Pimp My Ride: Designing Versatile eHMIs for Cyclists

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Fig. 1. Participants designing an eHMI in a real-world setting. (A) Participants sketching and sticking designs on the vehicle, (B) participant using a bike to immerse themselves in the session, (C) participant sketching directly on the car, and (D) an eHMI design.

Autonomous vehicles (AVs) must communicate their intentions to nearby road users and may use external Human-Machine Interfaces (eHMIs). Most eHMIs have focused on interaction with pedestrians at crossings. However, these may not work for cyclists, who can be anywhere around vehicles and encounter them in diverse traffic scenarios. We used participatory design with cyclists and AutoUI researchers ($N = 12$) collaborating in a real-world setting to design eHMIs around an actual vehicle. Participants preferred eHMIs that co-exist with traditional vehicle signals and use a single design language across traffic scenarios to communicate awareness and intent quickly without distracting their attention from the road. We used our findings to develop a taxonomy of eHMI features for cyclists, allowing us to synthesise the designs and contribute versatile eHMI concepts catered to cyclists' needs. This is important to ensure AVs can safely navigate and interact with cyclists in all road scenarios.

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

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1 INTRODUCTION

Cyclists must share the road with motorised vehicles, which they encounter across many traffic scenarios, such as intersections or overtaking [3]. These encounters often result in ambiguities and space-sharing conflicts that require social interaction to be resolved [23]. For example, a driver may use a hand gesture to signal a cyclist to proceed at an intersection, or a cyclist may raise their arm to indicate their intent to merge lanes with a driver behind them [3]. With motorised vehicles being a significant threat to cyclist safety (84% of fatal cycling collisions in the UK between 2015 and 2020 involved a motorised vehicle [2]), interactions are critical; over 11,000 cycling collisions occurred in the UK between 2015 and 2020 because the driver or cyclist failed to make themselves aware of the other road user [2].

Autonomous vehicles (AVs) will be on the road soon, and interactions will shift from interpersonal to human-machine [30]. Road users can no longer exchange facial expressions, hand gestures and other social cues to navigate traffic safely, but AVs must interact with cyclists, and other road users, to be successfully integrated into traffic. A growing consensus suggests using external Human-Machine Interfaces (eHMIs) on the AV to facilitate road interactions [14, 29]. eHMIs are displays of any modality placed on a vehicle's exterior [14]. Existing work for pedestrians has placed displays on the vehicle's front (e.g. bonnet or bumper) to communicate whether a pedestrian can cross the road [14]. It is critical to understand how eHMIs can facilitate interactions with cyclists who have very different needs. eHMIs must be versatile to facilitate interactions across diverse traffic scenarios, not just crossings. Cyclists also move at higher velocities than pedestrians and could be anywhere around a vehicle [3, 19]. Therefore, the likely presence of eHMIs in future traffic and cyclists' unique needs warrant investigating how eHMIs should be designed for this group.

In this paper, we used participatory design with cyclists and automotive user interface (AutoUI) researchers collaborating to design eHMIs around real vehicles in a real-world setting. We conducted a thematic analysis of the design session results to define the features eHMIs should have to interact with cyclists safely. We developed a taxonomy of these features and synthesised, for the first time, versatile eHMI concepts catered to cyclists' needs. We contribute:

- A novel participatory design method for designing on-vehicle interfaces in real-world settings;
- Themes representing cyclists' expectations from eHMIs;
- A taxonomy of cyclists' desired features in eHMIs;
- Versatile AV-cyclist eHMI concepts.

2 RELATED WORK

Interfaces are needed to facilitate interactions between AVs and cyclists. Hagenzieker et al. [17] conducted an experiment where cyclists judged photos of car-cyclist encounters with the car (AV or conventional vehicle) as an independent variable. Participants were more confident about being noticed by drivers than AVs; AVs must clearly communicate their awareness of cyclists to be accepted. Pokorny et al. [28] and Pelikan [27] observed autonomous shuttle-cyclist encounters. The shuttles' unclear intentions and hesitation to let cyclists pass caused many issues and hard stops. For example, some cyclists steered away from the shuttles and were exposed to oncoming traffic, impacting their safety. AVs must successfully communicate their intentions to cyclists to ensure safe future traffic. Berge et al. [8] conducted interviews with cyclists and Al-Taie et al. [4] conducted an online survey, both exploring potential placements of AV-cyclist interfaces. Participants from both studies said that interfaces should be placed on the AV or environment rather than the bike or cyclist, as this would put the responsibility on the vehicle rather than the rider, showing a place for eHMIs in future traffic and motivating us to explore how they may be designed to suit cyclists' needs.

Little work has explored how eHMIs may be designed to operate successfully around riders. Dey et al. [14] reviewed eHMI concepts from academia and the industry; most were designed according to pedestrian needs. Al-Taie et al. [3] gathered requirements for AV-cyclist interfaces through observations of driver-cyclist encounters across five traffic scenarios (e.g. roundabouts and lane merging) and a naturalistic cycling study with cyclists wearing eye trackers. Drivers and cyclists exchanged different social cues and driving/cycling behaviours in different traffic scenarios. So, interfaces must be versatile enough to accommodate these varied interaction behaviours. Cyclists could also be anywhere around a vehicle; eHMI messages should not only be perceivable from the vehicle's front. Cyclists fixated on various vehicle areas throughout, suggesting that vehicles are a feasible design space for AV-cyclist interfaces.

