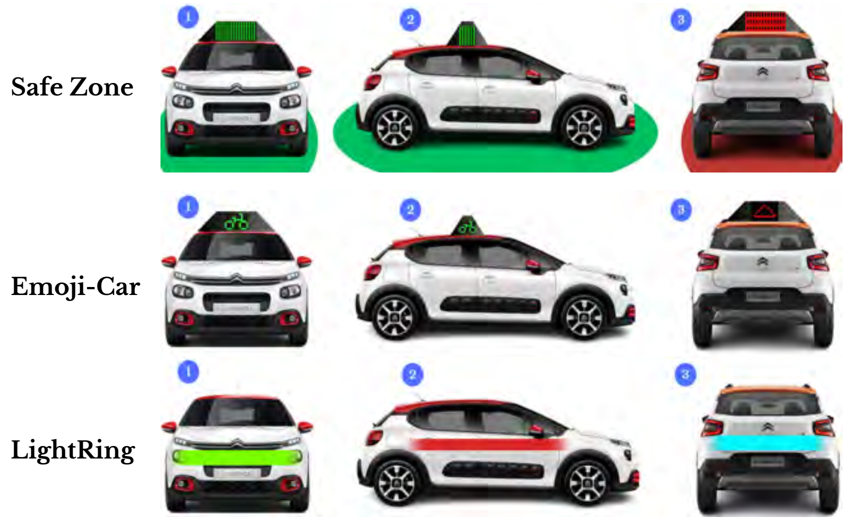

Fig. 9. Revised eHMIs. Safe Zone and Emoji-car (1-2) yielding conditions from the front and side, and (3) non-yielding conditions. LightRing (1) the yielding condition, (2) non-yielding, and (3) the communication of AV state in 'always-on' cyan.

workload to navigate in all *eHMI* conditions. Some participants did not notice the eHMIs here: *"I didn't see the eHMI, I saw a green light and went."* - P15. This coincides with results from previous work showing interaction with human drivers was unlikely at *Controlled Intersection*; cyclists relied more on traffic lights by fixating on them more than on cars around them [3]. Our results also showed that cyclists still fixated on traffic lights, even when eHMIs were present.

Participants preferred *Safe Zone* because it projected red and green signals onto the road, covering a large surface area. Hou et al. [18] also found that cyclists responded positively to red and green projections when lane merging, and Al-Taie et al. [3] discussed the advantages of using the road as a design space for eHMIs. *Safe Zone* led to fewer shoulder checks and reduced the workload. Eye-tracking data revealed that it was easily visible with quick glances; cyclists spent less time fixating on the eHMI compared to *Emoji-Car* and *LightRing*. Cyclists must not interpret red and green as *instructions* from the AV [1]; green, in this context, indicates that the AV was yielding, not instructing the cyclist to proceed. This was not an issue among our participants: *"It's slowing down, not telling me to go."* - P12. Participants did not pay much attention to the bonnet display used in *Safe Zone*. They were sometimes unaware of its presence; *"There was something on the bonnet? I did not know"* - P4. Therefore, we adjusted *Safe Zone* by relocating the bonnet display to the roof and replacing the traffic signs with colours synchronised with the projected signals. This spread the signals throughout the AV area and emphasised the idea of having displays in cyclists' peripheral vision, making it easier for them to process the colours and information. To accommodate cyclists with colour blindness, we further adapted the top display by incorporating patterns along with the colours, using vertical lines for green and crossed lines for red.

Cyclists were slower around *Emoji-Car* and performed more frequent shoulder checks than *Safe Zone*. This could be due to the eHMI placement; the roof currently does not display any signals for interaction, so participants were not used to this. They also paid greater attention to interpreting the icons than colours in *Safe Zone*; eye-tracking data supported this. Qualitative feedback indicated that participants had difficulty distinguishing between emojis, requiring more effort to interact with the AV. They were also confused by the lightning emoji and suggested a symbol more aligned with standard traffic symbols: *"I can't map the lightning to anything meaningful"* -P1. Therefore, eHMI signals must be easily distinguishable and understandable from a distance. Some participants incorrectly interpreted the top cyan light as a signal of the AV yielding, leading to potentially unsafe actions; P3 mentioned, *"I saw the light on top and thought I could pass."* The blinking arrow on the front interface, intended to echo directional indicators, proved redundant and ambiguous, as participants were unsure whether it instructed them to turn or displayed the AV's turn direction.

In response, we refined *Emoji-Car* by simplifying the design and keeping it focused on communicating the AV's intent and awareness of the cyclist. The revised version used red triangles to communicate non-yielding (commonly found in traffic signs, suggesting caution) and green bicycle symbols for yielding. Red/green made the emojis more distinguishable, drawing from the success of *Safe Zone*. We removed the cyan light and blinking arrow to avoid confusing riders, with the eHMI only communicating necessary information. To address the needs of colour-blind cyclists, we relied on icons to differentiate the signals. We deviated from Hou et al.'s [18] findings, which showed that AV-cyclist interfaces placed on specific car areas did not perform well for lane merging, as we wanted to investigate roof-placed interfaces visible from around the vehicle, recommended by previous research [3, 17]. This approach aimed to balance visibility and conformity to existing interface placements, such as taxi signs.

