Overcoming Critical Interface Design Challenges for Automated Vehicle-Cyclist Interaction

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This thesis is dedicated to the loving memory of my uncles Mazin and Laith and my grandmothers Mariam and Ruqaia.

Abstract

Cyclists are vulnerable road users who must share the road with motorised vehicles [66]. They rely on social interactions with drivers to resolve space-sharing conflicts safely and without ambiguity [82]. The advent of automated vehicles (AVs) will remove these social interactions, compromising the safety of cyclists [97]. AV-cyclist interfaces are promising solutions; these devices facilitate clear communication by allowing AVs to communicate explicit signals [37]. For example, displaying the AV's intentions via LED lights on the AV or augmented reality glasses worn by cyclists [67]. However, AV-cyclist interfaces must overcome four key design challenges to be usable on real roads: **acceptability** to match the needs and requirements of cyclists [41, 49]; **versatility** to operate across various traffic scenarios, such as intersections or roundabouts [12]; **cultural inclusivity** between countries with different cultural norms and traffic infrastructure [108], and **scalablity** for many-to-many AV-cyclist interaction [123].

This thesis describes 10 studies conducted to overcome these challenges. These established requirements for AV-cyclist interfaces through observations and eye-tracking studies conducted in real traffic. The requirements were used to design interfaces through participatory design and test them in outdoor and simulator-based user studies. Findings for **acceptability** showed that interfaces should be placed on the surrounding environment or the AV itself to avoid compelling cyclists to carry devices on every trip. However, optional wearable devices can be used for added support. Results for **versatility** showed that AV-cyclist interfaces must be viewable from anywhere around the vehicle, and the AV's intentions should be communicated in a simple, binary manner (i.e., AV-yielding or not yielding) to work consistently between traffic scenarios. Investigating **cultural inclusivity** showed that interfaces were needed to facilitate interaction regardless of the cultural setting. Cyclists accustomed to riding in mixed traffic found interface messages on AV intentions sufficient. However, those accustomed to greater segregation from vehicles needed to verify these messages with AV driving behaviours. For **scalability**, results showed that incorporating additional wearable devices was useful to avoid ambiguity in multi-cyclist situations and centralise information from multiple AVs. Multi-AV information should be communicated using visual and auditory signals without diverting cyclist attention from the road ahead, e.g. by integrating visual displays into the environment. The thesis contributes novel design guidelines for each design challenge. This is critical for supporting the large scale, global deployment of AVs and ensuring safe cycling experiences.

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Declaration and Contributing Papers

The research presented in this thesis is entirely the author's own work. The overall plan for the research was presented and discussed at the International Conference on Automotive User Interfaces and Interactive Vehicular Applications 2022 (AutomotiveUI '22):

> Ammar Al-Taie, Frank Pollick, and Stephen Brewster. 2022. Exploring Holistic Autonomous Vehicle-Cyclist Interfaces to Facilitate Versatile Interactions. In Adjunct Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '22).

All studies in this thesis received ethical approval from the University of Glasgow's College of Science and Engineering Research Ethics Committee. All data resulting from these studies can be found at: `zenodo.org/records/15569938`

Publications

All studies were published in various Human-Computer Interaction conference proceedings between 2022 and 2025. This was as follows:

Chapter 3

Study 1 Published as a Late Breaking Work in AutomotiveUI 2022:

> Ammar Al-Taie, Frank Pollick, and Stephen Brewster. 2022. Tour de Interaction: Understanding Cyclist-Driver Interaction with Self-Reported Cyclist Behaviour. In Adjunct Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '22). Association for Computing Machinery, New York, NY, USA, 127–131. `https://doi.org/10.1145/3544999.3552531`

Studies 2 and 3 Published as a full paper in Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23). The paper won an *Honourable Mention* award:

Ammar Al-Taie, Yasmeen Abdrabou, Shaun Alexander Macdonald, Frank Pollick, and Stephen Anthony Brewster. 2023. Keep it Real: Investigating Driver-Cyclist Interaction in Real-World Traffic. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23). Association for Computing Machinery, New York, NY, USA, Article 769, 1–15. https://doi.org/10.1145/3544548.3581049

Chapter 4

Study 4 Published as a full paper in AutomotiveUI '23. The paper won an *Honourable Mention* award:

Ammar Al-Taie, Graham Wilson, Frank Pollick, and Stephen Anthony Brewster. 2023. Pimp My Ride: Designing Versatile eHMIs for Cyclists. In Proceedings of the 15th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '23). Association for Computing Machinery, New York, NY, USA, 213–223. https://doi.org/10.1145/3580585.3607161

A virtual reality cycling simulator used in Study 4 was also demonstrated in the Augmented Humans International Conference 2023. This won the *Best Local Demonstration* award:

Ammar Al-Taie, Frank Pollick, and Stephen Brewster. 2023. A Virtual Reality Cycling Simulator. In Proceedings of the Augmented Humans International Conference 2023 (AHs '23).

Studies 5 and 6 Published as a full paper in CHI '24:

Ammar Al-Taie, Graham Wilson, Euan Freeman, Frank Pollick, and Stephen Anthony Brewster. 2024. Light it Up: Evaluating Versatile Autonomous Vehicle-Cyclist External Human-Machine Interfaces. In Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24). Association for Computing Machinery, New York, NY, USA, Article 90, 1–20. https://doi.org/10.1145/3613904.3642019

Chapter 5

Study 7 Published as a full paper in AutomotiveUI '24:

Ammar Al-Taie, Graham Wilson, Thomas Goodge, Frank Pollick, and Stephen Anthony Brewster. 2024. Bike to the Future: Designing Holistic Autonomous Vehicle-Cyclist Interfaces. In Proceedings of the 16th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '24). Association for Computing Machinery, New York, NY, USA, 194–203. https://doi.org/10.1145/3640792.3675727

Study 8 Published as a full paper in CHI '25 and won an *Honourable Mention* award:

Ammar Al-Taie, Andrii Matviienko, Joseph O'Hagan, Frank Pollick, and Stephen Brewster. 2025. Around the World in 60 Cyclists: Evaluating Autonomous Vehicle-Cyclist Interfaces Across Cultures. In Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25). Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3706598.3713407

Chapter 6

Studies 9 and 10 Published as a full paper published in CHI '25:

Ammar Al-Taie, Euan Freeman, Frank Pollick, and Stephen Brewster. 2025. evARything, evARywhere, all at once: Exploring Scalable Holistic Autonomous Vehicle-Cyclist Interfaces. In Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25). Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3706598.371341

Abbreviations

- **AOI:** Area of Interest
- **AR:** Augmented Reality
- **AV:** SAE Level 5 Automated Vehicle; capable of conducting all driving tasks without human intervention [117]
- **eHMI:** External Human-Machine Interface
- **HCI:** Human-Computer Interaction
- **HRU:** Human Road User; such as drivers, cyclists, e-scooter riders and pedestrians
- **HUD:** Head-Up Display
- **IQR:** Interquartile Range
- **POV:** Point of View
- **SD:** Standard Deviation
- **TOI:** Time of Interest
- **V2X:** Vehicle to Everything Communication
- **VR:** Virtual Reality
- **VRU:** Vulnerable Road User; subset of HRU. This features only unprotected road users, such as cyclists or pedestrians

"To be a true hero, kid, is a dying art. Like painting a masterpiece, it's a work of heart!"
- Philoctetes, Disney's Hercules (1997).

Chapter 1

Introduction

Cycling offers many benefits for individuals, communities, and the environment. It improves physical health and enhances mental wellbeing by reducing stress and anxiety [32]. Cycling also fosters social connections through group rides and strengthens community bonds by promoting active, eco-friendly lifestyles [93]. It is a sustainable mode of transport that helps lower carbon emissions, improve air quality, and reduce traffic congestion [102].

Many cities have recognised cycling's multifaceted benefits and invested significantly in cycling infrastructure [62]. For instance, Glasgow, Scotland, allocated £8 million from its 2020 budget to make the city more cycling-friendly [27]. Similarly, initiatives like the UK's Cycle to Work[1] scheme provide employees with discounts on commuter bikes, encouraging cycling as a daily practice. These efforts have contributed to a rise in cycling. Between 2003 and 2023, the total distance cycled annually in the UK increased by 29% [30].

1.1 Social Interaction is Key for Cyclist Safety

Despite cycling's many advantages, safety is a primary concern [16, 26, 137]. Cyclists are vulnerable road users (VRUs) without a protective vehicle layer shielding them from harm [16, 66]. Many cyclists are compelled to navigate mixed traffic and share the road with motorised vehicles [128]. However, these pose the greatest threat to cyclist safety [14, 66]. In 2023, 96% of cyclist injuries and fatalities in the UK involved a vehicle [2]. Given the substantial investments required to improve cycling infrastructure and segregate cyclists from vehicles [18, 27], it is unlikely that all cities will implement comprehensive cycle lane networks in the near future. Even in cities prioritising cyclist-friendly infrastructure, vehicle-cyclist encounters remain unavoidable, particularly at intersections or areas where cycle lanes are obstructed by parked vehicles, roadworks, or other obstacles that force cyclists to share the road with motorised traffic [12].

Therefore, despite their vulnerability, cyclists are likely to encounter vehicles throughout their journeys across different forms of traffic infrastructure, such as roundabouts or intersections

[1] Cycle to Work Scheme: `cyclescheme.co.uk/how-it-works` ; Accessed 01/04/2025

[12, 66, 67]. Such encounters often result in space-sharing conflicts, which refer to situations where *"at least two road users intend to occupy the same region of space at the same time in the near future"* [82]. Space-sharing conflicts between drivers and cyclists are frequent and have significant safety implications [37]. They result in collisions if not resolved [82]. Between 2018 and 2022, there were over 75,000 vehicle-cyclist collisions in the UK, with over 500 resulting in cyclist fatalities [2]. Globally, the World Health Organisation (WHO) estimates that over 41,000 cyclist fatalities occur annually due to collisions [71].

Interaction between road users, such as drivers and cyclists, is a common way to resolve space-sharing conflicts safely and without ambiguity [16, 37]. Road interactions are defined as *"situations where the behaviour of at least two road users can be interpreted as being influenced by a space-sharing conflict between the road users"* [82]. The road can be described as a *"shared social space"* [74] where cyclists, drivers, and other road users exchange social cues, such as hand gestures or facial expressions, to interact and negotiate the right of way [16, 37, 60, 82]. For example, a driver may use a hand gesture to signal a cyclist to proceed at an intersection [103], or a cyclist may extend their arm to indicate their intentions to merge lanes with a driver behind them [119, 141]. This communication helps road users understand each other's intentions, ensuring that only one proceeds to avoid collision [11, 37, 104]. The absence of such interactions is a significant safety concern, as evidenced by over 5,000 vehicle-cyclist collisions in the UK between 2015 and 2020, where at least one road user was unaware of the other's presence [36].

1.2 The AV Interaction Problem

Recent technological advancements are bringing Automated Vehicles (AVs) [117] closer to wide adoption [37, 97, 104]. AVs are *"vehicles capable of perceiving their environment and performing all driving tasks without human intervention"* [117]. They are becoming increasingly common. For instance, cities like San Francisco, USA, already operate over 300 automated taxis without human drivers, completing an average of 4,300 trips daily [23]. Cyclists must share the road with this new class of road users [66].

While AVs are expected to improve road safety by eliminating human error [73], they also introduce new challenges. The absence of a human driver removes the social interactions that cyclists and other road users rely on to navigate the road safely [82, 104]. Cyclists can no longer exchange hand gestures and other social cues with drivers to confirm their intentions. Instead, they must implicitly infer AV intentions through the vehicle's driving and braking behaviour [37, 98]. This will be ambiguous and misleading compared to the direct, explicit signals from human drivers. Such ambiguity poses a significant threat to cyclist safety [67, 88]. Cyclists may be uncertain whether they or the AV should proceed in a space-sharing conflict [82]. In worse cases, they may misinterpret the AV's braking behaviour, proceed, and collide with the vehicle. Additionally, the absence of human drivers may heighten cyclist anxiety, as the lack of eye contact prevents cyclists from confirming whether an AV has detected them [108].

These concerns were validated by AV-cyclist collisions reported in the media [63] and observations of AV-cyclist encounters on real roads [97]. The observed AVs had no way of communicating their intentions explicitly. Rather than negotiating with cyclists, they were programmed to yield the right of way whenever a cyclist was detected, even when they should not have yielded. This created significant ambiguities and unsafe situations [97]. For instance, AVs would emergency brake in a space-sharing conflict with a cyclist. This was uncomfortable for AV passengers and created ripple effects in traffic. Cyclists behind the AV were forced to avoid collision by swerving into the other lane with oncoming traffic, significantly compromising their safety [97, 101]. These issues would have been avoided if AVs had been able to negotiate with cyclists and state whether they intended to yield [67]. AVs must compensate for the lost social cues from human drivers to be a part of traffic [37, 82, 104].

1.3 The Need for AV-Cyclist Interfaces

The consensus within academia and the automotive industry recommends using interfaces to facilitate explicit communication between AVs and human road users (HRUs) [14, 37]. These interfaces compensate for the loss of driver social cues by conveying critical messages, such as whether an AV has detected the HRU and intends to yield in a space-sharing conflict [43, 80]. Interfaces can take different forms. Some are worn by the HRU [137, 138], such as AR glasses or smartwatches that vibrate to alert them when an AV has detected them. Others are mounted on the AV to signal its intentions [37], such as LED lights on the roof. Interfaces can also be integrated into the environment [80], such as smart traffic signs with LED signals to inform HRUs of an approaching AV's actions. More examples of AV-HRU interfaces are in Figure 1.1.

However, most of these interfaces were designed for pedestrians rather than cyclists [14]. While both are classified as VRUs [66], cyclists have distinct needs, so solutions designed for pedestrians do not necessarily generalise to cyclists [16]. Pedestrians will likely only encounter AVs at crossings [44], where they typically stand on a pavement separating them from motorised traffic and primarily see the vehicle's front [49]. In contrast, cyclists travel at higher speeds [126]. They will encounter AVs across a wider range of traffic scenarios, including crossings, intersections, roundabouts and dynamic situations where they may be sharing lanes with vehicles, such as being overtaken [12]. This places cyclists in a more vulnerable position. In 2018, cyclists were more than twice as likely to be killed or seriously injured during their commutes compared to pedestrians in the UK [35].

External Human-Machine Interfaces (eHMIs) are widely regarded as the optimal solution for AV-pedestrian interaction [37, 41, 58, 104]. These are displays placed on the vehicle's exterior to communicate with road users. For example, speakers on the roof [17], lights on the bonnet

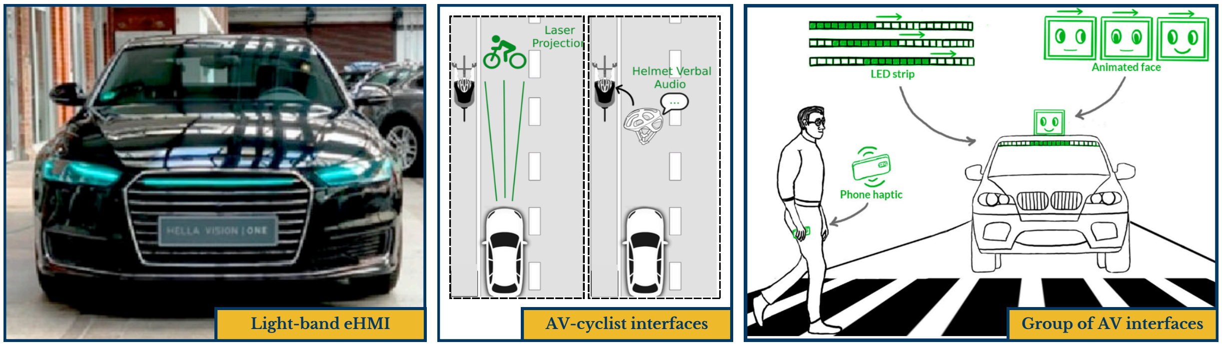

Figure 1.1: Example AV-HRU interfaces from previous research. Left: A real prototype of Dey et al.'s [44] *light-band* eHMI. Middle: Example AV-cyclist interfaces to assist cyclists merge lanes from Hou et al. [67]. Right: From Mahadevan et al.'s [80] study on concurrently using multiple AV-pedestrian interfaces in a crossing, including smartphone vibration and eHMIs.