2.1 Designing eHMIs for Cyclists

The specific features, e.g. modalities or display colours, eHMIs should use to communicate with cyclists remain unknown. Research with pedestrians showed that design sessions and focus groups help uncover these. Mahadevan et al. [22] and Asha et al. [5] conducted eHMI design sessions with participants who have user interface design experience, helping them contribute eHMIs suiting pedestrians' needs, as participants could design from both a pedestrian and expert perspective. For example, Mahadevan et al. [22] found that pedestrians prefer eHMIs to communicate awareness using LCD displays and intent using LED lights. Similarly, Dey et al. [16] ran a focus group with AutoUI researchers to contribute six AV-pedestrian eHMIs. Designing for more specific groups, such as cyclists, would require involvement from these users in addition to interface designers to gain insights from a lived experience [21, 25].

Hou et al. [20] hosted a design session with cyclists and interface designers to design interfaces for a lane merging scenario. Each participant sketched their design (individually without collaborating), and the authors synthesised six concepts (two were eHMIs) after the session. We built on this method, having cyclists and experts collaborate on designs. We also considered a wider range of road scenarios to investigate versatile eHMIs that could be used across different traffic situations. Asha et al. [6] showed the value of creating a more collaborative environment between experts and road users to design eHMIs. They conducted an iterative co-design study, remotely through video calls, with a wheelchair user to design an inclusive eHMI and contribute insights into AV-wheel chair user interfaces informed by a lived experience. Claes et al. [12] designed a public roadside display for cyclists by adopting Map-it [21], a participatory design method with teams of cyclists and experts sketching their designs on a map of the public display, prompting discussions between participants and raising key points about the design, e.g. it should have a footrest to keep cyclists stationary. These works motivated us to include cyclists and AutoUI researchers in our design sessions to gain insights from both perspectives and help cyclists contemplate the challenges of interacting with AVs and the potential of eHMIs.

There has been work utilising models and design objects at the scale of an actual AV to develop and evaluate novel interfaces, allowing participants to picture designs at the right scale in more realistic settings. Colley et al. [13] hosted focus group sessions to ideate and evaluate public display eHMIs by projecting them on an actual vehicle in an outdoor parking lot. Similarly, Severs et al. [31] built a to-scale mock-up of an AV to conduct a participatory design session with transport-excluded groups (e.g. senior citizens) to make AV interiors more inclusive. Participants placed their designs on relevant vehicle areas, and a thematic analysis of the session recordings was conducted to identify factors that would make AVs more inclusive. These studies inspired us to conduct design sessions around actual vehicles in a real-world setting so participants could consider how their designs would operate at the correct scale and proximities. We expanded upon them by supporting the design of any visual or non-visual interface anywhere on and around the vehicle through direct annotation, illustration or labelling on the car.

3 METHODOLOGY

Little is known about the features enabling eHMIs to communicate with cyclists in diverse traffic scenarios. This is necessary to design AVs that can drive safely around cyclists in all circumstances. Previous research showed the benefits

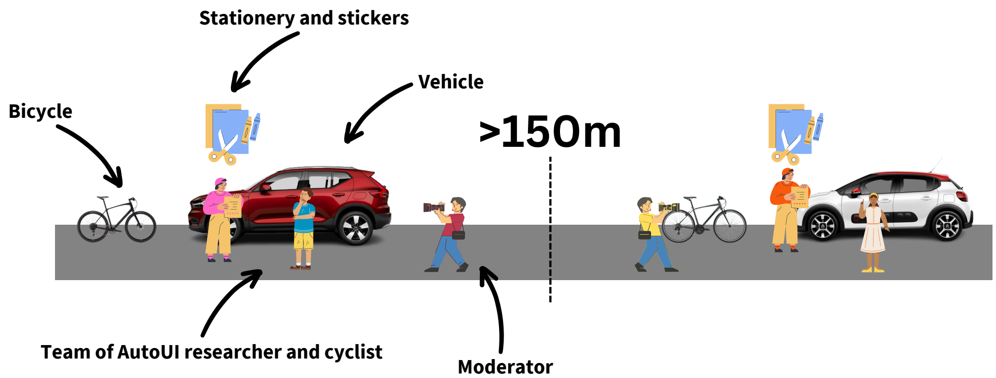

Fig. 2. Design study setup with design teams around each car.

of including cyclists when designing for them [12, 24]. We developed a novel participatory design method conducted with vehicles in a real-world setting to contribute eHMI concepts based on AutoUI researcher-cyclist collaborations.

3.1 Study Design

Six teams (one AutoUI researcher and one cyclist) designed eHMIs around actual vehicles in an outdoor car park. The car park had a flat paved surface, and the vehicles were parallel parked so participants could easily move around. Teams also had bicycles to act out scenarios with the car realistically at the right scale and contemplate how their designs would work in practice. Each team was assigned a moderator to brief them and ensure they remained focused. Moderators were regular cyclists with at least one year of AutoUI research experience. They also video-recorded the sessions and took photographs of the designs, allowing us to conduct a thematic analysis of the design process.

Three sessions were conducted, each with two teams designing for one traffic scenario category as identified by Al-Taie et al. [3]: (1) Controlled Scenarios (scenarios with traffic lights, e.g. controlled intersections), (2) Uncontrolled Infrastructure (no traffic lights but may have traffic signs or road markings, e.g. roundabouts) and (3) Dynamic Manoeuvres (could happen anywhere on the road, e.g. lane merging). This allowed participants to focus entirely on one interaction scenario and consider it in detail [21, 25]. Participants assumed they were designing for SAE level 5 AVs; no human driver in all road scenarios. The designs formed the basis for a taxonomy of eHMI features, which was used to synthesise versatile eHMIs by identifying overlapping features between scenario categories.