LightRing underperformed; cyclists did not respond positively to a new colour (cyan) in traffic. Animations conveying yielding intent imposed a higher workload than colours or icons, as cyclists found it difficult to differentiate between the directional animations. *LightRing* had a higher complexity; it incorporated features such as synchronising amber lights on the car's side with directional indicators, using navy blue lights to indicate the awareness of cyclists, and animations communicating intent. This proved a hurdle as cyclists preferred a more straightforward interface closer to *Safe Zone*. For example, P14 said: *"I think it would be my favourite if it used the same colours as Safe Zone." LightRing* drew inspiration from light band designs for pedestrians [10, 11]. However, cyclists' poor reception to new colours and animations could be due to the limited interaction time in cycling scenarios. Unlike pedestrians, who often are stationary at crossings and have more time to interpret animated signals and AV driving behaviour to deduce yielding intentions, cyclists have faster-paced interactions with AVs [20, 22].

We adjusted *LightRing* by modifying the animation and colour aspects during yielding/not yielding: lights now slowly pulse in green when the AV detects and yields to the cyclist and flash quickly in red when not yielding. This uses animations to complement the colour changes rather than being the primary source of information. It also helps colour-blind cyclists distinguish between yielding conditions, as the animations (speed-based rather than directional) are easier to differentiate. Flashing animations have been applied in traffic, e.g. some pedestrian crossing signs flash before transitioning to a different state. *LightRing* still communicates AV state using always-on cyan, as the signal changes are more apparent with animations and colours, it will not display multiple signals at a time, as in *Emoji-Car*.

Overall, red/green was a useful colour scheme for eHMIs to communicate easily distinguishable messages about the AV's yielding intent across various scenarios. More complex messages, such as echoing a directional indicator, only added to the workload of using an eHMI. We adjusted all three designs based on cyclists' feedback and behaviours observed in the simulator to evaluate a second iteration in a real-world setting.

4 STAGE 2: WIZARD-OF-OZ EVALUATION WITH AN 'AUTONOMOUS' CAR

Stage 1 compared three eHMIs in a controlled setting using a cycling simulator and provided valuable insights into improving these designs for real-world use. In Stage 2, cyclists encountered the eHMIs on a real car outdoors to evaluate the refined designs and explore how they may be realised through physical prototypes.

Fig. 10. Yielding states of real-world eHMIs used in Stage 2. (A.1-2) *Safe Zone*, (B) *Emoji-Car*, (C) *LightRing*

4.1 Participants

We recruited 20 participants (7 Female, 12 Male, 1 Non-Binary; Mean Age = 20.4, SD = 5.9) through social media advertising. Eleven cycled at least once a week, three at least once a month, two multiple times a year, and four once a year or less. Thirteen participants used their own bikes during the study. Five participated in the previous VR study. Participants were compensated with a £10 Amazon voucher. The University ethics committee approved the study.

4.2 Apparatus

We used a grey 2019 Citroen C3, the same car as in Stage 1 and took a Ghost Driver [29] approach: the driver wore sunglasses, black gloves and a car seat cover with holes for eyes and arms (see Figure 13). Participants never saw the driver to create the illusion that the car was an SAE level 5 AV. LED strips and an LED matrix were used to build the eHMIs (see Figure 10). They were plugged into the car’s USB port and controlled by an experimenter via iPad over Bluetooth. The matrix was placed on the roof using a custom-built panel on a removable rack[11]. The rack was present in all conditions; participants were told these were the AV’s sensors. Participants only encountered the car’s front or left side, so eHMIs were only visible in these directions; the LED matrix was flexible and wrapped around the roof panel on the left. We used velcro on the car body to attach/detach eHMIs between conditions, white chalk to draw appropriate road markings onto the ground, and traffic cones to represent obstacles (see Figure 12). Participants were given a Giant Escape 3 bicycle and a helmet if they did not have their own. The Tobii Pro Glasses 2 captured eye-tracking and head

[11]HandiWorld roof rack: handiworld.com/handirack/

Fig. 11. Pilot test comparing visibility of an LED matrix on the roof, LED strips on the car body and a projector on the front bumper.

rotation (shoulder-checking) data, and a Dell XPS laptop was used to calibrate them. An iPhone 12 mini was placed on the handlebars to record speed using Cyclemeter[12].

4.3 Implementing eHMIs

All eHMIs were placed on the Citroen and controlled by an experimenter standing outside the vehicle. They were activated when the car reached specific marked locations for each scenario. They worked as follows:

- *Safe Zone:* We did not use projections because the study was outdoors in daylight, so they were barely visible. This was determined through an early pilot test comparing the visibility of the LED matrix, strip and projection (see Figure 11). We experimented with different projectors, including a Dell 1100MP projector with a high (>11,000) Lumens, but the road projections were still not visible in daylight. We also tried using red/green ambient light through 15,000 lumens LED torches stuck under the car, but they also had minimal visibility. Eventually, we used an LED light strip stuck around the bottom of the front half of the car; this was attached with velcro. This approach brought the lights close to the road surface and still emphasised the concept of *Safe Zone* being in cyclists' peripheral vision, especially when used with a roof display. The roof display (LED matrix) showed the red pattern seen in Figure 18 synchronised with red lights from the LED strip when the AV detected the cyclist but did not yield, and the green pattern with green LED lights when the AV was yielding.
- *Emoji-Car:* The LED matrix displayed three bicycle icons (one on each side) if the cyclist has been detected and the AV will yield, and three red triangles resembling warning signs if not.
- *LightRing:* Two LED strips were placed on the car's left (2 meters long) and front (1 meter long) using velcro. The strips were always on in cyan to show that the car was autonomous and not reacting to the cyclist. They changed to green pulsing slowly if the AV will yield to the cyclist and red flashing rapidly if it is not yielding.
- *No eHMI:* Baseline condition where no eHMI display was present.