[39], or road projections from the bumper [43]. The most prominent eHMI is *light-band* (see Figure 1.1), which tested well with pedestrians [39, 44]. It is an LED light strip placed on the vehicle's bumper to communicate AV intentions using animated cyan-coloured lights. Lights moving toward the centre indicate that the AV will yield, while lights pulling apart signal that it will not. Elements of *light-band* are already appearing in traffic. For instance, the 2024 Mercedes S-Class features cyan lights to indicate the vehicle is in autonomous mode [132].

Despite its popularity, *light-band* may not be suitable for cyclists. It is only visible from the front of the vehicle, and its animations may be difficult to distinguish at higher speeds from different areas around the vehicle [37]. Cyclists may require signals that are easier to differentiate and perceive, such as icons or colour changes [67]. Cyclists may also be located anywhere around a vehicle, so placing an interface only on the AV's front is insufficient [66]. Understanding the specific requirements of cyclists is crucial to ensure that AV interfaces are inclusive of all road users, especially given the growing rates of cycling [14, 16].

1.4 AV-Cyclist Interface Design Challenges

Unlike for pedestrians, there is no consensus on the best AV-cyclist interface [14, 67]. Various interfaces have been designed, including wearables [137], eHMIs [37], and interfaces placed on the bicycle, such as vibrating handlebars [67]. However, most of these remain conceptual and were developed to address specific problems, such as facilitating interaction at an intersection [138] or when a cyclist merges lanes with an AV behind them [67]. Very little has been done to ensure these interfaces are usable on real roads throughout a cyclist's journey (see Figure 1.2) rather than just in a specific situation. AV-cyclist interfaces must overcome the following four design challenges to be acceptable and usable in real traffic.

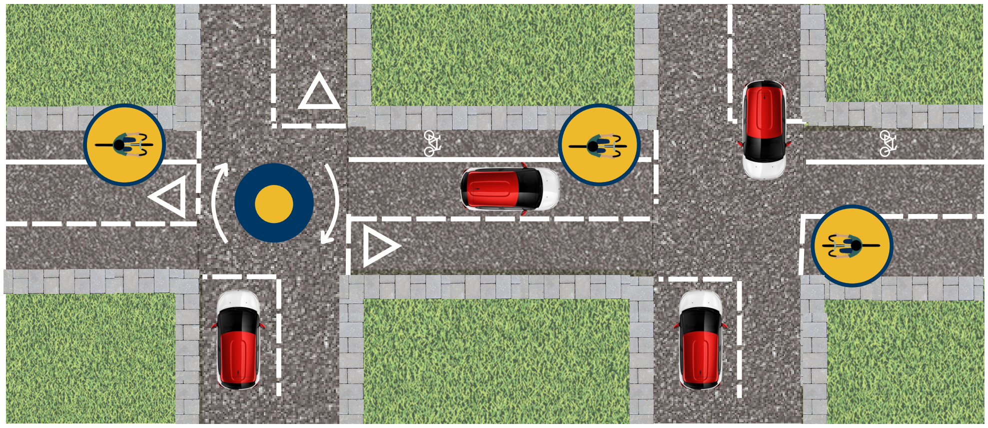

Figure 1.2: An overview of a cyclist's journey. Starting with a roundabout on the left and an intersection on the right. Cyclists may navigate multiple scenarios, so interface versatility is a core requirement. The intersection features multiple cyclists and AVs, including an AV approaching from behind a cyclist. Cyclists must know an AV's signal is for them and correctly associate the signal with the correct AV. This journey is not limited to a single cultural setting, and interfaces must be acceptable for cyclists to adopt them.

Acceptability

This refers to *an interface being available and acceptable to the broadest possible range of cyclists [16].* Cyclists represent a diverse user group, with the bicycle being the only common factor [64]. Even then, bicycles vary greatly, from mountain and road bikes to e-bikes and custom-built models [141]. Cyclists also differ in their approaches to safety. Some prioritise helmets and reflective gear, while others ride without safety gear [107]. It is essential to maintain the simplicity and accessibility of cycling [16]. Any efforts to complicate the experience could have significant negative implications. For instance, there was a 36% decrease in cycling trips when helmets were enforced in Australia [116]. This emphasises how additional requirements can discourage cycling. The safety of cyclists and the widespread adoption of AVs will be hindered if cyclists perceive interfaces as unacceptable or impractical in traffic, as there would be no effective way to facilitate AV-cyclist interaction [14, 37, 82]. AV-cyclist interfaces must accommodate the diversity of cyclists and require minimal changes to the current cycling setup to ensure adoption [16]

Versatility

This refers to *an interface's ability to consistently facilitate communication between AVs and cyclists across diverse traffic scenarios, regardless of the type of traffic control or the AV's position in that scenario [12].* The traffic scenarios in which cyclists encounter vehicles may vary in their levels of traffic control [67]. For instance, controlled intersections use traffic lights to determine the right of way, while roundabouts use road markings to promote negotiation between road users [128]. Some scenarios are dynamic; they could happen anywhere on the road without formal traffic control, such as a cyclist being overtaken by an AV [55]. Additionally, traffic scenarios may involve different AV positions relative to the cyclist [12, 31]. For example, an AV may approach from the cyclist's left at an intersection and behind during a cyclist's lane merging manoeuvre. As a result, cyclists are exposed to different vehicle sides [15]. Versatility is crucial for AV-cyclist interfaces to ensure cyclists can receive and understand AV messages across all traffic scenarios. An interface designed for one scenario may not generalise to others [37]. For example, LED lights on an AV may be visible at an intersection where the vehicle is within the cyclist's field of view [39] but difficult to see during a lane merging manoeuvre where the AV is behind the cyclist [67]. Requiring cyclists to use different interfaces between scenarios would be overwhelming and impractical [16, 79].

Cultural Inclusivity

This refers to *an interface's ability to consistently facilitate communication between AVs and cyclists, regardless of the interaction's cultural setting. [37]* Drivers and cyclists interact differently between cultures, including countries or even cities within the same country [62]. For example, a hand gesture may be interpreted as a gesture of thanks in one culture but as a request to stop in another [56]. Similarly, a driver flashing their headlights could mean a driver is yielding to the cyclist in one culture but proceeding without yielding in another [119]. AVs are currently trained and deployed locally in individual cities [23]. AV-cyclist interfaces have also only been designed and tested within a single country [14]. However, interfaces must be culturally inclusive to support the global deployment of AVs. This means they must adapt and work effectively in the cultural setting in which the interaction occurs. Interfaces designed to operate in one culture may not generalise to others.

Scalability

This refers to *an interface's ability to facilitate communication between multiple AVs and cyclists.* [123] Cyclists may encounter multiple AVs in a space-sharing conflict [37]. For instance, a cyclist might approach an intersection with one AV coming from the left and another from the right while simultaneously needing to merge lanes with an AV behind them due to an obstacle in the cycle lane (see Figure 1.2) [37]. Some AVs might yield to allow the cyclist to pass, while others may not. Cyclists must be able to correctly associate these intentions with the respective AV to avoid miscommunication. Similarly, an AV may encounter multiple cyclists simultaneously, yielding to some but not others [47]. For instance, one cyclist might approach from the AV's left at a roundabout while another approaches from the right, with the AV only intending to yield to the cyclist on the left [12]. Each cyclist must be certain that the AV's message is for them to ensure safe interaction.

Overall, AV-cyclist interfaces must overcome these four design challenges to be successful. They must be accepted by their end users to be adopted at a large scale [16], and they must consistently facilitate interaction between traffic scenarios, regardless of traffic control or AV position [12]. This is critical as AV-cyclist encounters will likely happen throughout a cyclist's journey, including at intersections, roundabouts and lane merging manoeuvres [67, 88]. Moreover, AV-cyclist interfaces must be generalisable between cultures to ensure the global deployment of AVs rather than in individual cities [108]. Finally, AV-cyclist interaction is not limited to one-to-one space-sharing conflicts, so interfaces must facilitate communication with an increasing number of AVs and cyclists to operate on real roads [123]. This thesis investigates these four design challenges to enable clear communication between AVs and cyclists.

1.5 Thesis Motivation and Research Questions

This thesis focuses on facilitating interaction between SAE Level 5 AVs [117] and cyclists. These AVs are capable of performing all driving tasks without human intervention and may lack a driver's seat or traditional driving controls, such as a steering wheel or pedals [117]. As a result, social interaction is not possible, and cyclists must rely on interfaces to receive explicit signals from the AV [14, 67]. The research investigates four AV-cyclist interface design challenges to ensure that interfaces are acceptable and usable on real roads. This is critical for the large scale, global adoption of AVs and safer future cycling [14, 37]. The research was guided by the following four research questions (RQs). Each RQ focuses on one of the key design challenges.

RQ1 How can insights from current driver-cyclist interaction inform the design of **acceptable** AV-cyclist interfaces?

RQ2 What features enable AV-cyclist interfaces to be **versatile**, supporting interaction across diverse traffic scenarios?

RQ3 What are the **cultural differences** in cyclist use and perceptions of AV-cyclist interfaces?

RQ4 How can AV-cyclist interfaces facilitate interaction between an increasing number of AVs and cyclists to support **scalable** communication?

1.6 Thesis Statement

Introducing AVs into traffic will diminish the social interactions cyclists rely on with drivers to resolve space-sharing conflicts and safely navigate the road. This thesis explores the design of new interfaces to facilitate AV-cyclist interaction by ensuring **acceptability** among cyclists, **versatility** across traffic scenarios, **cultural inclusivity** for clear communication across cities and countries, and **scalability** to support interaction with multiple AVs and cyclists. **Acceptability** was achieved by placing interfaces on vehicles to accommodate cyclists who may not use wearable devices; **versatility** required interfaces to convey binary signals (AV-yielding/not yielding) that generalise across scenarios; **cultural inclusivity** was ensured by communicating comprehensive messages adaptable to different cultural norms, and **scalability** was achieved by incorporating wearable devices to assure cyclists the messages were for them when other cyclists were nearby and centralising messages from multiple AVs into multimodal displays that maintain cyclist attention on the road.

1.7 Thesis Outline

The four research questions (RQs) address critical AV-cyclist interface design challenges: acceptability, versatility, cultural inclusivity, and scalability. A total of 10 studies were conducted to answer these RQs. Studies employed diverse methodologies, including online surveys, eye-tracking in naturalistic settings, participatory design sessions, and user studies evaluating interface prototypes. These studies are described in chapters of this thesis, each chapter focusing on a single design challenge. Each chapter concludes with a set of design guidelines synthesised from its studies. These guidelines serve as valuable contributions toward the real-world deployment of AV-cyclist interfaces. The thesis structure is outlined below.

Chapter 2: Literature Review

This chapter features a literature review exploring previous research on the AV interaction problem. The review highlights research gaps in the acceptability, versatility, cultural inclusivity, and scalability of AV-cyclist interfaces to inform the research directions of this thesis. It also explores existing work on AV-pedestrian interaction to understand how the AV-cyclist interaction domain can be advanced in a similar manner.

Chapter 3: Acceptability

This chapter describes three studies to answer RQ1. Study 1 was an online survey that provided an overview of the AV-cyclist interaction problem based on cyclists' perspectives. Study 2 was a set of observations of driver-cyclist interactions across five traffic scenarios in real traffic; this informed the messages and cues AVs should detect from cyclists and display in response. Study 3 was an eye-tracking study with cyclists riding in real traffic to record where they looked and inform the areas to place AV-cyclist interfaces. This chapter provides foundational knowledge to inform the design of acceptable AV-cyclist interfaces that correspond to the expectations and natural behaviours of cyclists.

Chapter 4: Versatility

This chapter describes three studies to answer RQ2. Study 4 used participatory design with AutomotiveUI researchers and cyclists collaborating around real vehicles to design AV-cyclist interfaces; this informed the design features that enhance interface usability, such as colours or animations. Study 5 evaluated the outcome interfaces in a virtual reality (VR) cycling simulator; participants used the simulator to interact with AVs across different traffic scenarios using each interface and provided feedback on usability and versatility. Study 6 revised the interfaces based on feedback from the previous study and evaluated them outdoors using a real vehicle across different traffic scenarios; the study employed a Wizard of Oz approach with a hidden human driver. This chapter provides insights into the design features that improve AV-cyclist interface versatility and usability.

Chapter 5: Cultural Inclusivity

This chapter describes two studies to answer RQ3. Study 7 uses participatory design to understand how AV-cyclist interfaces can be grouped to facilitate interaction collectively; HCI researchers and cyclists collaborated around real vehicles to design interface groups. This provided insights into taking full advantage of the AV-cyclist interface design space to enhance usability. Study 8 was a cross-cultural study to evaluate the resulting interface groups. The study used a novel AR cycling simulator that projected virtual objects onto real physical space; participants from three cities in different countries used the simulator to interact with AVs using each interface group. This chapter explains how comprehensive interface groups can be culturally inclusive and capable of adapting to diverse local norms.

Chapter 6: Scalability

This chapter describes two studies to answer RQ4. Study 9 used participatory design to understand how interfaces can display information from multiple AVs. HCI researchers and cyclists collaborated within the AR simulator to spawn, experience and refine their concepts iteratively in a scenario with three AVs. Study 10 evaluated the resulting interfaces; participants used the AR simulator to assess each interface in the three-AV scenario. This highlighted the strengths and weaknesses of each design feature that contributes to interface scalability. This chapter provides insights into how interfaces can be scalable to facilitate interaction with an increasing number of road users.

Chapter 7: Discussion

This chapter summarises the research within the thesis and reflects upon how it answers the research questions. The chapter also highlights the main thesis contributions, outlines its limitations and provides an overall discussion of the AV-cyclist interaction problem.

Chapter 2

Literature Review

This chapter presents a literature review that identifies the research gaps in the AV-cyclist interaction domain. This was a narrative literature review [53], with Google Scholar serving as the primary search tool. A wide range of keywords relevant to the research topic were used to guide the search process. These included AV-cyclist interaction, AV-HRU interaction, AV-VRU interaction, and cycling human-computer interaction (HCI). Each of these terms was also combined with relevant interface design challenges (e.g., scalability) to refine the search and identify domain-specific contributions. In addition to keyword searches, the review also included author-based queries, focusing on prominent researchers who have contributed more than two publications in this area. These included von Sawitzky et al., Matviienko et al., Dey et al. and Tran et al.. The majority of the literature identified was sourced from established digital libraries, including the ACM Digital Library[1], IEEE Xplore[2], and ScienceDirect[3]. No formal publication date restrictions were applied. However, the earliest cited work was published in 2014, and the most recent in 2025.

The review starts by providing an overview of the AV interaction problem, followed by an examination of existing AV-human road user (HRU) interaction solutions. The review then focuses on prior studies specifically addressing AV-cyclist interaction. This includes real-world observations of AV-cyclist encounters and previous research designing and testing AV-cyclist interfaces. Previous research on the four AV-cyclist interface design challenges highlighted in Chapter 1 is also explored in detail. Finally, cycling research within the HCI domain is revisited to inform the research methodologies adopted in this thesis.