In each session, the two teams worked in parallel, each around one of two vehicles positioned at least 150 meters apart, to avoid teams overhearing each other (see Figure 2). Sessions ran for 45 minutes, split into (1) 30 minutes of ideation and (2) 15 minutes of cyclists giving feedback on the other team's design. In the ideation phase, participants sketched their designs and placed them on relevant vehicle areas to visualise and discuss eHMI features in greater detail, *e.g.,* the icons a display should use. They also used whiteboard markers and drew directly on the car. Participants were encouraged to think aloud while ideating. Teams were given *lock* stickers to place on features that should not be altered, helping them form strong opinions about their designs and justify their decisions [21], which was useful for our analysis. The study was focused on eHMI design, so participants were constrained to designing interfaces placed on the vehicle rather than other potential placements, such as the bike. They had no other constraints, so participants were free to develop eHMIs using any modality or display type. In the feedback phase, cyclists switched teams to provide feedback on the other team's design, maximising cross-team discussions. Cyclists were given *like* and *bomb* stickers to place on features they liked/disliked, creating stronger negotiations between participants and helping us understand the advantages or limitations of different features from a cyclist's perspective [21].

3.2 Apparatus

We used two cars per session: a Citroen C3 2019 (light grey, used in all three sessions) and either a Volkswagen Eos 2010 (navy blue, used in two sessions) or a Volvo XC40 2023 (red, used in one session), based on availability. These were right-hand drive cars, as the study was conducted in the UK. We provided each team with a Giant Escape or Specialised Sirrus X; both are hybrid bicycles commonly used for commuting. Teams had A3 and A4 paper, sticky notes, laminate sheets, markers and adhesives to sketch and stick designs on the vehicle. Moderators recorded the sessions and took photos of the designs using an iPhone 12 mini or a Samsung Galaxy S10e.

3.3 Participants

We recruited six AutoUI researchers (mean age = 38.7, Male = 5, Female = 1) and six cyclists (mean age = 27, Male = 3, Female = 2, Prefer not to say = 1) through University mailing lists and social media advertising. Researchers were PhD students, postdoctoral researchers, or lecturers with at least one year of AutoUI research experience. Cyclists had been riding in mixed traffic multiple days a week for at least one year.

3.4 Procedure

Participants used an online survey to sign up and provide their demographic information and cycling/AutoUI experience. Cyclists ranked the traffic scenario categories from most to least dangerous, allowing us to assign them to the ones they perceived as dangerous. Participants who met the recruitment criteria were assigned a team and sent an eHMI design *information sheet* (with introductory information about eHMIs and their assigned scenario category; see supplementary material) at least two days before the session. Participants met their teammates and moderators in the car park where the study was conducted. Moderators briefed the teams about the task, provided them with the stationery and answered any questions. They then asked participants to familiarise themselves with the parked vehicle and encouraged them to use the bicycle to assist in ideation relevant to particular bicycle proximities or positions. The ideation phase then began, and moderators started the video recording. After 30 minutes of ideating, sketching, and *locking* key features, cyclists switched teams. For that phase, the researchers first presented their concepts, and cyclists placed any *like* or *bomb* stickers on eHMI features. Moderators then ended the recordings and took photographs of the designs. Participants were compensated with £5 Amazon vouchers. The University's ethics committee approved the study.

3.5 Analysis

We extracted themes from the designs and footage to identify the characteristics eHMIs should have to suit cyclists' needs. We then developed a taxonomy of eHMI features to understand cyclists' expectations from individual eHMI components, e.g. a display part of the overall eHMI, and identify versatile ones overlapping scenario categories. One author sketched each team's design on a Citroen C3 model using Canva[1] to gain a consistent representation of the results. A second author compared the sketches with photographs of the designs to ensure accuracy and found no discrepancies. Following this, one author manually transcribed the video footage to become familiar with the data,

[1]Canva visualisation tool: canva.com

and another author compared the transcripts with the video footage; no discrepancies were found. Given our diverse contributions, the analysis of the designs and transcripts was split into two phases.

3.5.1 Phase One: Extracting Themes. We conducted an inductive, data-driven, thematic analysis [10] of the designs and transcripts. The data was imported into NVivo[2]. One author extracted 92 unique codes from the data. Two authors sorted these into three overarching, distinct thematic categories based on code similarities. Any disagreements were discussed, and codes were remapped until resolved. The two authors then iteratively synthesised themes within each category; codes were combined into themes based on code similarity. Themes with two or more overlapping codes were reassessed and combined when necessary. Any disagreements were discussed, and themes were revised until resolved.

3.5.2 Phase Two: Taxonomy Development. Developing the taxonomy required knowledge focused on individual eHMI features and how participants' designs used them, prompting us to conduct a theoretical thematic analysis [10] of the data. We used NVivo to identify features (e.g. eHMI messages, modalities or placements) participants discussed when sketching a component, each feature being a taxonomy layer. One author identified unique codes related to eHMI features (e.g. visual cue or bumper placement); the codes were different to those from the previous phase, given that the focus here was exclusively on eHMI features. Two authors then independently organised these into themes based on code similarities, e.g. modality or placement. This was iterative; disagreements were discussed, and themes were revised until resolved. Five themes were extracted, each representing an eHMI feature.