4.4 Study Design

This within-subjects study had *Scenario* and *eHMI* as independent variables. Participants cycled around a moving vehicle with the four *eHMI* conditions in 4 traffic Scenarios: (1) *Roundabout*, (2) *Uncontrolled Intersection*, (3) *Lane Merging* and (4) *Bottleneck*. We excluded *Controlled Intersection* as Stage 1 showed it did not require an eHMI. The study commenced in an outdoor coned-off space on University grounds (see Figure 12): a 60m straight road intersecting with a 50m road on the left. We drew lane dividing lines on the roads replicating a two-lane road and used cones to mark start and end points for participants. Their task was to cycle along the 60m road in all scenarios until they reached the marked

[12]Cyclemeter iOS application: apps.apple.com/us/app/cyclemeter-bike-computer/id330595774

Fig. 12. The scenarios visualised on the study space. (A) Roundabout, (B) Uncontrolled Intersection, (C) Lane Merging and (D) Bottleneck. Traffic cones represent obstacles. Red flags represent endpoints.

endpoint, except in *Roundabout*, where they made a U-turn around the roundabout. They then cycled back to the start point. Like Stage 1, scenarios were grouped (in random order) into tracks. The AV used the same eHMI within a track. The sequence of *eHMIs* was balanced using a Latin Square.

The AV always yielded to maintain participant safety, but participants were shown both yielding states before each track and were told before each scenario that the AV may not yield to them. One driver was used for all sessions. They ensured at least a 1m distance from the cyclist, as the UK Highway Code advises. The driver accelerated to 20mph in *Roundabout* and *Uncontrolled Intersection* and stopped 50cm (marked using chalk) behind the give-way line. They drove at 15mph in *Lane Merging* and *Bottleneck* and decelerated (steered away to the left in *Bottleneck*) according to the cyclist's speed to yield. Directional indicators were used in *Roundabout* and *Bottleneck*. The measures were similar to those in Stage 1. Participants answered the *post-scenario* and *post-track* questionnaires. We collected cycling speed (meters per second), shoulder-checking (Tobii Glasses' Gyroscope Y rotation >90°, determined through pilot tests), and eye-tracking data mapped to the AOIs using Tobii Pro Lab's AOI tool[13]. A post-study interview was also conducted.

4.5 Procedure

Each Participant met the experimenter in the outdoor space allocated for the study. They first answered a survey about their demographics and cycling experience, and the experimenter briefed them about the study. The experimenter instructed them about the different scenarios and showed the start and endpoints. Before each track, the experimenter showed the participant how the eHMI worked (with the lights on the vehicle) so that they were familiar with the signals before encountering the eHMI. The participant was told to start cycling when they saw a thumbs-up from the experimenter. Those who did not use their bikes ensured they were comfortable with the experiment bike and checked the saddle height. The experimenter checked they had appropriate safety gear, mounted the iPhone to the handlebars, and calibrated the eye-tracking glasses. The experiment started, and the participant moved to the starting point. They started cycling, and the driver started driving once they saw a thumbs-up. The experimenter controlled the eHMI to react to the rider at the appropriate moment. After each scenario, the participant returned to their starting point and answered the *post-scenario questionnaire* on an iPad while the experimenter put scenario obstacles (cones) on the road to prepare for the next scenario. After each track, the experimenter switched the eHMIs as the participant answered the post-track questionnaire. The experiment ended once the participant cycled on all four tracks and experienced all *eHMI* conditions. This was followed by a semi-structured interview with the same structure as the one from Stage 1.

[13]Tobii Pro Lab AOI Tool: connect.tobii.com/s/article/digging-into-areas-of-interest-aois?language=en_US

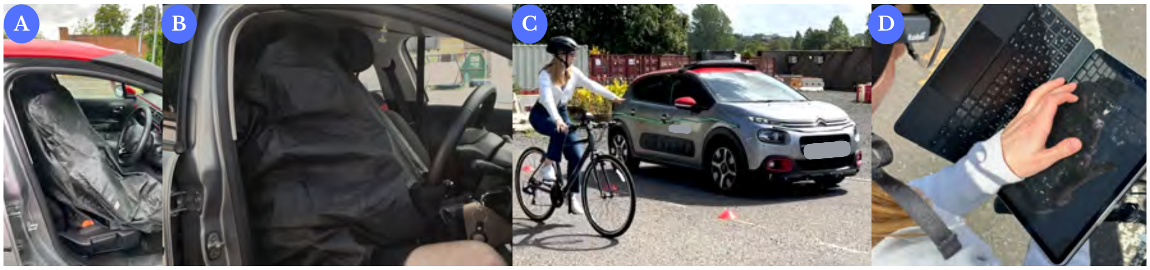

Fig. 13. The Stage 2 procedure visualised. (A-B) The driver hidden in a car seat costume, (C) the cyclist performing a lane merging manoeuvre around an AV with *LightRing* and (D) the cyclist answering the post-scenario questionnaire.