2.1 The AV Interaction Problem

Latham and Nattrass [74] described the road as a *"shared social space"* in which drivers, cy-

[1]ACM Digital Library: `dl.acm.org` ; Accessed 27/05/2025
[2]IEEE Xplore: `ieeexplore.ieee.org` ; Accessed 27/05/2025
[3]ScienceDirect: `sciencedirect.com` ; Accessed 27/05/2025

clists and other road users exchange social cues, such as hand gestures or facial expressions, to resolve ambiguities and negotiate the right of way [24, 37, 82, 104]. Social interaction is key to how drivers communicate their intentions and awareness of other road users [82]. For example, Haddington and Rauniomaa [59] conducted a study in which vehicles were equipped with cameras to film the inside and outside of vehicles to capture how drivers interact on real roads. They found that drivers frequently engage in social interaction with road users throughout their journeys, including cyclists, pedestrians and other drivers. The researchers described drivers yielding the right of way as a *"social practice"*. Drivers often established eye contact to communicate their awareness and used hand gestures to communicate that they were yielding. These cues assured other road users of the driver's intentions, helping them decide whether they should proceed. The other road users often responded with hand gestures or other social cues to negotiate the right of way or thank drivers, and drivers often thanked them back. This expressive two-way communication was observed in a range of encounters. Therefore, social interaction is a key component of traffic, and removing it could have significant safety implications, as road users would have to make decisions based solely on a vehicle's motion, e.g. its braking behaviour [37, 49, 82].

Recent technological advancements are bringing AVs closer to mass adoption [117]. AVs are expected to remove human error and drive more reliably [5]. However, the disappearance of human drivers will also eliminate the social interactions many road users rely on [24, 37, 104]. Alawadhi et al. [3] conducted a literature review to capture the factors delaying the large-scale deployment of AVs. One primary factor was the AV's inability to clearly communicate with road users in the same way that human drivers do [59]. Similarly, Sandt and Owens [113] contributed a discussion guide for policymakers to deploy AVs. They also highlighted the issues hindering mass deployment. Similar to Alawadhi et al.'s [3] findings, the inability of AVs to negotiate with road users was highlighted as a critical issue. This indicates that AVs must compensate for the lost social cues of human drivers to aid successful adoption on a large scale.

Stanciu et al. [119] reviewed research on social interactions between drivers and vulnerable road users (VRUs), such as cyclists and pedestrians, to understand the interaction challenges of AVs. Much of the reviewed research was observations of human driver-VRU interaction. The researchers found that little work has considered cyclists; this thesis addresses the research gap. The researchers [119] reached a similar conclusion Haddington and Rauniomaa [59]: Drivers often engage in social interaction by establishing eye contact for awareness and using hand gestures and facial expressions to communicate intentions. The researchers emphasised that these interactions are critical to overcoming ambiguity and deciding on a manoeuvre safely, so AVs must compensate for the lost social cues. They also emphasised that many VRUs used hand gestures and facial expressions to negotiate with drivers. For example, cyclists used arm gestures to indicate their turning intentions. Therefore, AVs must recognise these cues and respond appropriately. This review further highlights that social interaction is an integral part of traffic; AVs cannot be widely adopted until they can effectively communicate with road users.

This was confirmed through a real-world study by Brown et al. [20]. The researchers analysed 16 hours of video footage featuring AV-HRU encounters to understand how AVs interact with road users. The researchers found that many issues and ambiguities occurred due to AVs being unable to communicate with road users beyond slowing down or accelerating. For example, one AV slowed down to yield to a pedestrian, but the pedestrian found this ambiguous and did not trust the AV's intentions. They waved to signal the AV to proceed, but the AV did not recognise the gesture. The AV then started accelerating and braking until proceeding 30 seconds later, showing hesitant yielding behaviours not commonly seen in traffic [72]. This contrasts Haddington and Rauniomaa's [59] study with human drivers, who used social cues to confirm their intentions so road users can proceed without confusion. Brown and Laurier [21] took a similar approach in another study and found more issues in videos of AV-HRU encounters. They found that many problems arose when AVs drove around human drivers. For example, AVs approaching an intersection showed much hesitation by proceeding and braking abruptly. This was ambiguous to human drivers ahead and frustrating for those behind. This shows that AVs must drive predictably and be clearly able to communicate to be accepted in traffic.

These findings motivated new research in Automotive User Interfaces (AutomotiveUI) to investigate how AVs can compensate for human drivers and communicate with other road users [14, 24, 37, 104]. Markkula et al. [82] conducted a literature review of AV-HRU interaction research. They found it to be interdisciplinary, with no unified definitions of the types of cues and messages AVs could exchange with road users. The researchers contributed a conceptual framework to provide common ground between disciplines and inform future research about the types of cues and messages AVs should compensate for. These were *explicit cues*, which allow direct communication between road users, including social cues or vehicle signals, such as directional indicators, and *implicit cues*, which are indirect and movement-based, such as a vehicle's acceleration or braking behaviours. The researchers also reiterated that AV intentions and awareness of road users are key messages to communicate.

Explicit and implicit cues go hand-in-hand during interaction [46, 90, 118]. For example, human drivers slow down and use hand gestures to communicate yielding intentions [59]; it would be confusing if either cue contradicted the other [75]. AVs can already use implicit cues, as these do not require them to display any signals directly [106]. However, Markkula et al. [82] still emphasised that AVs should adopt implicit cues that are familiar to road users to be effective and predictable. This would overcome many of the issues observed by Brown et al. [20], where AVs showed hesitant driving behaviours that differ from those of human drivers.

AVs currently have no way for explicit communication beyond traditional vehicle signals, such as directional indicators, and these may be insufficient as drivers commonly utilise other methods for delivering social cues [37, 82]. This prompted researchers to investigate new ways for AVs to communicate with road users explicitly [14]. This involved the design and evaluation of different types of interfaces and devices placed on the AV, environment or worn by road users [39, 67, 80]. This research is covered in the following section.

2.2 The Need for AV-HRU Interfaces

There has been some work investigating the design of AV interfaces. The most common form is external Human Machine Interfaces (eHMIs) [37]. These are displays placed on the vehicle's exterior to communicate with other road users [37]. For example, lights on the bumper [39] or speakers on the roof [45]. eHMIs were tested with different types of road users and were found to be an effective alternative to driver social cues [37]. For example, Rettenmaier et al. [105] conducted a study in which human drivers used a driving simulator to navigate a space-sharing conflict with an AV. An eHMI display was placed on the AV's bumper, and different icons, including emojis or arrows, were tested in addition to a no eHMI baseline. All eHMI designs outperformed the baseline condition, showing that eHMIs are an effective approach for AV-driver communication. Papakostopoulos et al. [96] conducted an outdoor study in which human drivers interacted with a simulated AV at a closed-off intersection; the "AV" was driven by an experimenter in the passenger seat using dual-control pedals. It was either instrumented with an eHMI, which was an LED light strip on the windscreen, or no eHMI. Participants were more confident and drove at higher speeds when an eHMI was used, but showed hesitation and constant braking when there was no eHMI. This further shows that AV interfaces reduced ambiguity in space-sharing conflicts, even in outdoor settings.

By contrast, very little eHMI research has considered cyclists. Dey et al. [37] conducted a literature review of eHMI concepts proposed in academia and the automotive industry. They found that pedestrians were the target road users for 91% of concepts. This was also evident in the design features adopted by these concepts, as they were designed to facilitate interaction at crossings; they mostly used visual cues and were only placed on the vehicle's front. Cyclists were the focus of only 23% of the concepts that Dey et al. [37] reviewed. They were also not the sole target road users for these designs, meaning the eHMIs were not specifically catered to their needs. Most of these concepts were not tested in practice, questioning their effectiveness in real-world scenarios. This highlights a clear need for further exploration of the requirements for AV-cyclist interfaces and evaluation studies to ensure that these interfaces are effective. This thesis addresses these gaps.

The most established eHMI concept is Dey et al.'s [39] *light-band*. This is an always-on cyan light bar placed on the vehicle's bumper. It uses animations to communicate an AV's yielding intentions; lights stroking toward each other means the AV is yielding, and apart means it is not yielding. Light-band has gone through multiple iterations and tests with pedestrians [44, 47] to find optimal colours and animations. Notably, Dey et al. [39] conducted an online survey in which participants were shown different colour and animation variations of light-band from the perspective of pedestrians. Participants preferred colour changes over animations, and red and green offered suitably contrasting colours. However, the researchers proposed adding a new colour (cyan) to traffic for AV messages to avoid any potential misinterpretation of colours that are already established in traffic. They did not find a suitable contrasting colour to communicate AV messages through colour changes. This prompted them to use animation to distinguish between yielding states.

Following this, Dey et al. [44] built a real prototype of light-band and conducted a study comparing it with having no eHMI. The study was conducted outdoors in a closed-off crossing. It adopted a Wizard of Oz approach, in which a human driver was hidden in a car seat costume to create the illusion that the vehicle was automated. Participants stood at the crossing and indicated their willingness to cross and confidence in the vehicle's intentions as it approached. Light-band outperformed the no eHMI condition, showing that the eHMI provided clear communication between AVs and pedestrians. Follow-up studies from various researchers explored light-band in various contexts, including assessing its accessibility for supporting disabled pedestrians [52] or incorporating other modalities, such as audio [45]. The range of studies conducted with light-band shows how far AV-pedestrian interaction research has reached. However, the research must also consider other types of road users, such as cyclists, to ensure that interfaces cover all needs.

eHMIs are a popular interface due to being placed on the AV itself, where road users are accustomed to seeking social cues [37, 49]. However, the design space for AV interfaces is large and not limited to the vehicle. Wearable devices or on-environment displays can also be used for interaction. There has been some work exploring this extended design space. For example, Mahadevan et al. [80] designed and evaluated groups of interfaces that simultaneously work to communicate AV intentions and awareness to pedestrians. The interface groups used the environment (new types of street lights), AV and the pedestrian's smartphone as placements. The resulting interfaces were multimodal, using auditory, haptic and visual cues to communicate with pedestrians at crossings. The designs featured different combinations of interfaces, such as the phone and an eHMI, the phone and an environment display and all three devices. Designs were evaluated using Wizard of Oz setups. Participants reported that the larger group of interfaces could be overwhelming, but reassuring of AV intentions. This lowered perceived risk compared to having a single interface. Interface groups helped pedestrians understand the AV's intentions, even if they missed a cue. This could enhance interface accessibility and be useful, e.g. for older pedestrians. Therefore, while eHMIs are effective solutions [37], there is still room for other interfaces to add further support. AV interfaces are not limited to compensating for human drivers; they could improve upon today's interactions. This thesis explores the use of interface groups with cyclists.

In another study, Asha et al. [8] designed and grouped interfaces with different placements for wheelchair-using pedestrians. Interfaces were placed on the AV, environment and wheelchair.

They were implemented in virtual reality (VR) and evaluated with real wheelchair users wearing VR headsets. Results showed interfaces reflecting the eHMI state on the wheelchair helped participants make faster crossing decisions, especially if the AV was hard to see, e.g. due to other pedestrians standing in front of the wheelchair. At the same time, having an eHMI present increased trust, as the information was presented on the AV itself, so information on the wheelchair was straightforward to validate. Participants also suggested adding input to the wheelchair, such as a button communicating the pedestrian's willingness to cross the road. This study showed the many features interfaces could adopt by being interconnected, including accommodating two-way communication. These findings may generalise to cyclists, who also bring a large range of potential placements and use cases for interfaces. The topic of interconnected interfaces for cyclists is explored in this thesis.

Overall, this section showed that AV-HRU interfaces are critical for resolving space-sharing conflicts and successfully deploying AVs on the road [39]. eHMIs are useful for compensating the lost social cues of human drivers using a familiar placement: the vehicle itself [37]. However, interfaces have the potential to improve upon today's interactions and use new placements for added support [80]. Nevertheless, most AV-HRU interfaces were designed and tested on pedestrians [37]. This thesis focuses on cyclists, and the following section shows the many issues that arise from AV-cyclist interaction.

2.3 The AV-Cyclist Interaction Problem

The previous sections showed that the lack of explicit communication between AVs and HRUs causes many issues and ambiguities when resolving space-sharing conflicts. Despite the many AV interface designs and concepts, little has been addressed to facilitate AV-cyclist interaction. This section shows the real-world problems that arise during AV-cyclist encounters to motivate the design and evaluation of interfaces addressing cyclists' needs.

Pelikan [97] analysed video recordings of automated shuttle-cyclist encounters in real traffic in Sweden. The shuttles were programmed to drive cautiously and always yield the right of way, even when they should not have yielded. They had no way to communicate with HRUs explicitly, so their implicit cues were exaggerated. This led to many issues and hard stops. For instance, the shuttles would emergency brake even in situations that did not require a complete stop, such as when a cyclist merged lanes with them [67]. This abrupt braking disrupted traffic flow and caused discomfort for shuttle passengers. Cyclists behind the shuttles were forced to swerve into oncoming lanes, significantly compromising safety. Such issues could hinder the large-scale, long-term adoption of AVs. This study aligns with prior work showing that AVs must adopt similar implicit cues to human drivers to be accepted in traffic [20]. Even then, this would be insufficient. Negotiation is a crucial part of traffic, and many of the issues observed in this study could have been avoided if the shuttles were equipped with interfaces to negotiate with cyclists [82]. For example, the shuttles would not need to emergency brake if they informed cyclists that they would not yield.

These issues were not unique to the shuttles observed by Pelikan [97]. Pokorny et al. [101] analysed videos of automated shuttle-cyclist encounters at intersections and crossings in Norway and found similar concerns. Shuttles frequently used emergency brakes to yield, creating discomfort for AV passengers and confusion for nearby cyclists. Cyclists were unaccustomed to vehicles stopping abruptly in space-sharing conflicts and struggled to interpret the shuttles' intentions. This led to significant speed fluctuations as cyclists attempted to negotiate the right of way implicitly. The findings further highlight the need for clear AV-cyclist communication to prevent unnecessary hesitation and disruptions.

Research also showed that these issues are not due to the novelty of riding near the shuttles. Thellman et al. [120] provided a longitudinal perspective on the problem. They surveyed two groups of commuter cyclists who regularly shared the road with automated shuttles to assess the effects of AV-cyclist interaction. The first group had interacted with AVs for an average of two years, while the second group had done so for an average of seven months. Interestingly, the group with longer exposure expressed more negative attitudes instead of growing accustomed to the shuttles over time. They were 11% more likely to describe the shuttles' presence as "bad", citing their inability to resolve space-sharing conflicts effectively. This finding is crucial as it suggests that AV-cyclist interaction becomes less pleasant over time when intentions are not clearly communicated. Cyclists did not become accustomed to relying solely on AV implicit cues, and AV-cyclist interfaces are essential for clear communication, even in the long term.

Therefore, real-world evidence suggests that implicit cues are inadequate for AV-cyclist interaction [101, 121]. Interfaces offer a promising solution to facilitate explicit communication between AVs and cyclists [120]. These findings motivated the thesis to investigate the design of interfaces to overcome ambiguities in future traffic. The following section shows that existing solutions for other road users cannot be applied to cyclists, as cyclists have distinct requirements.

2.4 The Unique Requirements of Cyclists

The AV-cyclist interaction problem requires the development and evaluation of interfaces that support the exchange of clear communication between the two road users [120]. The previous sections showed that most interfaces were developed and tested for pedestrians [37]. However, this section shows that cyclists have distinct needs, and AV-pedestrian interfaces may not generalise effectively. Holländer et al. [66] conducted a literature review of previous AV-HRU interaction research to identify the specific road users investigated by prior work. They found that the majority of studies grouped pedestrians, cyclists, e-scooter users, and other unprotected road users under the broad category of VRUs without specifying the intended subset. Upon further analysis, they identified 35 papers on AV-pedestrian interaction published in HCI venues between 2000 and 2020, but only seven focused on AV-cyclist interaction. This suggests that researchers assumed that solutions for pedestrians would generalise between VRUs.