We needed to contribute insights into the relationship between eHMI features, such as optimal placements for components using a particular modality, as this would help designers better address cyclists' requirements. So, we derived a taxonomical hierarchy based on the most prominent order in which participants discussed the features (i.e. design decision sequence). For example, if they discussed the message an eHMI communicates before the modality it uses, the message would go above the modality in the hierarchy. This was done as follows: one author relabelled the codes in the transcripts with the higher level themes/features they were mapped to (e.g. visual cue would be relabelled to modality). Two authors then independently counted the frequency in which each feature appeared in a sequence of 1-5 or less, as we identified five themes in the previous step. No discrepancies were found. Participants were free to follow their own design process/sequence. However, the think-aloud nature of the study and mapping the codes to higher-level themes allowed us to identify the most common design decision sequence and for the taxonomy to have a hierarchal structure.

One author then populated each taxonomy layer with the features used in participants' designs and their appearance frequency. For example, the modality layer is populated with different modalities, such as visual or audio. A second author verified this, and no discrepancies were found. This allowed us to identify overlapping features between eHMIs designed to operate in different scenario categories.

4 RESULTS

Six videos were recorded, one vehicle per session. We report the study's outcome in the form of the designs from each session and the themes extracted from these designs and session recordings. We also present a taxonomy of eHMI features for cyclists.

[2]NVivo qualitative analysis software: lumivero.com/products/nvivo/

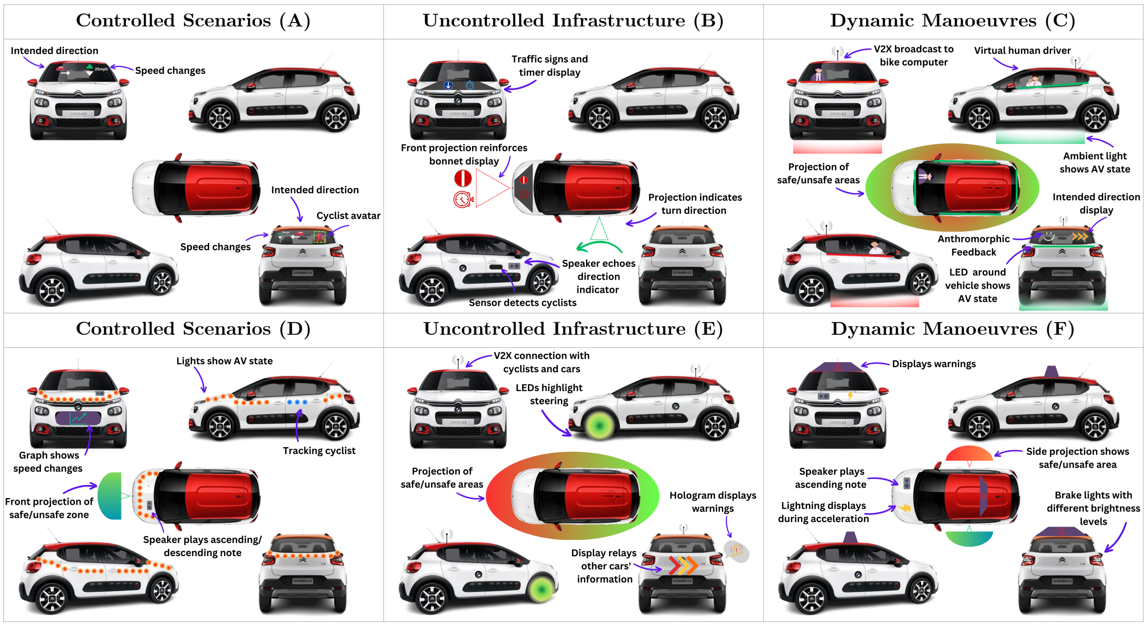

Fig. 3. Proposed AV-cyclist eHMIs from each design session (A-C, Team 1 designs. D-F, Team 2 designs).

4.1 Participant Designs

Figure 3 shows the designs from each session. We summarise how each design works according to participants' explanations in the video footage.

4.1.1 Session 1: Controlled Scenarios. Figure 3.A has two displays on the windscreen communicating the vehicle's intent by showing (1) a car icon next to an arrow pointing to the car's intended direction and (2) the current speed beside an upward or downward-facing arrow, indicating acceleration/deceleration. The same displays are on the back body, with an additional cyclist avatar reflecting the rider's movements to communicate the AV's awareness of them. Not all displays are necessarily active at once. Figure 3.D shows always-on LED lights around the vehicle, meaning that all sensors and components are functioning correctly. The lights respond to nearby cyclists to communicate awareness; cyclists see a blue light becoming wider as they move closer. The design includes a road projection from the vehicle's front bumper to indicate a safe (green) / unsafe (red) zone for riders in front of the AV. Speed changes are communicated through a graph on the vehicle's bumper display. This design has a speaker playing an ascending note (indicating the AV's distance relative to the rider) during overtaking at a controlled intersection once the traffic light turns green.

4.1.2 Session 2: Uncontrolled Infrastructure. Figure 3.B includes a display on the bonnet and a front projector using stop/go traffic signs to communicate instructions to the rider; both show a timer near the signs allowing for some right-of-way negotiation. The eHMI has a sensor detecting riders on the car's left to project a left-facing arrow and warn cyclists of left-hook turns. It also plays a directional indicator sound riders in front of the AV can hear. Figure 3.E projects a safe (green) / unsafe (red) zone for cyclists around the AV, with only the side a rider is on being active. LED lights on the front wheels communicate the AV's intended direction by highlighting the car's implicit cues. The design also includes a hologram from the vehicle's rear lights to display warnings (e.g. road works ahead). The eHMI also uses V2X (Vehicle-2-Everything communication) to broadcast information to cyclists' devices, communicating the state of other vehicles and guiding riders to their next manoeuvre by processing other vehicles' intent and displaying instructions to the cyclist on the back body.