4.6 Results

We report the results using the same structure as Stage 1. We start by reporting our *post-scenario* and *cycling behaviour* results, followed by findings from the *post-track questionnaire* (acceptability and usability) and qualitative feedback.

4.6.1 Post-Scenario Questionnaire. The data did not have a normal distribution, so we conducted an Aligned-Rank Transform (ART) two-way ANOVA exploring the effects of *Scenario* and *eHMI* on our outcomes. *Post hoc* tests between *Scenario* and *eHMI* pairs were conducted using the ART-C method.

Overall NASA-TLX Workload. Mean values are visualised in Figure 14. We found a significant main effect of *Scenario* with a medium effect size (F(3, 206.22) = 9.25, $P < .001$; $\eta^2 = 0.12$), and a significant main effect of *eHMI* with a large effect size (F(3, 207.09) = 26.52, $P < .001$; $\eta^2 = 0.28$). There was no interaction (F(9, 206.15) = 1.02, $P = .422$). Comparing *Scenarios* showed interactions when *Lane Merging* were more demanding than *Roundabout* ($P < .001$), *Uncontrolled Intersection* ($P < .001$) and *Bottleneck* ($P < .005$). Comparing *eHMIs* showed *No eHMI* was more demanding than *Safe Zone* ($P < .001$), *Emoji-Car* ($P < .001$) and *LightRing* ($P < .001$). Subscale results followed a similar trend: *Lane Merging* was the most demanding to navigate, and *No eHMI* was the most demanding *eHMI* condition. No significant interaction was found between *Scenario* and *eHMI* for all subscales. Details are in the supplementary materials.

Confidence in AV Awareness. We found a significant main effect of *Scenario* with a small effect size (F(3, 206.84) = 2.74, $P < .05$; $\eta^2 = 0.04$) and a significant main effect of *eHMI* with a large effect size (F(3, 209.86) = 30.16, $P < .001$; $\eta^2 = 0.3$). There was no interaction (F(9, 206.6) = 0.54, $P = .846$). Comparing *Scenarios* showed participants were less confident in AV awareness when *Lane Merging* than *Roundabout* ($P = .05$). Comparing *eHMIs* showed participants were less confident in AV awareness with *No eHMI* than *Safe Zone* ($P < .001$), *Emoji-Car* ($P < .001$) and *LightRing* ($P < .001$).

Confidence in AV Intent. There was no significant main effect of *Scenario* (F(3, 206.71) = 2.04, $P = .109$). We found a significant main effect of *eHMI* with a large effect size (F(3, 209.22) = 23.21, $P < .001$; $\eta^2 = 0.25$). There was no interaction (F(9, 206.53) = 0.90, $P = .526$). Comparing *eHMIs* showed participants were less confident in the AV's intent with *No eHMI* than *Safe Zone* ($P < .001$), *Emoji-Car* ($P < .001$) and *LightRing* ($P < .001$).

4.6.2 Cycling Behaviour. Data did not have a normal distribution, so we did a two-way ANOVA of Aligned-Rank Transformed data exploring effects of *Scenario* and *eHMI* on cycling behaviour, with *post hoc* comparisons using ART-C.

Cycling Speed. We found a significant main effect of *Scenario* with a small effect size (F(3, 252.43) = 3.61, $P < .05$; $\eta^2 = 0.04$), and a significant main effect of *eHMI* with a small effect size (F(3, 252.71) = 4.21, $P < .01$; $\eta^2 = 0.05$). There was

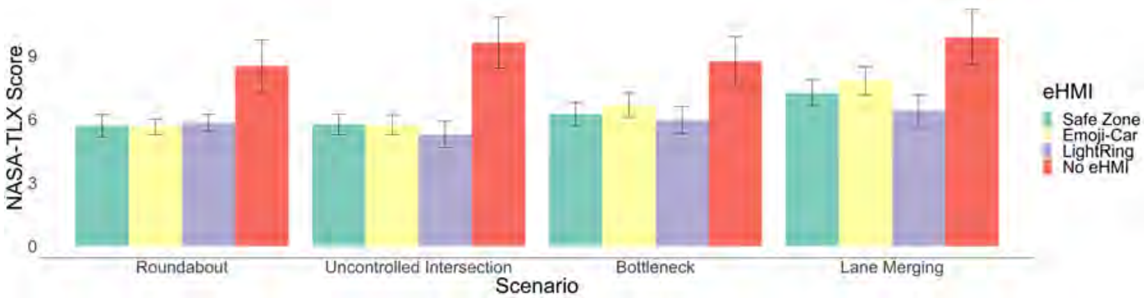

Fig. 14. Mean overall NASA TLX workload per Scenario and eHMI in Stage 2.