However, Holländer et al. [66] reiterated that this assumption may not be accurate. Consequently, they developed a taxonomy visualising the differences between VRUs to motivate future work to explicitly define its target users and ensure solutions match their specific needs. A comparison between pedestrians and cyclists based on the taxonomy illustrates key distinctions: Cyclists travel at higher speeds, frequently share the road with AVs, and encounter them in various traffic scenarios. In contrast, pedestrians primarily have slower-paced interactions with AVs at crossings. Cyclists' distinct requirements not only differentiate them from pedestrians but also from other VRUs. For example, the taxonomy also shows that e-scooter riders and motorcyclists use motorised transport modes, whereas cyclists use physical effort to navigate traffic; this might result in some distinctions in how the road users process information and how information should be presented. The taxonomy illustrates that the issue of AV-cyclist interaction is complex. Interfaces must be designed for faster-paced interactions beyond a single traffic scenario while accounting for the physical effort exhibited by cyclists, so interfaces should impose a minimal workload.

Previous research also illustrated that pedestrians and cyclists differ in more subtle characteristics, which can influence interface design. For example, Trefzger et al. [126] conducted an eye-tracking study comparing the gaze behaviours of cyclists and pedestrians. Participants were asked to walk and cycle along a predefined route while wearing eye-tracking glasses. Pedestrians exhibited more distributed gaze behaviour, frequently conducting shoulder checks and looking at nearby road users and advertisements. In contrast, cyclists focused more on the path ahead, likely due to their higher speed and the need for sustained attention to maintain stability [50]. This shows that the differences between pedestrians and cyclists are not limited to their speed or scenarios in which they will encounter AVs, but also their nuanced behaviours. AV interfaces must not disrupt the reflexive behaviours of HRUs [49], and this study provided valuable insights into designing interfaces accordingly.

To further explore these subtle differences, the researchers conducted a follow-up study comparing the gaze behaviours of cyclists and e-scooter riders [127]. While both VRU types moved at similar speeds, their gaze patterns differed significantly. E-scooter riders spent more time looking at the path ahead, while cyclists fixated more on obstacles such as parked cars. These findings further illustrate the distinct characteristics of cyclists. Researchers should take care when categorising their target road users [66]; even ones that use similar transport modes (cyclists and e-scooter riders) showed key differences in how they process information.

Aside from their behaviours, road users also have distinct expectations and perceptions of AVs. Thellman et al. [121] conducted an online survey with 536 participants to compare how cyclists and pedestrians interpret AV intentions. Participants watched videos of AV-VRU space-sharing conflicts from both pedestrian and cyclist perspectives and were asked to rank their confidence in whether the AV would stop to yield the right of way. Pedestrians were more likely to expect AVs to yield, whereas cyclists were more cautious and less confident in AV-yielding behaviours. These differences influence AV interface design. For example, cyclists may require a stronger emphasis on AV intentions, as they are likely more accustomed to non-yielding behaviours and may experience greater uncertainty in AV interactions.

These studies showed that cyclists are a unique type of road user: They use physical effort to travel at higher speeds and encounter vehicles across a range of traffic scenarios [66]. Therefore, solutions for AV interaction with other road users may not generalise to cyclists [121], and it is critical to investigate how interfaces may be designed to accommodate cyclists' needs. The following section shows some interface concepts developed for AV-cyclist interaction.

2.5 AV-Cyclist Interface Studies

The previous section showed that cyclists have distinct requirements from other road users, and interfaces must be designed to address these requirements. This motivated some work to explore the design of AV-cyclist interfaces. One of the earlier studies indicating the significance of AV-cyclist interfaces was Hagenzieker et al.'s [60] photograph study. Cyclists were shown images of vehicle-cyclist encounters and asked to rank their confidence in the vehicle's intentions and awareness of them. The vehicles were either human-driven, automated with no identifying marks, or AVs labelled automated with a sticker on the side or a panel on the roof. In photographs where cyclists had the right of way, participants were more confident that an AV had noticed them than a human driver. However, when they did not have the right of way, they were more confident that a human driver had noticed them. This further suggests a need for explicit communication of AV awareness to compensate for the lack of eye contact for cyclists to be confident in all cases. In particular, participants were more confident in an AV's intentions when it was labelled automated than when it had no label. This indicates that cyclists may be receptive to AV-cyclist interfaces.

Vlakveld et al. [136] conducted an online survey with 1009 participants to investigate cyclists' yielding intentions in space-sharing conflicts with AVs at intersections. Participants were shown videos from the cyclist's perspective. Cyclists had the right of way in all videos, and the vehicle was either human-driven, an AV, or an AV with an eHMI on its roof, using icons to communicate its yielding intentions. Participants were more likely to yield and give up their right of way to AVs with no eHMI than to human drivers. This suggests that they were unsure of the AV's intentions but were confident that drivers would give them the right of way. However, they were less likely to yield to AVs with eHMIs than to human drivers. This suggests that the interface successfully clarified ambiguities in the space-sharing conflict even more than human drivers did. This research provided promising insights into the potential of AV-cyclist interfaces to facilitate interaction.

However, Vlakveld et al. [136] only investigated eHMIs, so it was critical to explore other types of interfaces. Hou et al. [67] investigated different interface types to facilitate interaction in a scenario where cyclists had to merge lanes with an AV approaching from behind. The researchers took a two-study approach. First, they conducted design sessions where participants sketched interfaces to facilitate interaction in the scenario. They contributed various multimodal concepts, incorporating visual, auditory, and haptic modalities. The designs also varied in placement, using wearable devices, bike-mounted displays, and eHMIs to deliver messages. This highlights the large design space available for AV-cyclist interfaces, so it is critical to understand the optimal form of AV-cyclist interface, similar to eHMIs for pedestrians. The researchers then synthesised new interfaces based on these sketches. These new designs all communicated AV-yielding intentions. They took various forms, including an eHMI using road projections, another using light-up AV windows, an AR Head-Up Display (HUD) worn by the cyclist, helmet-mounted audio, and handlebar vibrations. This was the first step toward understanding the optimal form of the AV-cyclist interface.

In the second study, Hou et al. [67] implemented the interfaces in a virtual reality (VR) cycling simulator. Participants wore a VR headset and rode a stationary bike to navigate the lane merging scenario using each interface and a no-interface baseline condition. The baseline condition consistently underperformed. This further shows that AV-cyclist interfaces are critical to resolving space-sharing conflicts. Participants favoured AR HUDs and road projections from the AV because these provided clear visual signals without requiring them to shoulder-check the AV behind them or divert their attention from the road. The non-visual displays still outperformed the light-up windows eHMI as it was not in the cyclist's view, and participants had to shoulder check to understand the AV's intentions. This shows that optimal solutions for pedestrians are not always suitable for cyclists. Ultimately, this research confirmed that AV-cyclist interfaces are a feasible solution. However, it had a limited scope: The interfaces were only tested in a lane merging scenario with a single AV. It is unclear how this study's findings generalise throughout a cyclist's whole journey. This motivated the studies in the thesis to conduct a comprehensive exploration of AV-cyclist interfaces to prepare them for real-world use.

Hou et al.'s [67] findings demonstrated that AR displays are highly usable for cyclists. They can present messages tailored to the cyclist and augment their surroundings, reducing the need to divert attention from the road. This motivated further research into AR-based AV-cyclist interfaces. For example, Von Sawitzky et al. [140] designed three AR displays to facilitate interaction at an intersection. The displays included an *x-ray* helping cyclists see AVs through obstacles and buildings, AR road projections of a bicycle lane signifying whether cyclists are safe to proceed, and a warning traffic sign appearing as an AR HUD when an AV approaches. These were tested in a VR cycling simulator. Road projections performed best as they allowed cyclists to process information without taking their attention away from the road. This study reinforces that AV-cyclist interfaces must not obstruct or disrupt natural cycling behaviours to be effective, even when using AR. This suggests that further research should explore cycling behaviours during interaction before designing solutions, an approach taken in this thesis.

Matviienko et al. [88] further explored Von Sawitzky et al.'s [140] x-ray concept for interaction at intersections. They compared it with an AR timer (showing the available time for cyclists to proceed) and a baseline condition with no interface. The researchers used a novel AR simulator to test the interfaces. This was deployed on a HoloLens headset that participants wore. The simulator projected an urban environment with roads and AVs onto real physical space. Participants cycled in the physical space to experience the interfaces. The baseline consistently underperformed. It produced the highest collision rates, and cyclists were least confident in AV intentions. This reinforces that interfaces are critical for safe and unambiguous AV-cyclist interaction, even at intersections where the AV is in view. Participants felt safer when the AR timer was used. However, the x-ray display allowed them to proceed through smaller gaps between themselves and the AV while maintaining a low accident rate. This shows that it is not always sufficient to measure cyclist perceptions in user studies; cycling behaviour data is crucial to gaining a holistic view of an interface's performance. This approach was adopted in user studies in this thesis.

Even though AR displays were found to be useful for cyclists, these devices may not be accessible to all riders [16]. Smartphones present a more accessible alternative in the immediate future. To explore this, Lindner et al. [77] developed a smartphone application mounted on the bicycle handlebar to facilitate negotiation between cyclists and AVs. The app featured a map interface for navigation, which was overlaid with AV intentions when an AV-cyclist encounter occurred. The researchers conducted a cycling simulator study to evaluate the system, where participants rode a stationary bike connected to a desktop screen. They measured cyclist speed changes when using the app. The results showed that cyclists maintained their speed when the AV signalled it would yield and decreased speed when the AV signalled it would not yield. This suggests that clear messages on AV intentions positively influenced cycling behaviour, reducing unnecessary braking and hesitation. This study highlights that AV-cyclist interfaces have a large design space. While emerging technologies like AR displays offer new interaction possibilities, existing devices like smartphones can also provide feasible solutions. This thesis explores a combination of existing and emerging AV-cyclist interaction devices.

These studies showed that there has been some work investigating the design of AV-cyclist interfaces. However, they had a limited scope, such as only exploring AR displays [88] or facilitating interaction during lane merging [67]. It is critical to understand the optimal form of AV-cyclist interface and how this can be used throughout a cyclist's journey. The following section shows a clear need for a more comprehensive investigation of AV-cyclist interfaces to address these gaps.

2.6 AV-Cyclist Interface Design Challenges

Even though there has been some work designing and evaluating AV-cyclist interfaces [67, 88, 140], these studies had a limited scope. For example, exploring AR displays to facilitate one-to-one AV-cyclist interaction at an intersection [88]. There is no comprehensive investigation of AV-cyclist interfaces to prepare them for real-world use [14]. AV-cyclist interfaces must be available and acceptable to cyclists, who are a diverse user group with distinct requirements from other road users [66]. These interfaces must also operate successfully throughout a cyclist's journey, which may feature numerous traffic scenarios, not just an intersection or a lane merging scenario [12, 66]. Moreover, factors such as cultural differences [108] or the number of cyclists and AVs involved in the space-sharing conflict [123] could have significant implications on the design of these interfaces [37]. Therefore, this section details the prior work to overcome the key design challenges for AV-cyclist interaction and justifies the need for studies in this thesis to overcome these challenges and contribute design guidelines that are essential for the successful global adoption of AV-cyclist interfaces.

2.6.1 Acceptability

The acceptability design challenge ensures that AV-cyclist interfaces align with cyclists' needs and requirements [16]. This would encourage the success and widespread adoption of interfaces [37]. Acceptability requires conducting foundational studies that investigate cyclist perceptions of AVs and interfaces [60]. It also requires an extensive understanding of cycling behaviours on real roads to gain a holistic perspective of how interfaces can facilitate interaction without obstructing cyclists' natural behaviours or imposing a steep learning curve [49, 76].

AV-pedestrian research has successfully informed the design of eHMIs due to a strong foundation of studies investigating pedestrian behaviours in real crossing scenarios. This was validated by a literature review from Rasouli and Tsotsos [104]. They found that human driver-pedestrian interaction studies contributed to more effective interface solutions, allowing AVs to replicate familiar interactions and ensure minimal learning effort for pedestrians [24]. Foundational AV-pedestrian interaction studies captured the cues interfaces must recognise from pedestrians [133], the messages AVs should convey in response [143] and ideal interface placements [49]. A notable example is Dey and Terken's [46] observations of driver-pedestrian interactions at crossings in the Netherlands. The study found that drivers commonly use a combination of social and implicit cues to signal pedestrians to cross, such as hand gestures and decelerating. This demonstrated that AVs should explicitly communicate their yielding intentions while ensuring their braking behaviours match their explicit signals to be acceptable to pedestrians.

Dey et al. [49] followed their observations with an outdoor eye-tracking study to explore pedestrian gaze behaviour at crossings. Participants wore eye-tracking glasses to determine where they focused when a vehicle approached a real crossing. Results showed that pedestrian gaze was distance-dependent; participants fixated more on the windscreen as the vehicle got closer, as they expected eye contact and social interaction. These findings suggest that acceptable interfaces should also match the natural behaviours of road users. This supported the acceptability of eHMIs [37]. The study illustrates the subtle details captured by AV-pedestrian interaction researchers and the extensive requirements that enabled acceptable eHMI design. This knowledge currently does not exist for AV-cyclist interfaces, but it is critical to ensure interface acceptability. Although some real-world observations and eye-tracking studies have examined cyclist behaviours around human-driven vehicles [54], these were not directly designed to inform AV interface design. Consequently, they provide insufficient data for AV-cyclist interfaces. For example, Pokorny and Pitera [99] observed truck driver-cyclist interactions in Norway to inform safe cycling infrastructure. The study only recorded cyclists' social cues, not the cues from drivers. This limits its applicability to AVs. It showed the cues AVs should recognise, but not the messages they should communicate in response.

The most notable work supporting AV-cyclist interface acceptability is Berge et al.'s [16] interviews with cyclists. The researchers asked cyclists about the messages AVs should communicate and the feasibility of wearable devices for AV-cyclist interaction. Cyclists reported that understanding AV intentions is critical, reinforcing the need for explicit AV-cyclist interaction. However, they found wearable and bike-mounted interfaces unacceptable, as these would significantly alter their current cycling setup and place more responsibility on cyclists. While these findings are valuable, they are based on cyclist perceptions. It is essential to complement them with data from real-world observations, similar to the approach taken in AV-pedestrian research [49]. This would allow interfaces to adhere to more subtle behaviours that may be difficult to capture through perception [69, 81]. In a follow-up contribution, Berge et al. [15] reanalysed their interview data to design acceptable AV-cyclist interfaces. The researchers designed an eHMI that builds on Dey et al.'s [39] *light-band* design but caters to cyclists' needs. This was a cyan LED light strip around the vehicle body. The relevant eHMI side changes colours when a cyclist is detected to communicate awareness. The entire eHMI changes to green if an AV intends to yield to the cyclist. This is a clear example of how eHMIs differ from pedestrian interfaces when taking cyclist requirements into account; it shows that it is essential to capture cyclist requirements to provide a starting point for informing the design of acceptable interfaces that are inclusive of all road users, beyond pedestrians. The researchers explained that this design may be more acceptable to cyclists as it is viewable from all vehicle sides and communicates AV awareness and intentions visually without requiring them to carry additional devices. However, this remains untested. The researchers outlined a plan to test the eHMI and confirm interface acceptability.