4.1.3 *Session 3: Dynamic Manoeuvres.*

Figure 3.C has a display on the windscreen and side windows showing a virtual human driver, replicating current social cues. The design includes road projections displaying a safe (green) / unsafe (red) zone for cyclists around the vehicle and an antenna using V2X to broadcast information to riders. The eHMI communicates positive/negative feedback to riders using an anthropomorphic display on the back body. Arrows on the car's back body also display the AV's intended direction. An LED strip around the AV and ambient lights under the vehicle communicate that all AV sensors are functioning correctly (green). Figure 3.F has a taxi-like display on the AV's roof to warn cyclists (e.g. road works ahead), with side projections displaying a safe (green) / unsafe (red) zone for cyclists. The eHMI also communicates the AV's acceleration by displaying a lightning bolt on the bonnet and using a speaker to play a car's revving sound. This design alters existing vehicle signals by having different brake light brightness levels to communicate braking intensity.

4.2 Themes

We present themes from the designs and video recordings representing participant design decisions. We identified three thematic categories, each containing themes supported by participant quotes.

4.2.1 *Category 1: Messages Exchanged Between AVs and Cyclists.*

Essential messages to communicate. Participants discussed the messages that should be exchanged with AVs:

- *Awareness and intent.* Cyclist 5 (C5) described the AV's intent and awareness of them as *"basic information coming from the AV"*. C6 said, *"[awareness] is useful. It lets me know that the car is making eye contact with me"*. Awareness also increases perceived safety and trust in AVs. C6 mentioned, *"you could be confident that you're currently being taken into account based on what it's doing."* Intent takes two forms (1) directional intent (e.g. C4 said, *"it's all about where the car is going to go."*) and (2) changes in speed (e.g. C6 said, *"it should communicate accelerating, decelerating and holding steady states"*). Intent helps riders determine their next manoeuvre; C5 explained, *"I would want to know what the car would do next. So, I can plan around what would happen"*. AVs should communicate both awareness and intent to riders: *"eye contact may not be enough here. If they gesture, I can make my manoeuvre because the car is going to make that a safe thing to do."* - C5. Communicating awareness and intent would help riders know they are being seen, the eHMI message is for them, and how to plan their next manoeuvre.
- *Vehicle State.* Cyclists wanted to know the AV's state (if it was in autonomous mode with all components functioning correctly). C3 said, *"It's nice to show that the car is not dead."* This would make them confident that the vehicle is functioning appropriately. For example, when talking about an always-on lightband, Expert 6 (E6) explained, *"If you're worried the light ring is broken, you can check easily by noticing it's all blue."* Communicating the vehicle state could be a fail-safe for eHMIs.
- *Instruction.* C2 explained the AV is *"not the boss of the road"*. Cyclists will likely make their next manoeuvre based on the AV's intent and awareness rather than following its instructions; C5 said, *"I don't want a car to suggest that I turn or do a certain thing, because I make these decisions, not the car."* Therefore, instructions from the AV to the cyclist were especially unwelcome.

eHMIs, driving behaviour and vehicle signals. C3 explained the importance of vehicle signals in future traffic: *"if the indicators would change a lot, it would need a Master's for a cyclist!"* eHMIs may echo signals but should not alter them: *"when the blinker is on, it [projects] the arrow [on the road]"* - C1. E1 emphasised the role of driving behaviour: *"If it were a nice car, it wouldn't need a display – just slow down."* eHMIs must not contradict driving behaviour, especially when communicating speed changes; C5 said *"If it's suddenly speeds up again, that's good to know. So, [if the eHMI indicates] that it's speeding up relative to me then it's fine for me to hang back"*. Therefore, eHMIs could introduce some novelty to traffic, but it is important to integrate these interfaces with more traditional signals.

Approaches to communicating eHMI messages. We identified three *familiarity levels* that eHMIs could adopt to communicate with cyclists:

- *Level 1: Introducing new concepts to traffic.* For example, displaying an avatar of the cyclist. This could overcome some issues in today's interactions; C5 said, *"AVs can signal more actively than drivers who do their thing until you meet their eyes or wave at them"*. However, too much deviation from today's signals may challenge cyclists. For example, C3 said, *"We need to make indicators simple without much deviation from the general understanding"*.
- *Level 2: Reusing traffic control features.* Using traffic signs and colours (e.g., red and green) to communicate with riders. The AV may display a stop sign or a red light to signal a cyclist not to proceed; cyclists are used to seeing these signals in traffic, but there are some ambiguity and inclusivity issues. For example, E1 said, *"Is it red for you to stop or the AV to stop? Also, people who are colour blind won't know"*.
- *Level 3: Replicating current social cues.* For example, anthropomorphic visual displays with a virtual human driver establishing eye contact with the cyclist. This could decrease the learning curve for cyclists but also inherits the flaws of today's interactions. E3 explained: *"you can have the virtual human. It's not great because humans also have some ambiguous signals, so are you recreating a bad way of communicating to the cyclist?"*

4.2.2 Category 2: Challenges for AV-Cyclist eHMIs.

Ambiguity. E6 mentioned, *"the challenge is ambiguity; knowing what that represents"*. Using icons instead of colours could make messages more understandable, e.g., E1 said, *"who is it red for? An icon is colour independent"*. Cyclists must interpret messages quickly, so too much detail could hinder their comprehensibility: *"too much complexity would make the interface not meaningful"* - C3. Care should be taken to ensure that eHMIs are comprehensible in all interactions.

Scalability. Cyclists must know the communicated message is for them. C1 mentioned, *"we need to indicate to the cyclist that if we had a sound, it is for them"*. eHMI messages must still be comprehensible in busy environments; E3 explained, *"in busy roads where every car has LED strips… Is that going to impact visibility?"*. Therefore, eHMIs must function appropriately in one-to-one, one-to-many and many-to-many interaction scenarios.