Fig. 15. Cyclists' gaze fixations visualised as a heatmap for each eHMI condition. The dots show the number of fixations. Green represents smaller numbers and red represents larger numbers.

no interaction (F(9, 252.59) = 1.35, P = .211). Comparing *Scenarios* showed participants cycled faster in *Uncontrolled Intersection* than *Bottleneck* (P < .05). Comparing *eHMIs* showed participants cycled slower around *No eHMI* than *Safe Zone* (P < .05) and *LightRing* (P < .01).

Shoulder Checking. Like Stage 1, data were binary; we analysed each condition's mean number of shoulder checks. We found a significant main effect of *Scenario* with a large effect size (F(3, 149.38) = 8.71, P < .001; η^2 = 0.15), but no significant effect of *eHMI* (F(3, 154.5) = 0.97, P = .410). There was no interaction (F(9, 150.07) = 0.42, P = .923). Comparing *Scenarios* showed participants were more likely to shoulder check when *Lane Merging* than *Roundabout* (P < .05) and *Bottleneck* (P < .001).

4.6.3 Eye Tracking. Figure 15 shows a heat-map of cyclists' fixations with each *eHMI*. We conducted a Chi-square test of independence investigating the relationship between *eHMI* and *fixation counts*. *Post hoc* tests were performed using a Chi-Square test of independence with a Bonferroni correction. We found a significant association between *eHMI* and *fixation counts* (χ^2(30, 9263) = 2158.2, P < .001). Pairwise comparisons showed participants relied more on AV driving behaviour (by fixating on the bumper more often [3]), direction indicators and road markings when there was *No eHMI* compared to *Safe Zone* (P < .001), *Emoji-Car* (P < .001) and *LightRing* (P < .001). *Safe Zone* required less attention than *Emoji-Car* (P < .001) and *LightRing* (P < .001) as participants fixated less often on the light displays. *LightRing* also required less attention than *Emoji-Car* (P < .001); participants fixated more often on *Emoji-Car's* roof display.

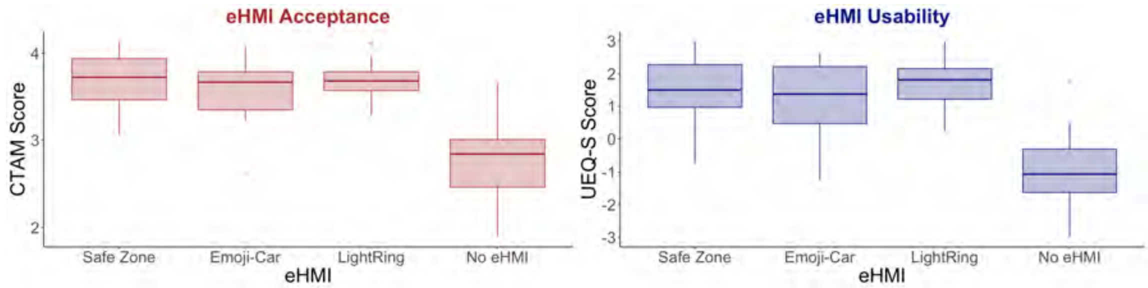

Fig. 16. Post-track survey results in Stage 2.

4.6.4 Post-Track Questionnaire. Figure 16 shows the mean scale ratings. A Friedman's test was conducted to investigate the impact of *eHMI* on the results. Pairwise *post hoc* comparisons were conducted using the Nemenyi test.

Overall CTAM Score. We found significant differences among the eHMI conditions (χ^2 = 24.929, df = 3, $P < .001$; η^2 = 0.29). Comparing *eHMIs* showed *No eHMI* was less acceptable than *Safe Zone* ($P < .001$), *LightRing* ($P < .001$) and *Emoji-Car* ($P < .005$). Subscale findings can be found as supplementary material. They followed a similar trend to the overall score: *No eHMI* was less acceptable than all conditions, except for *Perceived Safety* (χ^2 = 9.94, df = 3, $P < .05$; η^2 = 0.0913) where there were significant differences between only *No eHMI* and *LightRing* ($P < .05$).

UEQ-S. We found significant differences among the eHMI conditions (χ^2 = 34.5, df = 3, $P < .001$; η^2 = 0.41). Pairwise comparisons showed that *No eHMI* was less usable than *Safe Zone* ($P < .001$), *Emoji-Car* ($P < .005$) and *LightRing* ($P < .001$). Analysis of *Pragmatic Qualities* showed significant differences (χ^2 = 32.117, df = 3, $P < .001$; η^2 = 0.38). Comparing *eHMIs* showed that *No eHMI* had lower pragmatic qualities than *Safe Zone* ($P < .001$), *Emoji-Car* ($P < .01$) and *LightRing* ($P < .001$). We also found significant differences for *Hedonic Qualities* (χ^2 = 18.484, df = 3, $P < .001$; η^2 = 0.2). Pairwise comparisons showed that *No eHMI* had lower hedonic qualities than *Safe Zone* ($P < .05$), *Emoji-Car* ($P < .01$) and *LightRing* ($P < .005$).

4.6.5 Qualitative Results. We used the same process as Stage 1. One author extracted 31 unique codes from the data. Two authors sorted these into three themes based on code similarity. eHMI rankings are visualised in Figure 17.