Berge et al. [13] also conducted an eye-tracking study to understand cyclists' perception of AVs and investigate how eHMIs may be acceptable for cyclists. They used a Wizard of Oz approach, in which a human driver was hidden using a car seat costume to create the illusion of an AV [109]. Participants cycled on a closed-off straight road, and the AV approached from the opposite direction. They found similar findings to Dey et al.'s [39] with pedestrians; participants expected some social interaction because they focused on the windscreen as the AV moved closer. Post-study interviews also confirmed this, as participants emphasised that AVs should communicate their intentions to avoid ambiguity. While these findings suggest that eHMIs offer a familiar placement for cyclists, it is critical to note that the results do not directly address the acceptability of eHMIs. Cyclists may be anywhere around a vehicle, and this study only investigated the AV approaching from ahead. Even if eHMIs are an acceptable approach, it remains unknown where these interfaces should be placed on the vehicle to account for cyclists' needs. Therefore, it is critical to collect such data from vehicle-cyclist encounters on real roads to fully correlate interface design to cyclists' reflexive behaviours [57].

In another study, Berge et al. [14] attempted to identify the requirements for acceptable AV-cyclist interfaces by reviewing previous HCI contributions designed to support cyclists. This review involved classifying 92 cycling support systems into a taxonomy that captured key aspects such as interface placement and the types of messages communicated. While these interfaces were not necessarily designed for AV-cyclist interaction, analysing their role in supporting cyclists could provide valuable insights for designing acceptable AV-cyclist interfaces that build upon similar features. However, the review did not establish a clear consensus on the optimal form of cycling support systems, as interfaces were distributed almost equally across wearable, bicycle-mounted, and on-vehicle devices. This underscores the need for a more comprehensive investigation into AV-cyclist interface requirements to ensure acceptability and determine the most effective placement and modality for communication.

This section showed that it is crucial to form a structured research foundation for AV-cyclist interaction, similar to the one developed for pedestrian research [104]. This would contribute to the design of acceptable interfaces that adhere to cyclists' needs and requirements without obstructing their setup or behaviour [16]. Real-world studies with cyclists and human drivers are a good source for gathering requirements, as these could produce results that generalise to AV interaction while maintaining familiarity and a minimal learning curve for cyclists [46]. This led to RQ1: *"How can insights from current driver-cyclist interaction inform the design of acceptable AV-cyclist interfaces?"*. This is answered in Chapter 3 of the thesis.

2.6.2 Versatility

One particular factor differentiating cyclists from most VRUs is that they often share the road with motorised vehicles [54]. This means they are more likely to be in space-sharing conflicts with AVs in many traffic scenarios [66]. Scenarios may have different levels of traffic control [67], ranging from traffic lights in controlled intersections or crossings to no traffic control in scenarios such as lane merging. They may also feature different AV positions relative to the cyclist. For example, an AV may approach from the cyclist's left at an intersection but behind during lane merging [88, 140].

Ackermann et al. [1] conducted a naturalistic cycling study to gain an overview of the scenarios in which AVs will need to interact with cyclists. Participants mounted cameras on their bikes and recorded their commutes. The authors confirmed that cyclists navigate various scenarios and sorted them into three categories depending on the level of traffic control they feature. The authors captured some driver-cyclist interactions in these scenarios but only reported the implicit cues, not social cues. There were still notable differences in interactions between scenarios. For example, cyclists were more likely to accelerate and overtake drivers in scenarios with no traffic control, such as a vehicle leaving a parking space. In contrast, drivers were more likely to accelerate in scenarios with some traffic control, such as intersections. This shows that the interaction behaviours of road users differ between scenarios, and AV-cyclist interfaces must be versatile to accommodate these differences to be usable throughout a cyclist's journey.

However, it is unclear how AV-cyclist interaction can be facilitated across these varying scenarios. Existing research has only designed and tested interfaces in specific traffic scenarios [14]. For example, Von Sawitzky et al. [140] and Matviienko et al. [88] only explored intersections. Other works investigated scenarios that differentiate cyclists from pedestrians. For example, Hou et al. [67] explored AV-cyclist interfaces to support cyclists merging lanes with an AV approaching from behind. Similarly, Fritz et al. [55] described a work plan for an AV-cyclist interaction project which only focuses on more dynamic scenarios with both the cyclist and AV moving, such as lane merging.

These studies offered a first step toward understanding AV-cyclist interfaces [14], and the choice of scenario ensured that the research was distinct from crossing-based pedestrian studies [37]. However, they are insufficient for preparing interfaces for real-world use [66]. AV-cyclist interfaces must be versatile and facilitate consistent interaction throughout a cyclist's journey [14, 37, 66]. Nevertheless, previous works have shown that versatility is a key AV-cyclist interaction design challenge. For example, Hagenzieker et al.'s [60] photograph study, in which participants judged images of vehicle-cyclist encounters, featured vehicles approaching from different locations around the cyclist. Participants judged the photographs differently depending on the vehicle's location. They were more confident that a human driver had detected them when the vehicle approached from their left or right but more confident in the AV when it approached directly opposite them. This shows that cyclist perceptions are not consistent between scenarios. AV-cyclist interfaces must be designed to accommodate these differences; AVs currently underperform when approaching from the cyclists' side, but they must show consistent performance across scenarios to be effective.

While the naturalistic study from Ackermann et al. [1] did show the categories of scenarios cyclists navigate, the results do not feature a list of scenarios within each category. This is critical to inform situations to test AV-cyclist interface versatility. Therefore, Berge et al. [12] conducted a three-step study to deduce potential AV-cyclist interaction scenarios. First, a systematic review of AV-cyclist interaction research to deduce potential scenarios in which cyclists may encounter AVs. They followed this with interviews with traffic experts to expand the scope of these highlighted scenarios. Finally, they visualised these scenarios in an online survey and asked cyclists to rank the likelihood of a collision. This not only identified some scenarios but indicated the perceived risk for cyclists [12]. A total of 20 scenarios were identified, including lane merging or overtaking a vehicle.

These were classified into four groups based on the vehicle's position relative to the cyclist. Cyclists perceived right-hook turns and dooring as the most dangerous scenarios. However, it is important to consider that these two scenarios are also perceived as dangerous with human drivers [7, 137], and there is currently no effective way to overcome them. Therefore, these findings point to key issues but not necessarily areas where AVs must compensate for human drivers [37]. Berge et al.'s [12] three-study exploration offered a starting point for acknowledging the importance of versatility. However, the findings were based on expert and cyclist perceptions; another approach could be identifying scenarios through real-world studies [78]. Ackermann et al. [1] showed that this approach helps identify more spontaneous or unexpected encounters, such as interaction during parking manoeuvres.

Together, these studies show that AV-cyclist interaction is not limited to one type of traffic scenario, and it is critical to compensate for human drivers in all traffic scenarios to ensure cyclists can safely share the road with AVs and complete their journeys. This research gap informed RQ2: *"What features enable AV-cyclist interfaces to be versatile, supporting interaction across diverse traffic scenarios?"*. This is answered in Chapter 4 of the thesis.

2.6.3 Cultural Inclusivity

An important observation about these studies [14] is how AV-HRU interfaces have only been designed and tested in individual, mostly Western, countries and cities [14, 37]. However, they must be culturally inclusive for widespread adoption [108]. This issue was highlighted in Dey et al.'s [37] review of AV interfaces. The researchers highlighted cross-cultural research as a key research gap in AV-HRU interaction, and this could significantly hinder the global adoption and acceptability of AV-cyclist interfaces.

Traffic culture plays a crucial role in how cyclists perceive motorised vehicles and interact with drivers [119], directly impacting the design of AV-cyclist interfaces [130]. Rodríguez Palmeiro et al. [108] replicated Hagenzieker et al.'s [60] photograph experiment to gain a cross-cultural perspective on AV-cyclist interaction. Participants from 15 Western countries evaluated photographs of AV-cyclist encounters. Cyclists from all countries were more confident when AVs displayed a visible sign indicating they were self-driving. This suggests that AV-cyclist interfaces could enhance trust in AVs across these regions. However, cyclists' perceptions varied depending on their local level of cyclist segregation from motorised traffic. Cyclists in countries with sophisticated cycling infrastructure, such as the Netherlands and Denmark, exhibited greater confidence in AV awareness and expected AVs to prioritise them in traffic. This suggests that AV-cyclist interfaces may need to focus more on communicating AV intentions rather than simply signalling awareness in such countries. In contrast, cyclists from regions with less developed cycling infrastructure, such as North America, expressed lower confidence in AVs and were concerned about their reliability on shared roads. In these settings, AV-cyclist interfaces may need to convey both AV intentions and awareness more explicitly to reassure cyclists. These findings indicate that AV-cyclist interfaces should adapt to regional differences in cyclist expectations and trust levels to ensure safety and usability. However, the findings also illustrate that interface designers must clearly understand cultural differences to develop fitting solutions.

Similarly, Chataway et al. [26] conducted a survey comparing self-reported cycling behaviour in Brisbane and Copenhagen, two cities with different levels of cyclist segregation from vehicles. Cyclists in Brisbane, where cycle lanes are only partially segregated, reported greater fear of traffic and felt less prioritised on the road. In contrast, cyclists in Copenhagen, where lanes are highly segregated, were more likely to cycle while distracted, suggesting greater trust in vehicle awareness. These findings highlight how differences in infrastructure shape cyclist expectations and behaviours. Therefore, interfaces should be tested across regions with varying levels of cyclist segregation from motorised traffic to ensure they can consistently facilitate interaction across these settings. Even countries with similar cycling infrastructure can exhibit distinct cyclist behaviours.

Haustein et al. [62] conducted a survey comparing cycling behaviour in Stockholm and Copenhagen, two cities with highly segregated cycling lanes. Despite these similarities, cyclists in Copenhagen perceived themselves as having a higher priority in traffic and cycled more frequently than those in Stockholm. Therefore, local norms can influence AV-cyclist interface design, even if the traffic infrastructure is similar. Additionally, a large-scale survey by Useche et al. [130] collected data from cyclists in 19 countries. The researchers found notable cross-cultural differences in cycling behaviours. For example, cyclists from African and Asian countries were more likely to engage in risky manoeuvres. These findings underscore the importance of cross-cultural AV-cyclist studies to ensure global AV deployment. This approach will ensure that AV-cyclist interfaces are designed to accommodate varied expectations, behaviours, and cultural norms. Designing and testing an interface in a single cultural setting is insufficient as it does not generalise to other regions.

Most cross-cultural studies in the AV interface domain are online surveys rather than user studies [108]. This prohibits participants from directly interacting with AVs and using the interfaces, so researchers must rely on perceptions, as it is challenging to measure participant behaviours in this context. For example, Colley et al. [29] conducted an online survey testing a variation of the light-band eHMI [39] between Germany and the USA. Participants downloaded software showing a pedestrian crossing and the AV approaching; they clicked on the other end of the street to indicate their willingness to cross and answered questions on the workload this imposed. The eHMI was effective in both countries, further emphasising that AV interfaces are valuable across cultures. However, there were still some cultural differences. For example, USA participants reported lower mental workloads for processing the eHMI signals than those in Germany. This suggests that the eHMI may need to adapt to local norms and cater to these differences. This study shows that it is critical to understand cultural differences in how end users perceive interfaces to support the global deployment of AVs. However, there was no indication of pedestrian behaviours toward the eHMI, such as their crossing speeds or gaze patterns. Understanding the impact of interfaces on user behaviours could reveal more cultural differences. This is critical to gaining a holistic view of the interface's performance, especially given the impact traffic infrastructure may have on these behaviours. Moreover, cross-cultural studies may be more necessary for cyclists because there is greater variation in cycling infrastructure between cities than pedestrian crossings [128], which would maximise cultural differences [130].

These studies showed that cyclists perceive and interact with vehicles differently depending on their cultural norms [62] and local traffic infrastructure [26]. AV-cyclist interfaces must account for cultural differences and adapt to support the global adoption of AVs [108]. This informed RQ3: *"What are the cultural differences in cyclist use and perceptions of AV-cyclist interfaces?"*. This is answered in Chapter 5 of the thesis.

2.6.4 Scalability

The scalability design challenge is critical for ensuring that AV-cyclist interfaces facilitate interaction as the number of AVs and cyclists increases. So far, AV-cyclist interaction research has focused solely on one-to-one interaction. However, scaling these interfaces for many-to-many interaction is essential for real-world deployment. While scalability has been explored in AV-pedestrian interaction, the setup for cyclists is more complex due to the versatility challenge and the diverse scenarios they navigate [12]. Pedestrians will typically only encounter multiple AVs at crossings, where both vehicles are clearly visible and often equipped with eHMIs [43, 66]. This makes it easier to associate AV signals with specific vehicles. In contrast, cyclists can navigate multiple traffic scenarios simultaneously, each with different traffic control features and vehicle positions, leading to contrasting AV-yielding intentions [12, 66]. For example, a cyclist approaching an intersection may encounter an obstacle in the cycle lane, requiring them to merge into another lane with an AV behind them. In this case, the AV at the intersection may yield while the one behind the cyclist may not; these contrasting signals may be overwhelming for cyclists to process while moving, especially when the AVs are in different locations.

Scalability is a two-sided problem. AVs must communicate with multiple cyclists, and cyclists must interpret messages from multiple AVs [37]. Both cases were explored with pedestrians [47, 123]. Dey et al. [47] evaluated different eHMIs for multi-pedestrian scenarios, including the light-band, road projections and windscreen displays. Participants used a VR simulator, which projected a virtual crossing. The crossing featured a virtual pedestrian in addition to the human participant, and participants had to indicate their confidence that an AV's message was for them once an AV approached. Participants were most confident when road projections were used, as they were directly opposite them and farther away from the virtual pedestrian. However, they were not confident when the eHMI was on the AV's windscreen or bumper. This highlights a key issue: Road users must be sure that an AV's message is intended for them to resolve space-sharing conflicts effectively without ambiguity, and eHMIs have limitations here.

In a follow-up study, Tran et al. [125] used a multi-user VR simulator to project a virtual crossing with two human participants. Three displays were tested: road projections, LED road markings on the crossing's pavement, and AR displays worn by each pedestrian. Participants were most confident when wearable AR displays were used. This aligns with Dey et al.'s [47] finding that pedestrians may need messages that are personal or in close proximity so that there is no ambiguity about who the message is directed toward. This may generalise to cyclists, especially as previous work on AV-cyclist interfaces showed that AR displays performed well in facilitating interaction at intersections and lane merging manoeuvres [67]. However, the primary issue lies in the acceptability of these interfaces, as Berge et al. [16] showed that cyclists do not perceive wearable devices as the ideal solution. This thesis investigates the issue of using wearable devices to remove ambiguity in multi-cyclist scenarios while maintaining acceptability.

Regarding multi-AV challenges, Tran et al. [123] conducted a literature review on scalable AV-pedestrian interaction. They highlighted key issues that scalable interfaces must overcome. For example, there were some challenges with using non-visual modalities, particularly for eHMIs. Auditory cues were challenging to associate with a particular AV when another was nearby, and it was challenging to overcome ambiguity about which road user this audio was directed toward when there were multiple HRUs around the AV. The most prominent challenge was information overload in multi-AV scenarios. Road users must process and correctly associate signals from multiple AVs, and this may be overwhelming. As a result, Tran et al. [123] recommended centralising AV signals into a single display in the environment or worn by pedestrians. Pedestrian wearables, such as AR glasses, seemed particularly promising as these already overcome ambiguity in multi-pedestrian scenarios and could also use non-visual signals without creating confusion. This centralised approach may generalise to cyclists, especially when considering that some AVs may not be in the cyclist's view; for example, they may be approaching from behind. A central display could lower the workload and reduce the need to constantly track and associate AV signals.