Versatility. C6 explained, *"having something for just one scenario is too much. I have to learn so much more"*. eHMI components should be reusable with a single design language across traffic scenarios: E6 said, *"use the same colour scheme etc., across interfaces and scenarios."* E4 also reiterated, *"they can have the same symbols to get consistency in meaning"*. eHMIs must function across different road scenarios to avoid the need to learn multiple interaction techniques.

Varying road conditions. Participants considered fail-safes for their designs to function in changing road and weather conditions; E2 mentioned, *"We need something other than visual if the road conditions aren't great"*. Fail-safes should not distract riders: *"you shouldn't create something super distracting or harder to see at night"* - E3. For weather conditions, participants suggested solutions communicating a message from multiple areas, e.g. E1 said, *"having it in 2 places is good because if you look on the ground, it might be difficult in a really snowy day"*. Another approach is to avoid placements and display types that are easily affected by weather changes, such as road projections (*e.g.,* C1 said, *"maybe there will be something preventing us from seeing the projection"*) or windows (*e.g., "it might be tinted, tilted or have some reflection from the sun"* - C6).

Adhering to cycling behaviour. Cyclists may be moving during an interaction, so messages should be *"something that I can process and make an action in the split of a second"* - C1. eHMIs must not distract riders; C2 said *"if I don't need to take my eyes off my path, it's better"*. They should also communicate messages, even when not in a cyclist's field of view (e.g., behind them), C3 explained, *"[I should perceive messages from] anywhere I am around the vehicle"*. There were some differences in cyclists' self-reported behaviours (*"it's interesting; the differences in cyclists' wider confidence and experience."* - E6). Younger cyclists may exhibit different behaviours to older, more experienced ones: *"a cyclist that is a kid or teenager not paying attention to much detail"* - C3. Traffic culture also plays a role. Some traffic colours and vehicle signals, such as flashing headlights, may have different meanings between cultures. E3 explained, *"to adopt traditional signals, you need to adopt ones in that cultural context"*. eHMIs must communicate understandable messages to a broad range of cyclists without significantly affecting their road behaviours.

4.2.3 Category 3: AV-Cyclist eHMI Specifications.

eHMI modalities. All designs included a visual component; participants expected some visual feedback from eHMIs. Auditory cues were also used. These helped riders interact with vehicles out of their view. E1 explained, *"the first way you know there's something behind you"*. Audio is already used in traffic; cyclists may be used to these signals: *"you've probably heard [tarmac trucks] 'warning this vehicle is turning left'" - E2.* However, audio may not be scalable enough. C1 mentioned, *"if all the cars start playing a sound that's going to be bad"* and has some inclusivity issues (e.g., C2 asked, *"what about people wearing headphones?"*). Some teams suggested sounds already used in traffic (e.g., *"speakers to sound like a direction indicator"* - C1). Others opted for new sounds (e.g., *"alternative sound, perhaps just because continuous tone has it where it may or may not give you a sense of distance?"* - C5) but none used horns as they may be culture dependent; E4 said, *"In the UK, it's a sign of annoyance"*. Some designs were multimodal, combining visual and auditory cues. E2 said, *"that's only a visual cue; it's easy to miss."* Multimodality could provide eHMIs with redundancy, helping riders receive messages across modalities. Individual components in multimodal eHMIs could operate sequentially; E1 explained, *"this speaker, which plays the car's indicator sound indicates it will turn. As the car gets closer to you, the sensors on the side fire off a light projector"*. Both modalities may also operate simultaneously; for example, E6 mentioned, *"sound to indicate the action of speeding up, with visual signs to indicate the details of the speed change"*.

Sensing and V2X. Participants suggested more complex feedback, e.g., C5 described a display showing *"an abstract graphic that moves the way I move"*, involving the vehicle's sensors tracking the cyclist with eHMIs reacting to movements. Participants wanted to use V2X in future connected traffic (*e.g.,* C2 said, *"we extend the 'eyes' of all vehicles for the benefit of cyclists"*). This took two forms: (1) AVs communicating the state of other vehicles; for example, C6 suggested, *"what if the car could tell me what the car behind it is going to do"* and (2) a direct connection between the AV and the cyclist. For example, C5 mentioned, *"I think communication between the AV and bike computer is really important"*. eHMIs connecting to cyclist devices might have some inclusion problems. Not all cyclists carry the same devices or wear safety gear. For example, E5 explained, *"there's an inclusion element to that one. So, maybe more subtle stuff should be broadcast [to the bike computer]"*.

Fig. 4. A taxonomy of eHMI features from the design study. Each branch is labelled with: *eHMI feature (frequency of appearance)*

4.3 Taxonomy of eHMI Features

Figure 4 shows a tree diagram of our taxonomy. We identified 32 eHMI components and branched them according to their traffic scenario category. We then branched components to the hierarchy from our analysis. The taxonomy is structured as follows: eHMI component → traffic scenario category → message (e.g., awareness or intent) → familiarity level (e.g., using social cues or traffic signs) → modality (visual, auditory or sensing/v2x) → technology (e.g., speaker or road projection) → placement (we used Al-Taie et al.'s [3] vehicle Areas of Interest, e.g. bonnet or windscreen).