Theme 1: The eHMI should be viewable anywhere around the vehicle. Participants preferred *LightRing* over the other interfaces because it used the entire vehicle surface. For example, P8 said, *"You see better because you can kind of see the edge of the LED strip from wherever"*. *Emoji-Car*, which was placed on the roof, was harder to quickly recognise: *"Compared to LightRing, then you have to really look at the roof to see the emoji"* - P18.

Theme 2: Redundancy can be good for eHMIs. Participants preferred the pulsing animation supporting *LightRing* as it reinforced the AV's yielding intent (*"LightRing flashing drew attention to itself and different flashing speeds were easy to spot"* - P4). Redundant messages presented on the top and bottom of the AV in *Safe Zone* were well received. For example, P20 said, *"Always redundancy is better. The top and bottom displays accommodated that"*.

Theme 3: Scenarios with no set right-of-way rules are harder to navigate. Participants found eHMIs helpful overall: *"I think they're necessary. It adds clarity and reassurance to cyclists"* - P17. However, they saw better value for the interfaces

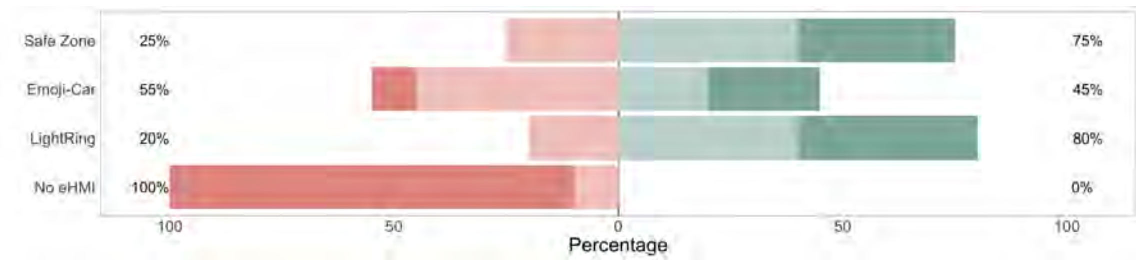

Fig. 17. Participant ranking of eHMI conditions in Stage 2. Red (worst) to dark green (best).

when right-of-way was up for negotiation with little or no traffic control. For example, P19 said, *"I think that will be beneficial in all of these scenarios, but especially lane merging. I think I would say it's crucial"*.

4.7 Discussion

Like Stage 1, all refined eHMIs maintained their versatility in real-world settings. However, the differences between them and the *No eHMI* condition became more apparent than in Stage 1. *No eHMI* received the lowest ratings across all metrics. Cyclists were slower and performed more frequent shoulder checks. Visual attention was more spread out; they relied on more AOIs to infer whether the AV would yield. Two factors may contribute to this. First, the study included a real vehicle, so cyclists may have felt less secure when encountering obstacles. Second, design improvements made the effect of having an *eHMI* more noticeable. Results from Stage 2 emphasise that developing eHMIs that communicate clear messages that are consistently easy to understand and distinguish significantly improves AV-cyclist interaction.

The design changes from Stage 1 resulted in more subtle differences between the *eHMIs*, so the differences in their performance were less prominent in Stage 2. *LightRing* received better feedback in several metrics, with participants expressing a greater sense of safety and ranking it as the most preferred eHMI. One contributing factor was its communication of the AV's state through always-on cyan lights: *"I liked the cyan colour telling me everything is fine"* - P12. *LightRing*'s placement around the vehicle allowed it to cover a larger surface area; Stage 1 showed this was a desirable feature. The animations used in *LightRing* provided redundancy in conveying AV-yielding intentions, enhancing participants' confidence. In comparison, *Emoji-Car* was not as well-received. Its roof placement drew significant attention from riders, as indicated by eye-tracking and speed data; riders were slower than with the other eHMIs. The interface's use of icons rather than just colours added complexity. For example, P16 noted, *"Using emojis stops it from using the entire display space, and the colours were less apparent."* This finding aligns with Hou et al.'s [18], who noted that placing eHMIs on specific AV areas could divert cyclists' attention from the road. In comparison, participants could quickly infer signals from *Safe Zone* despite being more abstract and relying solely on colour changes without icons or animations. The widespread distribution of lights (roof and car bottom) made them easier to locate through quick glances, as supported by eye-tracking data, which suggested that cyclists often looked at the car's centre, not just the eHMI itself, to interpret the signals. According to our results, the design changes to enhance the visibility of *Safe Zone* have succeeded, even when no road projections were used.

Similar to Stage 1, *Scenarios* with more traffic control, e.g. *Roundabout*, needed lower workloads than spontaneous ones, e.g. *Lane Merging*. Participants had greater confidence in the AV's awareness at *Roundabout*. This can be attributed to the well-defined right-of-way rules in the Highway Code, making interactions more predictable. Give-way lines indicated where the AV would stop, and the AV's gradual slowing down gave cyclists more time to interpret implicit cues from driving behaviour. In comparison, *Lane Merging* was challenging and less predictable. Cyclists were in front of the moving vehicle and needed to conduct more shoulder checks. They had limited time to process signals while moving. Right-of-way was unclear; it was up to the AV to slow down and let them pass. The differences observed among the scenarios and how cyclists behave in them emphasise the challenges in achieving eHMI *versatility*. Despite this, we found that all scenarios would benefit from an eHMI; all required a higher workload when there was *No eHMI*.