Tran et al. [124] followed their review by designing AR displays connected to multiple AVs to centralise their eHMIs. For instance, when two AVs approached a pedestrian crossing, the glasses projected green crossing lines if both AVs would yield and red if at least one would not. The researchers conducted a VR simulator study and compared the AR displays to only eHMIs. Participants felt more secure and confident when AR displays were used, as they could receive AV signals from a central location. The effort to associate different AV signals was significantly reduced. However, participants expressed concerns about cases where they do not have access to AR glasses, so eHMIs are still needed. This suggests that multiple interface types could co-exist to support acceptability while removing ambiguity from the interaction. However, it is unknown how this generalises to cyclists; this thesis explores this for the first time.

These studies showed that AV-cyclist encounters would not necessarily be one-to-one [37]. Interfaces must scale and facilitate interaction with an increasing number of road users [123]. Some work has been done with pedestrians but not cyclists [47, 124]. This leaves a critical research gap that must be resolved before deploying AVs on real roads. This informed RQ4: *"How can AV-cyclist interfaces facilitate interaction between an increasing number of AVs and cyclists to support scalable communication?"*. This is answered in Chapter 6 of the thesis.

2.7 Research methods for cycling HCI

HCI research has explored various devices to help cyclists navigate traffic [142, 148]. Not all studies specifically focused on AV-cyclist interaction. Still, the approaches adopted in these studies directly influenced the research methodology of this thesis. Notably, numerous cycling HCI studies followed a two-stage design-evaluate approach [84], where researchers first conducted participatory design sessions to incorporate end-user perspectives and enhance interface acceptability, followed by simulated or real-world evaluations to test and refine the concepts. For instance, Matviienko et al. [84] studied interfaces communicating lane-keeping cues for child cyclists. They first conducted preliminary design sessions using Lego bricks, which immersed children in the design process. New interface concepts were synthesised based on the children's input and evaluated in a cycling simulator (a stationary bike connected to desktop monitors). The simulator study helped identify design strengths and weaknesses in a controlled setting. Following this, the researchers refined and tested their designs on an outdoor test track, providing more realistic cycling to complement the simulator findings. A similar approach is taken in Chapter 4 of this thesis.

Another example is Claes et al.'s [28] study on public displays for cyclists. They began with a design session incorporating urban planning experts and cyclists. The researchers adopted the Map-it [70] design method. This is a collaborative method where participants discuss the problem, co-design their concept, and use stickers to highlight aspects they like or dislike about their design. This study showed that Map-it is applicable for cycling displays and informed the design session methods in this thesis. Map-it ensured balanced input from experts and cyclists, fostering a rich discussion on interface usability and acceptability. In contrast, Mahadevan et al. [80] (study on grouping AV-pedestrian interfaces, see section 2.2) and Hou et al. [67] (AV-cyclist lane merging study, see section 2.5) used the PICTIVE [91] approach. Here, end users and experts individually sketched designs. While this generated a broader range of concepts, it lacked in-depth discussions, limiting the depth of thematic analysis. Claes et al. [28] evaluated their public display by deploying it on real roads and conducting in-the-wild observations to study how cyclists interacted with it. This allowed the researchers to contribute to public display design guidelines based on real interaction. This underscores the importance of evaluating interfaces, even when the design process features in-depth insights and discussion.

2.7.1 Immersive Participatory Design

Immersing participants in the design process can lead to more effective and contextually appropriate solutions [144]. AutomotiveUI research has implemented strategies to achieve this. For example, Severs et al. [115] conducted a participatory design session with people with disabilities to develop accessible user interfaces for automated shuttle passengers. Participants sketched and attached their concepts onto a to-scale vehicle mockup, allowing them to appreciate the spatial constraints and design at the appropriate scale. This inspired the design sessions in Chapter 4 and Chapter 5 of the thesis. Participants designed interfaces around real vehicles, allowing them to contemplate and discuss their concepts in a representative setting.

Similarly, Zavin Asha et al. [149] developed a VR platform that projected a high-fidelity interior of an AV, allowing participants to use the PICTIVE approach to spawn or sketch interface elements directly onto the virtual environment. This immersive approach was particularly beneficial compared to traditional paper-based sketches for designing AV passenger interfaces. The design sessions in Chapter 6 expand on this by incorporating real-time experience testing, allowing participants to immediately evaluate their concepts after creating them.

2.7.2 Simulators in Cycling HCI Research

Simulators are integral to cycling HCI research, particularly for AV-cyclist interaction, where access to real AVs may be limited and riding around them is dangerous [67, 88, 140]. Rothenbücher et al. [109] developed the Ghost Driver approach to test AV interfaces in real-world setups by hiding a human driver in a car seat costume. This creates the illusion that the vehicle is automated. This approach is used in Chapter 4 of this thesis. However, since the vehicle is real, it limits the ability to simulate dangerous or non-yielding vehicle driving behaviours. Simulators remain critical for testing more complex or risky scenarios. A common simulator approach for cyclist interface studies involves a stationary bicycle connected to a display, such as a VR headset or desktop monitor [89]. von Sawitzky et al. [137, 138] commonly uses this setup to evaluate AR displays warning cyclists about dooring hazards; this scenario occurs when a passenger opens the vehicle door to exit, and the door abruptly obstructs the cyclist's path. This scenario is challenging to test in real-world settings without compromising participant safety. von Sawitzky et al. [138] use a simulator that projects a virtual environment onto the walls surrounding the bike; this is also known as a CAVE setup. Participants rode a stationary bike to navigate the environment and wear a Microsoft HoloLens AR headset [4] to receive the AR cues.

von Sawitzky et al. [139] conducted a study to compare data from the simulator with results from an outdoor test track. Cyclists navigated either a virtual or an outdoor track with parked cars while wearing the HoloLens, which displayed dooring alerts. No significant differences were found in cyclist behaviours or perceptions of any interfaces between the two studies. This suggests that cycling simulators are a valid way of testing interfaces. However, the primary limitation of cycling simulators is the lack of real riding dynamics [86]. Stationary bicycles do not replicate the natural leaning movements of real cycling, which affects balance and turning. Wintersberger et al. [145] attempted to overcome this by installing a motion platform under the stationary bike. This improved the experience for subtle turns but not for sharp manoeuvres. One of the most significant advancements in cycling simulators is the AR approach. Matviienko et al. [88] developed an AR simulator and deployed it on a HoloLens headset. This allowed participants to navigate a virtual environment while cycling in real physical space. However, the HoloLens has limitations, including translucent object projections and a narrow field of view. Recent studies have addressed these issues with advanced mixed-reality headsets featuring passthrough technology; this uses cameras on a VR headset to display the real world overlaid with any virtual objects. For example, Aleva et al. [4] conducted a study on AV-pedestrian interaction. Participants wore mixed reality headsets projecting opaque AVs and interfaces onto the real world. This method allowed for high-fidelity AV interface testing without compromising real-world interactions.

This section showed that it is not enough to solely rely on participatory design for AV-cyclist interfaces [28]. These concepts must also be evaluated to confirm their effectiveness and highlight any strengths and weaknesses [84]. Design sessions should immerse participants to contribute more fitting solutions while leaving room for discussion rather than only design generation to contextualise design decisions [28, 149]. Evaluation studies can use simulators to present high-fidelity interface prototypes. Still, these should be complemented with outdoor studies or use new approaches, such as AR headsets, to allow real riding and collect data on realistic cycling behaviours [84, 88]. This directly informed the methods in this thesis.

2.8 Literature Review Summary

Overall, the research covered in this review shows a clear need for AV-cyclist interaction to resolve space-sharing conflicts [20, 59]. However, very little research has explored this. Real-world studies and observations showed many issues and hesitant behaviours from AVs and cyclists [97, 101]. These issues were still prevalent among cyclists who encountered AVs across longer periods and reported that the experience was unpleasant due to a lack of clear, explicit

[4] Microsoft HoloLens AR Headset: `learn.microsoft.com/en-us/hololens/` ; Accessed 01/04/2025

communication [120]. Existing research on AV-cyclist interaction consistently showed that interfaces outperform baseline conditions with no interface [67, 88]. However, this research had a limited scope. For example, facilitating one-to-one AV-cyclist interaction [67] at an intersection [140]. They also evaluated a specific type of interface, such as AR displays in single, mostly Western countries [88, 140]. The literature review revealed four key AV-cyclist interface design challenges that must be overcome before using interfaces on real roads:

- **Acceptability:** There is no strong foundation informing how AV-cyclist interfaces can be designed to match the needs and expectations of cyclists [14]. AV-pedestrian research has produced generalisable requirements from real-world studies exploring driver-pedestrian interaction at crossings [41, 49]. AV-cyclist interaction research would benefit from similar studies exploring driver-cyclist interaction [16]; this informed RQ1;
- **Versatility:** Cyclists will likely encounter AVs across traffic scenarios with different traffic control features and vehicle positions [1]. Cyclists perceive these scenarios differently [60] and exhibit distinct cycling behaviours when navigating them [12]. However, AV-cyclist interfaces were only tested in single scenarios like lane merging [67]. Interfaces must be versatile to work consistently between traffic scenarios; this informed RQ2;
- **Cultural Inclusivity:** Drivers and cyclists interact differently depending on their local norms [62]. Cyclists also perceive vehicles differently depending on their local traffic infrastructure [130]. AV-cyclist interfaces must be culturally inclusive and accommodate these factors to support the global deployment of AVs [108]. However, they have only been tested in single, mostly Western cities [37]; this informed RQ3;
- **Scalability:** AV-cyclist interfaces have only been tested for one-to-one interaction [67, 140]. However, they must scale to facilitate interaction across an increasing number of road users [123]. Previous work with pedestrians showed that wearable devices overcome ambiguities in multi-pedestrian encounters [125] and can centralise information from multiple AVs [124]. It is unknown how this generalises to cyclists; this informed RQ4.

The research methodologies adopted in prior work directly informed the methods in this thesis. The acceptability design challenge requires real-world studies that capture driver-cyclist interaction behaviours to inform the messages and cues AVs should recognise and respond with [41, 49]. Research on cycling HCI also showed that cyclists should be involved in designing any interfaces through participatory design sessions [28, 84]. These should be complemented with user studies evaluating interfaces to identify their strengths and weaknesses [67, 140]. This is important for iterating on interface designs to prepare them for real-world use [84]. This research approach was used in the thesis. It provided a comprehensive investigation of cyclist perceptions and behaviours toward AVs and AV-cyclist interfaces [67].

Chapter 3

Acceptability

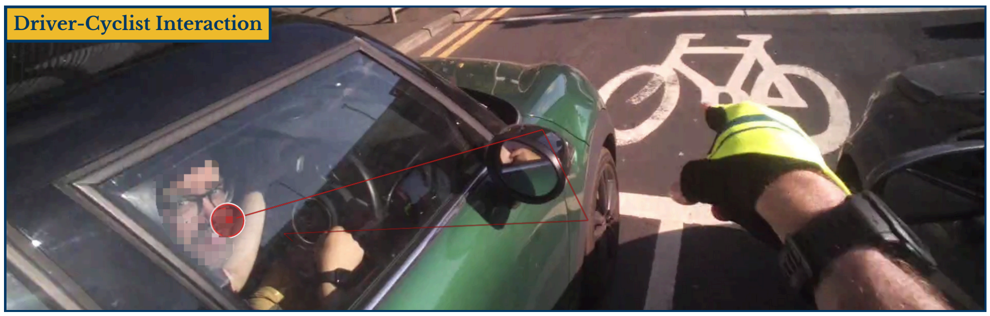

Figure 3.1: Driver-cyclist interaction in real traffic captured in Study 3. The red dot represents the cyclist's gaze fixation.

Acceptability refers to an interface's ability to be accessible and acceptable to the widest possible range of cyclists [16]. This presents a key design challenge because cyclists are a diverse group. The bicycle is their only common factor, and any AV-cyclist interface must be usable regardless of their bike type, safety gear, or smart devices [14]. Cyclists may not use an interface if it disrupts their cycling or is difficult to access. Previous research showed that clear communication is essential for resolving space-sharing conflicts [82, 104]. So, an unacceptable interface would hinder cyclist safety and the large-scale adoption of AVs [3]. It could also lead cyclists to avoid riding near AVs [113, 120], reducing participation in active travel, which is both sustainable and beneficial to public health [93].

AV-cyclist interfaces must align with cyclists' unique needs and requirements to ensure acceptability [16, 60]. However, no comprehensive design requirements currently exist. Prior work has primarily relied on design sessions [67], collision reports [88], and insights from AV-pedestrian interaction research [140]. In contrast, AV-pedestrian research benefits from a strong foundation of studies on pedestrian perceptions of AVs and interfaces [33] and pedestrian behaviour at real crossings [49]. These studies provide a detailed understanding of how pedestrians exchange messages with drivers and which vehicle areas they observe [42]. This knowledge directly influenced message content and placements of AV-pedestrian interfaces [39]. For example, eHMIs were shown to align with pedestrians' natural gaze behaviours [49], and this advanced the field to explore more nuanced eHMI design features, including colours and animation patterns that improve usability [39]. A similarly strong research foundation is necessary to understand the potential placements and types of AV-cyclist interfaces that align with cyclist perceptions and natural behaviours before investigating more specific design features.

This chapter adopts a similar approach to the research framework for AV-pedestrian interaction to establish foundational knowledge for AV-cyclist interface design before developing and testing interfaces. Studies in this chapter address RQ1: *"How can insights from current driver-cyclist interaction inform the design of acceptable AV-cyclist interfaces?"*. The studies focused on understanding how interactions occur with human drivers to reduce the learning curve of AV-cyclist interaction and ensure that AVs respond appropriately to cyclists' cues. They measured cyclist perceptions and real-world behaviours to identify the messages AVs should exchange with cyclists and inform the design of interfaces that do not disrupt their natural behaviours while riding. Three studies were conducted:

1. **Study 1 - Online Survey:** This was an initial exploration of the AV-cyclist interaction problem through cyclist perceptions. It covered a range of topics; cyclists self-reported the cues and messages they exchange with human drivers and their expectations of AVs and AV-cyclist interfaces. These insights informed cyclist expectations and openness toward AV-cyclist interfaces, including the types of devices that can be used and the limitations in current interactions that interfaces could overcome.

2. **Study 2 - In-the-Wild Observations:** This study systematically recorded real-world driver-cyclist interaction behaviours in five traffic scenarios. This includes the exchanged messages, social cues and implicit cues. The findings directly inform interface acceptability by identifying the cues AVs should recognise and respond to throughout a cyclist's journey across different scenarios.

3. **Study 3 - Eye-Tracking in Real Traffic:** This study investigated the nuances of driver-cyclist interaction. Cyclists were equipped with eye-tracking glasses and asked to record two home-office commutes. This showed the areas cyclists focused on the most to make decisions during interaction (see Figure 3.1). The study directly informs acceptable AV-cyclist interface design by providing insights into the placements interfaces could use without obstructing the natural and reflexive behaviours of cyclists.

This chapter establishes a comprehensive set of AV-cyclist interface requirements based on cyclist perceptions and real-world behaviours. Findings from the three studies were combined to contribute design guidelines for acceptable AV-cyclist interfaces that facilitate clear communication, maintain familiarity with current interaction methods, and minimise disruption to existing cycling setups.

3.1 Study 1: Online Survey

It is critical to understand how cyclists interact with drivers and their perceptions of AVs to develop interfaces that align with their needs and expectations [66, 82]. This study was an online survey in which cyclists reported the messages and cues exchanged with drivers, their perceptions of different traffic scenarios, expectations of AVs, and the feasibility of repurposing their personal devices as AV-cyclist interfaces. The findings from this study provided a foundation for the design and evaluation of acceptable AV-cyclist interfaces in the remainder of the thesis.