5 DISCUSSION AND SYNTHESIS OF VERSATILE CONCEPTS

We present four versatile AV-cyclist eHMIs, each representing a key finding from the design sessions. We use these as case studies to discuss our results. The concepts (see Figure 5) were synthesised using the taxonomy to identify primary eHMI components overlapping the scenario categories and reviewing each team's designs to identify secondary components that co-exist with primary ones; we did this iteratively until we had a complete eHMI. Table 1 shows each concept's primary component and a classification of components based on our taxonomy. We did not consider V2X; participants explained there might be inclusivity issues, and cyclists prefered eHMIs over on-cyclist devices [4, 8, 18]. Research suggested V2X as an optional component in larger AV-cyclist interfaces; for example, Al-Taie et al. [3] proposed optional AR glasses connected to eHMIs. We focused on essential interfaces between AVs and cyclists: versatile eHMIs.

Anthropomorphism in AV-Cyclist Interaction. The "Virtual Driver" displays a human driver replicating current social cues on the windscreen, side windows and mirrors. This could result in a lower learning curve as riders are used to these

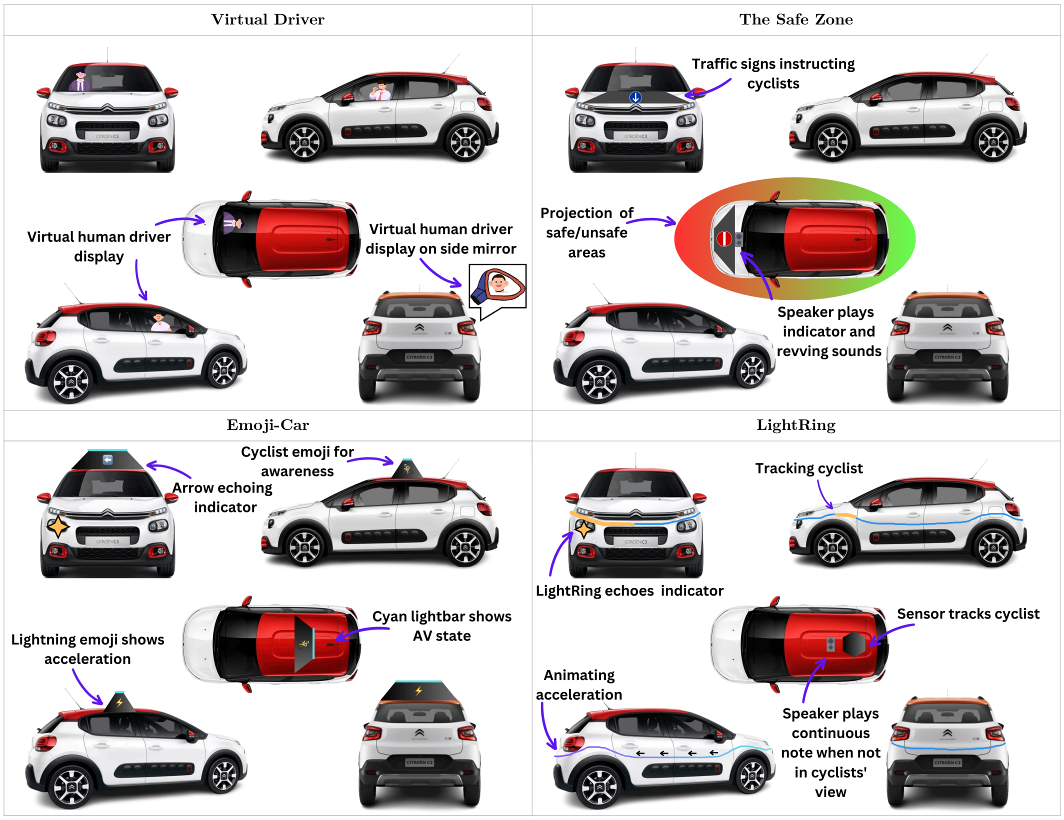

Fig. 5. Versatile AV-cyclist eHMIs synthesised from our taxonomy and results.

	Primary Component	Messages	Familiarity Levels	Modalities	Technologies	Placements
Virtual Driver	Anthropomorphic display of human driver	Same as current interaction	Replicating social cues	Visual	Display	Windscreen, side windows, side mirrors
The Safe Zone	Road projection around vehicle	Instruction, intent	Reusing traffic control	Visual, audio	Projection, display, speaker	Bonnet, around vehicle
Emoji-Car	Visual display on roof	Awareness, intent, AV state	New to traffic	Visual	Light, display	Roof
LightRing	LED lightband around vehicle	Awareness, intent, AV state	New to traffic	Visual, audio, sensing/v2x	Light, display, speaker	Roof, around vehicle

Table 1. Our four examples of versatile eHMI designs classified according to the taxonomy.

cues. We found that intent and awareness are two key messages to exchange with AVs. Cyclists already exchange these with drivers [3], so communicating them may cause a smaller deviation from current interaction behaviour. Exploring less essential messages, e.g. the AV thanking the cyclist, is still interesting, as these are also exchanged today [23]. This eHMI can expressively communicate these. Still, this approach does not solve today's ambiguity and scalability issues. For example, eye contact cannot be established with multiple riders in the same direction (e.g. opposite the windscreen) of the AV [11], so the eHMI does not fully use the AV's sensors to signal more actively. We found that windows may not be optimal eHMI placements because they may be tilted and reflective, and the display may not perform well under varying weather conditions. Replicating today's social cues could also limit the eHMI to only facilitating *essential* interactions rather than resolving other challenges cyclists face, such as dooring or left-hook turns [32].