Overall, Stage 2 showed a significant improvement in AV-cyclist interaction when eHMIs effectively convey clear, understandable, and easily distinguishable signals about the AV's intentions. *LightRing* demonstrated the benefits of communicating messages through colour changes and animation from all around the AV, while *Emoji-Car* faced challenges because it was more complex due to its placement and use of icons, which required more attention from cyclists attention, and *Safe Zone* effectively balanced abstract signals with visibility enhancements.

5 LIMITATIONS AND FUTURE WORK

All road infrastructure was based on the UK Highway Code and UK cycling footage, and participants were UK-based. Future work should replicate our methods in different regions with different traffic cultures. We also only evaluated the eHMIs on a Citroen C3, a city car, so it is unknown how our findings will generalise to other vehicles, such as SUVs or buses. Stage 1 evaluated the eHMIs using a VR simulator; these have some known limitations. Cyclists were not moving in physical space, and there were no real obstacles around them. This could impact results such as perceived safety. There were also some rendering limitations with the Quest Pro, as some displays were not clearly rendered from a distance due to the headset resolution, which may have impacted our findings. The Quest Pro has a similar resolution and slightly higher pixel density than common VR headsets such as the Quest 2, so limitations apply across similar simulators. We overcame some of Stage 1's limitations in Stage 2. Participants cycled outdoors and encountered a real car. However, we did not conduct the study on real roads due to safety concerns. Instead, we used chalk to draw relevant road markings on the outdoor space. Future work can evaluate the eHMIs on real roads with real intersections and scenarios. This is important, as the scenarios may be more complex; we focused on one-to-one encounters, but real scenarios may have multiple cars or cyclists, so eHMIs must also be *scalable*. We chose single interactions as a starting point to give baseline knowledge that others could extend to more complex ones. We focused on *versatility*, covering a broader range of scenarios. Both issues must be resolved for AVs to work effectively. Our eHMIs communicate yielding intent through colour changes; we hypothesise that they are already scalable, as they are only active on the side the cyclist is on and communicate what the AV will do rather than what the cyclist should do. Stage 2 took a Wizard of Oz approach; the driver was hidden under a car seat costume, and the vehicle was not actually autonomous. Participants did not see the driver throughout the study and behaved as they would around a self-driving vehicle, this was evident in the results as *No eHMI* significantly underperformed compared to when an eHMI was present. Qualitative feedback also emphasised this: *"It's so hard with no driver in the car!"* - P3 and *"I couldn't see anything! There were no signals."* - P11.

6 OVERALL DISCUSSION AND GUIDELINES

We answered RQ1 and RQ2 by measuring cyclist perception and behaviour towards the eHMIs in both stages. For versatility, we found that the eHMIs performed consistently across the traffic scenarios. Stage 2 showed all the interfaces significantly improved the AV-cyclist interaction experience despite the differences in scenario characteristics. Our results emphasised that eHMIs need to communicate simple messages that are easy to understand and differentiate through quick glances to be acceptable and usable in real traffic. We achieved this by utilising large surfaces, such as the AV body or road around it, to display simple red/green signals about its intent. In this section, we discuss the takeaways of our two-stage investigation with the design guidelines as headlines for our discussion.

eHMIs are key facilitators of AV-cyclist interaction. Cyclists were more confident in the AV's intent and awareness of them when eHMIs were present; they conducted fewer shoulder checks and were more comfortable riding at higher speeds. Qualitative findings reinforced this. For example, P2 from Study 2 said *"You definitely need eHMIs. When there was no intervention, I had no idea and no control. I felt unsafe."* Human drivers communicate their intent and awareness to cyclists in a range of scenarios [3], and previous work has shown that these messages help riders safely plan their next manoeuvre [5, 22]. Our findings suggest that eHMIs are an encouraging replacement for these human cues.

eHMIs should use large surfaces around the vehicle. Placement is key to eHMI versatility, as cyclists may be anywhere around a vehicle. While previous research suggested areas like the roof are appropriate placements to be visible from all directions [3, 5, 17], we found that this is not enough. Cyclists preferred that signals be quickly viewable at a glance, and this requires using large surfaces, such as the road through *Safe Zone* projections or the vehicle's body in *LightRing*.

eHMIs should communicate minimal information. Riders prefer clear, concise messages about the AV's yielding intent and awareness in a single, colour-coded signal. For example, the updated *LightRing* used green to indicate that the AV would yield, and as the colour change occurred when the cyclist was detected, it also implicitly communicated the AV was aware of them. However, messages that separated the two signals to communicate each one explicitly, such as the updated *Emoji-Car* (awareness through bicycle symbols, intent by having the symbols green), confused riders. Abstract signals that explicitly communicate intent and implicitly communicate awareness are the most favoured by cyclists.