3.1.1 Study Design

The survey was designed to inform the upcoming studies in this thesis and serve as an initial exploration of the AV-cyclist interaction problem. Therefore, it examined the self-reported interaction behaviours of cyclists. Participants reported the messages and social cues they exchanged with drivers. Moreover, interfaces must be versatile and work successfully across traffic scenarios for cyclists to accept them [12]. Therefore, participants also indicated their perceived difficulty in navigating various scenarios with different setups.

To begin exploring the AV-cyclist interaction problem, participants indicated their perceptions and expectations of AVs and their opinions of reusing personal devices as AV-cyclist interfaces. This would provide insights into how AV-cyclist interfaces could be designed to align with cyclist expectations, enhancing acceptability.

Study Scope

The survey began with questions on participant demographics and cycling experience. Following this, questions were divided into four blocks of questions, each exploring a specific theme. Each block comprised five-point Likert-scale questions and an open question related to the theme, such as perceptions of AVs. Open questions added context to the Likert-scale answers and allowed participants to highlight any additional points not covered by the survey. Blocks are detailed below, and the complete set of questions is in Appendix B.4.

Block 1 - Interaction Behaviour The first block examined how cyclists interact with drivers. AV-cyclist interfaces may be more acceptable and easier to learn if they recognise the cues cyclists already use and respond with messages similar to those from human drivers [46]. To assess this, the block asked cyclists how often they interact with drivers, the reasons for these interactions, and the specific messages and social cues they exchange, such as intentions and hand gestures. This block's open-ended question allowed cyclists to provide further details about their interactions. This included the perceived importance of specific social cues or identifying key messages not captured in previous research.

Block 2 - Perception of Traffic Scenarios This block began exploring the versatility design challenge by asking cyclists to rank the perceived danger of thirteen traffic scenarios identified from previous research [67, 122, 140] and vehicle-cyclist collision reports [36, 128]. These scenarios varied in traffic control and vehicle positions, ranging from controlled intersections with traffic lights to dynamic situations like lane merging with a vehicle approaching from behind. An open-ended question allowed participants to report additional scenarios they found particularly challenging. These insights were essential for informing the next chapter, helping to determine which traffic scenarios should be further investigated.

Block 3 - Perception of AVs This examined cyclist perceptions of AVs by adapting the Pedestrian Receptivity Questionnaire Towards Autonomous Vehicles [34] for cyclists. It also included an open-ended question, allowing participants to share their expectations of AVs. The findings from this block were particularly valuable for shaping future studies. They helped determine whether cyclists already had well-defined perceptions of AVs or if practical experiments involving direct interaction with AVs were necessary to clarify these expectations.

Block 4 - Current and Future Device Use Placement is a key factor in AV-cyclist interface acceptability [49]. Understanding cyclist preferences for wearable or bike-mounted interfaces versus alternatives like AV-mounted or environmental displays is essential for acceptability [16]. This block investigated the devices and safety gear cyclists typically carry to explore their potential for repurposing as AV-cyclist interfaces. Participants then responded to an open-ended question asking them to discuss the feasibility of using their devices as AV-cyclist interfaces. This provided insight into cyclists' openness to reusing existing devices for AV interaction.

3.1.2 Apparatus

The survey was hosted online using the Qualtrics[1] platform, which is GDPR compliant and available to University of Glasgow researchers. As a result, all surveys and questionnaires in the subsequent studies of this thesis were also hosted on Qualtrics. In this study, participants accessed the survey using their personal devices via a URL link or QR codes included in survey advertisements.

3.1.3 Participants

The survey received 383 valid responses after social media advertising. Responses were considered valid if they did not originate from duplicate IP addresses and correctly answered attention checks, such as *"Select Strongly Disagree"*.

[1]Qualtrics Online Survey Platform: `qualtrics.com` ; Accessed 01/04/2025

Participants were adult cyclists (18+) who had been riding multiple days a week for at least one year. They were from 23 countries, with the majority (41%) from the UK and USA (33%). Participant demographics were: $M_{\text{age}} = 30$, $SD = 7.1$; *Male* = 242, *Female* = 131, *Non-Binary* = 8, *Prefer not to say* = 2.

3.1.4 Procedure

The survey was hosted online for one month to reach a large, international sample of cyclists. It was advertised on social media, including online cycling forums like the *r/Cycling* subreddit and city-specific groups such as the *"Cycling in Glasgow"* Facebook group. Advertisements were posted across these channels every three days to ensure a steady flow of responses.

At the start of the survey, participants were presented with the study information sheet and consent form. Upon agreeing to participate, they provided their demographic and cycling experience information. Participants then proceeded to complete a set of Likert-scale questions, followed by open-ended questions. Ten pilot tests showed that completing the survey took approximately 15 minutes. Participants could provide their email addresses to enter a prize draw for a £20 Amazon voucher upon survey completion.

3.1.5 Analysis

The survey collected quantitative data in the form of five-point Likert-scale answers and qualitative data from open-ended questions. These data were analysed as follows.

Quantitative Data Analysis

Descriptive statistics were used to calculate the frequency and percentage of responses for each response category (e.g., *Strongly Agree* or *Disagree*) for each Likert-scale statement. This was critical for identifying patterns across the data.

Qualitative Data Analysis

An inductive, data-driven, thematic analysis [19] was conducted on the open-ended questions. Qualitative data were exported from Qualtrics and imported to NVivo[2] for coding. One researcher identified 98 unique codes from the data. Two researchers then collaboratively sorted these into five overarching themes based on their similarities. This process was iterative; disagreements were discussed until resolved, with codes being remapped when necessary. Themes containing two or more overlapping codes were reassessed and combined where appropriate.

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

3.1.6 Results

Five themes were derived from the open-ended responses. This section presents each theme alongside three example quotes from participants for context. Additionally, the percentage of respondents who selected *Agree* to *Strongly Agree* or *Most of the Time* to *Always* on the associated Likert-scale statements is reported. This provides a quantitative measure to support the identified themes.

Theme 1: Social Cues in Driver-Cyclist Interaction

Participants reported that eye contact is essential for confirming the driver's awareness of them, and hand gestures are useful for negotiating the right of way and communicating intentions:

> *"I follow road rules and use hand signals to show my intent to turn or stop. I make eye contact with cars [...] I wave thank you if a driver is courteous"*

> *"I ride in traffic daily. I rely on eye contact and hand signals to communicate with drivers"*

> *"Hand signalling, eye contact, thumbs up or thank yous for appropriate vehicular behaviour"*

Likert-scale data reinforced these statements; 80.6% of respondents indicated that they use hand gestures to interact with drivers, and 65% said they feel safer when establishing eye contact. Prior work showed that exchanging intentions is key to resolving space-sharing conflicts [82]. The survey revealed similar findings, as 91.1% of respondents said they interact with drivers to communicate their intentions. Similarly, 92.4% said they need to know a driver's next manoeuvre when sharing the road, and 89.3% said they need to know that drivers are aware of their presence. Cyclists preferred that these messages be communicated explicitly. Only 34.2% of cyclists said they could tell a driver's next manoeuvre by looking at their driving behaviour. This motivates the development of AV-cyclist interfaces.

Theme 2: Scenario Traffic Control and Cyclist Perceived Risk

Respondents reported that traffic scenarios with little or no traffic control are more challenging to navigate than those with higher traffic control levels. For example, intersections without traffic lights were perceived as more dangerous than those with traffic lights. Cyclists also identified dynamic scenarios which can occur anywhere on the road, such as lane merging, as high-risk:

> *"Cycling in areas with many taxi or rideshare drop-offs, because these stops are unpredictable"*

> *"Lane merging - vehicle moving into the lane I'm in"*

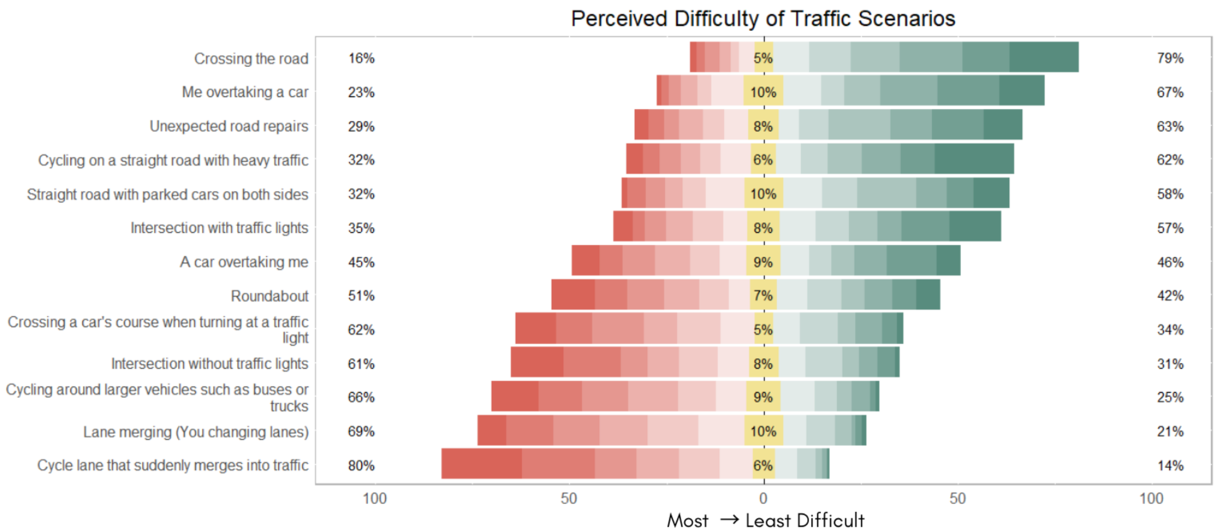

Figure 3.2: Participant rankings of traffic scenario difficulty; these are ordered from least to most challenging, with green bars signifying less challenging rankings and red as most challenging. They ranked crossings as the least difficult and cycle lanes merging into traffic as the most difficult. Scenarios labels are in the form of the questions in the survey; Intersection with Traffic Lights is also known as Controlled Intersection [128], Intersection without Traffic Lights is also known as Uncontrolled Intersection [128].

> *"Cycle lanes disappearing at the most dangerous sections of road (junctions, overtaking lanes)"*

Figure 3.2 illustrates participant rankings of the traffic scenarios. It shows similar outcomes. For example, 57% of respondents ranked controlled intersections as not challenging, while 69% ranked lane merging as challenging. This theme highlights the diversity of traffic scenarios that cyclists encounter. It underscores *versatility* as a critical challenge for AV-cyclist interactions because not all scenarios are perceived as equally difficult.

Theme 3: Cyclist Expectations of AVs

Respondents indicated they did not feel sufficiently informed about AVs to provide clear perceptions or expectations. This finding motivated upcoming experiments in the thesis to adopt a more practical approach through user studies where cyclists directly interact with AVs rather than relying solely on self-reported perceptions.

> *"Unfortunately, I do not know enough about the systems of [automated] vehicles at this time"*

> *"I feel I don't know enough about how [automated] vehicles work and what's being done for them to recognise cyclists"*

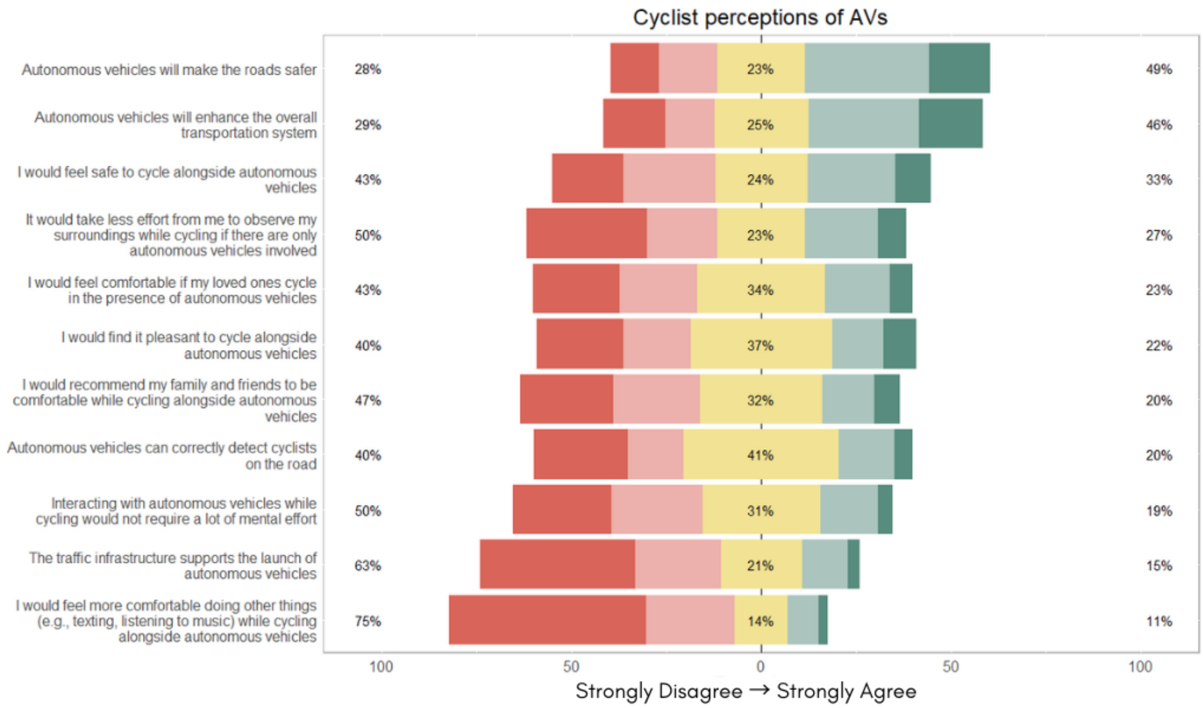

Figure 3.3: Participant perceptions and expectations of AVs. Results show that participant perceptions were mostly split and no consensus was reached.

> *"Don't know enough about [automated] vehicles to make a comment or judgement"*

Figure 3.3 shows responses to the Receptivity Questionnaire Towards Autonomous Vehicles. Similar to the qualitative findings, answers to the questionnaire were divided, with no clear consensus emerging. For instance, 33% of respondents felt they would be safer riding around AVs, while 43% disagreed, and the remaining respondents were unsure. This highlights the uncertainty surrounding the impact of AVs on cycling behaviour and underscores the need for further investigation.

Theme 4: Cyclist Device Use on the Road

Participants identified smartphones as the most carried device on the road. Qualitative data showed that smartphones are rarely in cyclists' field of view. This has direct implications for AV-cyclist interface design. It suggests that visual displays on smartphones may not be ideal:

> *"I carry my phone in my bike bag"*

> *"I never use my phone while in motion [...] To use my phone for navigation or any other purpose, I stop cycling"*

> *"Phone (in pocket only)"*

Quantitative data showed that 92.4% of participants carry their phones while cycling, and 41.5% said they wear a smartwatch. In comparison, only 14.9% said they use cyclist-specific smart devices such as rearview radars or bike computers. Regarding how cyclists use smartphones on the road, only 17.8% said they use their phones for cycling-related tasks such as navigation, and 5.5% said they use their phones for non-cycling-related tasks such as texting. This further suggests that smartphones are likely to be hidden from the cyclist's sight.