Instruction in AV-Cyclist Interaction. "The Safe Zone" displays traffic signs to instruct riders to yield or proceed, with road projections using traffic colours to indicate areas cyclists can or cannot access. This reflects a finding from our taxonomy; repurposing traffic signs and colours is correlated with instructing cyclists, which could be because traffic control is used to authorise or prohibit road users from performing certain manoeuvres. A consensus on AV-pedestrian interaction suggests eHMIs should not use traffic colours or communicate instructions [1]. While our cyclist participants said they should not receive instructions from AVs, their designs still had this. Cyclists welcomed using red and green for instruction in Hou et al. [20]'s eHMIs when lane merging, so this should be further explored across a wider range of scenarios. "The Safe Zone" represents how cyclists expect these instructions to be communicated by a versatile eHMI. Still, projecting colours rather than icons onto the road may cause ambiguity issues, as it may be unclear whether the AV is communicating instruction or an awareness cue and whether projecting green means the cyclist or AV should proceed.

Combating Ambiguity with Icons. Ambiguity is a significant challenge for eHMIs; colours and abstract symbols may not be enough. For example, an LED flashing green does not clarify whether the rider or the AV should proceed, or displaying an arrow makes it unclear if this is an instruction to the cyclist or an AV indicating its intended direction. More expressive icons and animations could make messages more comprehensible. "Emoji-car" uses emoticons to interact with riders. It is a "taxi-like" roof display, with the cyclist emoji communicating awareness, a blinking (animation) left or right arrow echoing directional indicators and lightning to communicate acceleration. Cyclists may be used to emojis as these symbols are already used, e.g. in smartphones [7]. Emojis are already used in traffic; for example, some roadside displays show a smiley face when drivers are within the speed limit [26]. Emojis were also explored within the AutoUI domain, e.g. to react to dangerous driving behaviours by displaying emojis to influence drivers to drive more safely [9]. Still, these icons may be culture-dependent and not universal [7]. Participants explained that too complex messages could hinder their comprehensibility. For example, an arrow next to a cyclist's emojis could be perceived as instructions to the cyclist and cause dangerous encounters. "Emoji-Car" displays emojis sequentially, one emoji at a time. The interface may be less costly compared to others, such as safe-zone, which uses projection, and riders may already be used to interfaces on the roof, such as taxi displays or police sirens. However, the eHMI only relies on visual cues and only utilises the roof as a placement, so it may demand more attention from riders compared to the other designs, especially with different vehicle heights, e.g. buses and city cars.

Introducing New Concepts to Cyclist Interactions. The "LightRing" concept is based on Dey et al.'s [15] light-band design, readjusted to also address cyclists' needs. This is beneficial, as the design may be universal enough to work with other road users such as pedestrians. It uses an always-on cyan lightbar around the vehicle to communicate that all sensors function correctly. The cyclist is tracked using a visible sensor on the AV's roof, and LightRing displays an amber colour, reacting to the cyclist and getting wider as the cyclist moves closer. Directional indicators are echoed with the side of LightRing blinking in amber in sync with the vehicle's indicators. Speed changes are communicated through animations, strokes of cyan lights being pulled apart for acceleration and pulsing toward each other when decelerating. These animations are only on the vehicle's front and sides, not the back, avoiding ambiguity. The always-on lightbar is critical as participants highlighted the importance of having a fail-safe for eHMIs; this may be relevant to real-world scenarios of AVs using hazard lights to indicate failures[3]. This often caused ambiguity, with bystanders unsure of what hazard lights mean in that context. Asha et al. [6] had a similar finding with wheelchair users wanting a failsafe for eHMIs using V2X to trigger haptic cues on the wheelchair. Still, it is unknown how scalable this approach is, as having multiple AVs with always-on lightbands in the same scenario may impact cyclists' visibility and overwhelm them. We identified three *familiarity levels* to communicating these messages, and it is unknown how this variable would affect cyclists' acceptance of eHMIs. Novel concepts, such as Dey et al.'s [15] light-band design, were accepted by pedestrians. This design introduces new concepts to cyclist interactions, including colours (cyan), animations and a new approach to sensing in traffic. It is unknown how they will perform in practice, as riders are unfamiliar, so evaluating this across a range of traffic scenarios is critical.

6 LIMITATIONS AND FUTURE WORK

All sessions were conducted in dry weather to prevent sketches from being affected by external factors, such as rain or wind. Whether participants would have different ideas in different weather conditions is unclear. However, varying weather conditions were discussed amongst participants (see Section 4.2.2), so the designs may be generalisable to work in these situations.

Our design sessions were conducted around cars, so it is unclear how our results generalise to other vehicle types, such as buses or lorries, leaving room for future work replicating our sessions with these. Participants designed eH8MIs for SAE level 5 AVs; it is unclear how our findings will generalise to AVs with other automation levels. Teams developed their concepts around parked vehicles, and while the study's outdoor nature provided participants with a more realistic setting, future work should still evaluate the designs in scenarios with moving vehicles and cyclists.

7 CONCLUSION

This paper investigated the design of eHMIs to support interaction between cyclists and future AVs. We showed how eHMIs could be designed according to the unique needs of cyclists using a series of participatory design sessions ($N = 12$) with cyclists and AutoUI researchers collaborating around real vehicles. We analysed each session's designs and video recordings. We found that cyclists prefered eHMIs that co-exist with traditional vehicle signals, such as direction indicators and those that do not affect their cycling behaviour. Participants expressed that eHMIs should not communicate instructions to the cyclist but rather the AV's intent and awareness of them. eHMIs should use a single design language to communicate these messages across different traffic scenarios to avoid a learning curve for cyclists. We used our findings to develop a taxonomy of eHMI features and synthesised four versatile eHMI designs from that. Our results lay out the features that eHMIs should have to interact with cyclists safely; this is a crucial step to ensure the successful integration of AVs into traffic.

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