Versatile eHMIs can use the same signals between scenarios. This solves a key issue in AV-cyclist interaction; riders previously expressed concerns about interacting differently with AVs depending on the scenario [5]. A single, scenario-independent *language* can be devised. Red/green signals were the most promising in our investigation. Human drivers interact differently with cyclists between scenarios, e.g. hand gestures communicating intent in uncontrolled intersections and facial expressions communicating awareness in roundabouts [3]. This could be due to varying traffic control levels, so different levels of detail were required. Still, we found that explicitly communicating intent and implicitly communicating awareness using the same signals was enough for riders to navigate all scenarios safely.

eHMI messages must be easily understandable. Cyclists must quickly and easily distinguish between eHMI messages and understand their meaning. We found that colour was a primary distinguishable feature for the eHMIs tested, which can be supported by animation or icons. However, using icons or animations alone did not work in Stage 1; riders required more effort to differentiate between the yielding conditions according to NASA TLX scores and eye-tracking results showing they fixated more on the eHMI itself than others like *Safe Zone*. It is also important to ensure that eHMIs are distinguishable from traditional vehicle signals so riders know the information source; this can be done by using underutilised placements, such as the roof, or having the eHMIs use easily distinguishable animations.

eHMIs should not significantly depart from traffic norms. Participants preferred eHMIs using familiar signals in traffic; deviating from these may cause confusion and less consistency between signals on the road. Red/green colours were favoured over others, e.g. cyan, as they are easily learned. P18 (Stage 2) said, *"Having the Emoji-Car bicycles in green helped, If they were purple, it would be difficult because I will have to learn what the bicycles mean, and what purple means."* So, having some eHMI aspect close to the current traffic vocabulary helps avoid a significant learning curve.

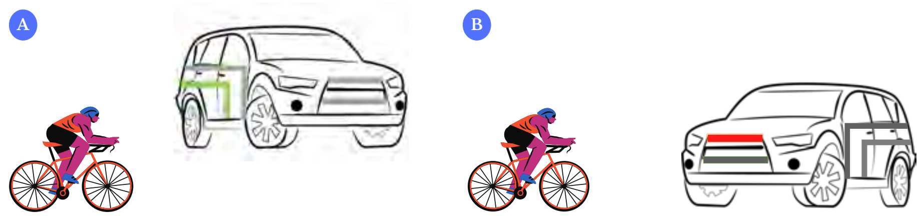

Fig. 18. The two-strip eHMI. (A) Shows an encounter on the AV's side with AV yielding, (B) in front of the AV (AV not yielding).

Current vehicle signals should be maintained as eHMIs are introduced. eHMIs should not interfere with existing vehicle signals like directional indicators. It was previously suggested that eHMIs echo vehicle signals [3, 5], but this did not work in Stage 1 when *LightRing* and *Emoji-Car* echoed directional indicators. Instead, eHMIs should clearly communicate the AV's intent and awareness without obstructing current signals. This can be achieved by placing the eHMIs on areas further from indicators, such as the bonnet, or using distinct animations. Riders can then quickly understand messages from the eHMI rather than learning new ways to interpret traditional vehicle signals.

eHMI usefulness is negatively correlated with the traffic control level. eHMIs were most useful in scenarios such as *Lane Merging* and *Bottleneck*, as right-of-way was ambiguous and up for negotiation, and there was little traffic control to help them. This was expected, as previous work found that interaction with human drivers was more likely in these settings [3]. Participants still saw the value of having eHMIs in more controlled scenarios, allowing designers to consider the eHMI level of detail in these scenarios. For example, messages may be displayed earlier to avoid overwhelming riders in uncontrolled scenarios rather than in controlled ones where they can infer AV intent from driving behaviour.

Using the guidelines, we formed a new eHMI design (see Figure 18). It uses a two-strip light band. The top displays red lights, conveying that the AV sees the cyclist without yielding to them. The bottom shows a green light when the AV is yielding. Separating them into top/bottom makes it easier for colour-blind cyclists to distinguish, as they can rely on the light position, similar to traffic lights. This way, designers can use animations (e.g., flashing or progress bar) to communicate messages with a higher level of detail, which may be helpful in some scenarios.

7 CONCLUSION

We conducted a two-stage investigation comparing and evaluating three AV-cyclist eHMIs to test their versatility, acceptability and usability. First, we assessed each interface in a VR cycling simulator ($N = 20$) across five traffic scenarios with varying levels of traffic control. Cyclists preferred eHMIs that use red/green signals to communicate the AV's intent. Second, based on the results, we refined all three eHMIs and compared them outdoors in a Wizard of Oz study ($N = 20$). Participants cycled around an 'autonomous' moving car with real implementations of the eHMIs placed on it. Cyclists preferred eHMIs that used large surface areas surrounding the vehicle and were viewable through quick glances. They also appreciated animation patterns to support the colour (red/green) changes. Our results contribute insights into how cyclists respond to eHMIs across various traffic scenarios. We combined findings from both stages and developed novel guidelines for AV-cyclist eHMIs, drawing from firsthand interaction experiences. These guidelines offer valuable recommendations on how eHMIs can effectively support cycling in future traffic and mitigate potential ambiguities and conflicts related to space-sharing with AVs. Our research paves the way for safer and more pleasant interactions between cyclists and AVs in diverse traffic scenarios.

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