Theme 5: Wearable and Bike-Mounted Devices for AV-Cyclist Interaction

Respondents showed concerns about using wearable or bicycle-mounted devices as AV-cyclist interfaces. This would significantly alter the traditional cycling setup as cyclists would be compelled to carry these devices at all times. Participants also reported that this will impose an added responsibility on them:

> *"The responsibility is not on me to carry a device to enable a self-driving car to see me and secure my safety"*

> *"Relying on cyclists having such devices for safe interaction is creating two classes of cyclists (those with vs those without such devices). [Automated] vehicles should not rely on selective solutions and should be safe around all road users"*

> *"Solutions that require the rider to be equipped with some kind of smart device are not adequate. [Automated] vehicles must be capable of recognising all road users"*

Quantitative data revealed a similar consensus. Only 19.6% of respondents said they would buy new smart devices to help them interact with AVs. However, they were more accepting of existing devices being repurposed for interaction; 48.3% said they would use devices such as their phones to interact with AVs.

3.1.7 Discussion

The survey served as a foundation to provide an overview of the AV-cyclist interaction problem and motivate upcoming studies in the thesis. It addressed the interface acceptability challenge by asking cyclists about the feasibility of reusing their current devices as interfaces. Participants responded that this would significantly alter the current cycling setup as they would always be compelled to carry these devices. It would also place greater responsibility on them compared to current interactions, as cyclists must carry these devices to receive AV signals. This finding aligns with Berge et al.'s [16] who interviewed cyclists about wearable devices for interaction. This reinforces that AV-cyclist interfaces must maintain the simplicity and accessibility of cycling to be acceptable. Therefore, this narrows the design space for interfaces to be on the AV, through eHMIs, or environment, using smart traffic signs and road markings. These can be used to compensate for human drivers and communicate the intentions of AVs. However, previous work with pedestrians shows that it is also feasible to group multiple interfaces to facilitate interaction collectively [80]. This way, additional wearable devices can be used for added support without compromising the acceptability of AV-cyclist interfaces because cyclists will still have on-AV or environment displays. This leaves room for wearable devices to improve upon today's interactions and communicate new types of messages and cues, not just compensate for human drivers. This is similar to how cyclists today use rearview radars to receive alerts on approaching vehicles from behind without needing to shoulder check. This approach informed the subsequent research in the thesis, which examined the use of interface groups to facilitate interaction while maintaining interface acceptability.

Interestingly, participants indicated that their smartphones are often out of view, in their pockets or bags, rather than being mounted on the bicycle handlebar while riding. This finding challenges the acceptability of previous AV-cyclist interfaces in the form of smartphone applications [77]. Previous work with pedestrians suggested using vibrations from the smartphone to overcome this challenge [80]. Survey participants highlighted that the driver's intentions and awareness of them are critical messages they rely on to navigate traffic safely. This aligns with prior work with pedestrians and provides a common ground between the two VRU groups [80]. It offers a positive step toward designing interfaces that are inclusive of all road users. However, some differences were reported by participants. For example, many responses showed that cyclists are more likely to exchange positive or negative feedback by thanking or even yelling at drivers. This was less prominent with pedestrians [46]. It was critical to explore other messages exchanged by drivers and cyclists in greater detail, and this motivated the observations in the following study. It remains unclear how interfaces should be designed to display vehicle intentions, awareness and other information to cyclists, or if these messages generalise from human driver to AV-cyclist interaction. This motivated the studies in the thesis to investigate optimal messages for AV-cyclist interaction and how to present these messages accordingly.

One particular challenge that the survey addressed was versatility. It is unclear how cyclists interact with drivers in different traffic scenarios and how cyclists perceive these scenarios. This goes hand-in-hand with the acceptability challenge because acceptable interfaces should work throughout a cyclist's journey [12]. The survey showed that cyclists do not perceive all scenarios to have a similar difficulty, and the general trend illustrated that traffic control made these scenarios easier. AV-cyclist interfaces may provide the clarity that traffic control provides, helping cyclists safely navigate all scenarios. However, this finding shows the challenges to achieving versatility. For example, whether AVs should display consistent signals throughout or adapt their signals between scenarios. Survey respondents ranked a cycle lane abruptly ending in traffic as the most challenging scenario. This is critical as it is a cyclist-specific scenario that will not be investigated with other road users, showing that not all AV interaction research generalises to cyclists [66]. Interestingly, they ranked crossings as the least challenging scenario, suggesting that

AV-pedestrian eHMIs designed to work in crossings [37] may not be effective. This motivated an in-depth exploration of versatile AV-cyclist interfaces in the following thesis chapter.

Respondents did not have a clear idea of how to interact with an AV. Many stated that they could not form any expectations until they interacted with these new road users. Berge et al.'s [16] interviews with cyclists reached a similar conclusion. This highlights the importance of in-the-wild AV-cyclist observations [97], as relying on cyclist perceptions is not always reliable. However, testing new interfaces through real-world observations is challenging, as these may be unsafe to deploy in the wild [44]. Research with pedestrians has conducted methods such as online surveys with videos [39]. However, this still may not be enough. It is important to collect data from direct interaction so cyclists can form strong opinions about interacting with AVs and using interfaces [28]. This motivated upcoming studies in the thesis to employ simulators and Wizard of Oz techniques to allow cyclists to interact with simulated AVs instead of relying on surveys and focus groups.

Overall, the online survey was critical for informing the remainder of the thesis. It informed the methods and research directions of upcoming studies. The first step was in the following observation study. The observations would complement this study as they would capture the messages and cues drivers and cyclists exchange between scenarios; this could indicate whether these cues changed depending on the scenario or remained consistent. They would also further inform the design of AV-cyclist interfaces that maintain familiarity between interactions with drivers and AVs [46].

3.2 Study 2: In-the-Wild Observations

The survey revealed self-reported insights into the messages and cues cyclists currently exchange with drivers. It also showed that cyclists do not have the same perceptions of *Traffic Scenario*s, and this may depend on traffic control. Therefore, it was important to gain more detailed insights into driver-cyclist interaction behaviours between *Traffic Scenario*s to ensure that AVs can recognise and respond appropriately to messages throughout a cyclist's journey.

This study was in the form of real-world observations of driver-cyclist interaction behaviours. Observations were conducted across five *Traffic Scenario*s with different levels of traffic control. The exchanged messages, social cues and implicit cues were recorded in each *Traffic Scenario*. The observations complemented the survey by providing a deeper and more objective understanding of driver-cyclist interaction, contributing to a holistic view of the problem.

3.2.1 Study Design

This study used an observational approach to examine how drivers and cyclists interact across different *Traffic Scenario*s. The independent variable was the *Traffic Scenario*, while the dependent variables included driver and cyclist interaction behaviours, including the *Exchanged*

Messages and *Social* or *Implicit Cues* used during interactions. This approach was essential for informing the design of acceptable AV-cyclist interfaces, ensuring their signals align with existing driver-cyclist communication.

Study Scope

All observations were conducted in Glasgow, UK. This is a dense urban city with diverse road infrastructure. Glasgow has few dedicated cycle lanes, and cyclists often have to ride in mixed traffic on their trips. This provided a suitable environment to observe driver-cyclist interactions in real-world traffic conditions. Only adult drivers and cyclists were observed; data were not recorded for child cyclists or young adult-looking road users to ensure all data were from adult (18+) participants. Five *Traffic Scenarios* were selected for observation. These were a subset of those included in the previous online survey. The scenarios were chosen because they reflected varying levels of perceived difficulty among cyclists; not all were considered challenging. This allowed for a broader range of interaction behaviours to be observed and helped reveal how cyclist perceptions of a scenario influence their interactions with drivers. Survey results indicated that perceived difficulty was closely linked to the level of traffic control in each scenario. Accordingly, scenarios were selected to represent a range of traffic control, from traffic lights to road markings to no control at all. This maximised the contrast between scenarios and highlighted how different traffic configurations affect interaction behaviour. The selected scenarios are also commonly encountered in urban settings [12, 67] and follow standardised formats in the UK Highway Code [128], enhancing the generalisability of the findings. Other scenarios from the survey—such as navigating around large vehicles or roadworks—were excluded due to their spontaneous nature [6], which would have made it difficult to gather sufficient observations. The selected scenarios, listed from most to least traffic control, were:

- **Controlled Intersection:** A four-way intersection with traffic lights to determine the right of way and stop lines on each arm;
- **Roundabout:** A roundabout with four arms and a single lane in the roundabout itself. There were give-way lines on each arm to encourage approaching road users to decelerate before proceeding;
- **Uncontrolled Intersection:** A four-way intersection with a dedicated bicycle lane between the top and bottom arms. Give-way lines were present on the left and right intersection arms, so cyclists on the dedicated lane had the right of way;
- **Ending Cycle Lane:** A dedicated bicycle lane that abruptly ends in a two-way intersection, forcing cyclists to transition into mixed traffic while accounting for any vehicles approaching from their right. There is a give-way line present at the edge of the bicycle lane to prompt cyclists to reduce their speed before transitioning;

Figure 3.4: The five observed sites, with one site per Traffic Scenario. The top photographs show a top-view of the sites, the middle shows the co-ordinates (locations) of the sites, and the bottom photographs show the observer's view on the study day.

- **Lane Merging:** A straight road with an adjacent dedicated bicycle lane on the left. The dedicated lane ends and reappears on the right 35 meters later, forcing cyclists to merge lanes with vehicles approaching from behind.

The observer recorded data for driver-cyclist encounters in each *Scenario*. These are situations where a driver and a cyclist are in close proximity in a *Traffic Scenario* to the point where a space-sharing conflict may arise, and interaction would be needed. This allowed the study to quantify the likelihood of interaction in each *Traffic Scenario* instead of simply recording interaction behaviour. This is useful for understanding the role of traffic control in determining right-of-way and informing upcoming thesis chapters exploring *versatility*.

The observer used an online form for data collection. First, they specified whether an interaction occurred. This was when the driver or cyclist changed their behaviours [82], including braking or using a hand gesture or shoulder check as a response to avoiding or resolving a space-sharing conflict. In cases where there was interaction, they recorded the *Exchanged Messages*, *Social Cues* and *Implicit Cues* from each road user. They also specified any *On-Vehicle Signals* used by the driver, such as directional indicators or hazard lights. These were identified from the UK Highway Code [128] and did not include implicitly triggered signals such as brake lights. Eye contact was not an option for social cues, as this is difficult to observe. Instead, observers recorded the head movements *toward a road user*. This could indicate eye contact being established [131]. The content of the online form is in Table 3.1. This was synthesised from prior work that identified the messages and cues that road users exchange during interaction [46, 82].

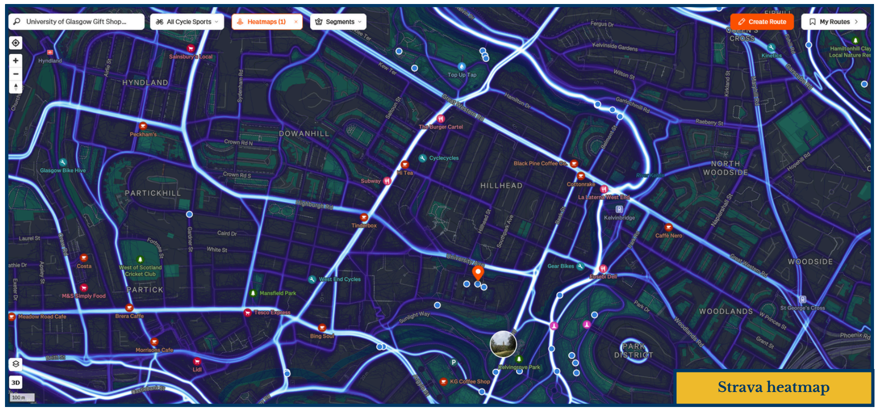

Figure 3.5: The Strava heatmap showing crowdsourced cycling routes close to the University of Glasgow. Thicker and brighter lines on the map show more popular cycling areas, while thinner and darker ones show less popular ones.

Study Setup

Five sites were observed in total, one for each scenario. These are shown in Figure 3.4. Sites were selected after ensuring that they were in close proximity to the University, had high cycling traffic, and allowed a clear view for the observer. Previous research has shown that lower-speed roads feature more expressive interactions and are more straightforward to observe and record interaction behaviours [112, 131]. Therefore, all observed sites had a speed limit of 50 km/h. This is the standard UK speed limit for urban roads [128].

Each site was observed for one day over two sessions during rush hour on weekdays (session 1: 08:00-10:00; session 2: 16:00-18:00) to maximise the number of observations. For scenarios with multiple cyclists, only the first cyclist was considered to avoid situations where a preceding cyclist could influence the observed cyclist's behaviour [68, 82]. Only the vehicle closest to the cyclist was observed to ensure it was the most likely to be in a space-sharing conflict.

3.2.2 Apparatus

The Strava heatmap[3] was checked to filter the potential sites and choose the one with the highest cycling traffic for each scenario. Google Street View was utilised to ensure that these sites provided a clear view for observers. The observer used an iPhone 12 mini to complete online forms.

Category	Options
Interaction Occurrence	Yes / No
Exchanged Messages	Negotiating right of way Cyclist indicating intentions Cyclist indicating awareness Driver indicating intentions Driver indicating awareness Cyclist positive reaction (e.g., thanking) Cyclist negative reaction (e.g., yelling) Driver positive reaction (e.g., thanking) Driver negative reaction (e.g., rude hand gesture) Other
Driver/Cyclist Social Cues	Selected separately for driver and cyclist:
	Hand gestures Head movements toward other road user Nodding Facial expression Voice Unclear Other
Driver/Cyclist Implicit Cues	Selected separately for driver and cyclist:
	Accelerate Decelerate Maintain speed Stop Parked Unclear
On-Vehicle Signals	Honk Direction indicators Flashing headlights Hazard lights Unclear Other

Table 3.1: The observation form filled in by the experimenter when a driver-cyclist encounter occurred. This captured the exchanged messages, social and implicit cues. Form contents were populated from prior work by Markkula et al. [82] and Dey et al. [41]

3.2.3 Procedure

Selecting sites to observe

The study followed a systematic process to select observation sites. First, the Strava heatmap (see Figure 3.5) was queried using the University postcode to identify popular nearby cycling routes. Strava is a widely used fitness app that generates a heatmap from crowdsourced data, highlighting areas with high or low cycling activity. This identified locations with high cycling traffic, maximising the potential number of observations. Next, areas with high cycling activity were examined by manually checking the map to locate relevant traffic scenarios, such as a roundabout.

For each scenario, three candidate sites were shortlisted; all candidate sites had a speed limit of 50 km/h as determined in the study design. Google Street View was then used to assess whether each site offered a clear line of sight for observers. Sites with an unobstructed view were visited in advance to confirm visibility and to note any traffic signs or roadworks that might influence interaction behaviour. Finally, for each scenario, one site was selected based on having both the clearest view and the highest cycling traffic.

Observing driver-cyclist encounters

Upon arriving at each site, the observer stood at the predefined spot and photographed their field of view. They filled in an online form to specify the site's conditions, including weather, road works or any new traffic signs installed after the site's initial inspection. The observer then waited for any driver-cyclist encounters. They filled in the online form in the sequence presented in Table 3.1 every time there was a driver-cyclist encounter.

They carried the study's information sheet and ethics approval in case any bystander or observed person approached. Each observation session lasted two hours, with the observer returning to the site for an afternoon session on the same day. This resulted in a total of four observation hours per site. The same observer recorded data for all encounters in all sites.

3.2.4 Inter-Observer Reliability

Two researchers stood 5 metres apart and independently observed *Ending Bicycle Lane* scenario over one session to eliminate bias. An inter-observer reliability analysis using the Kappa statistic was performed to determine consistency among observers. The reliability for the observers was found to be: Kappa = 0.857 ($P < .001$), suggesting strong agreement.

[3]Strava Heat Map: `strava.com/maps/global-heatmap` ; Accessed 01/04/2025

3.2.5 Results

This section reports the findings of the messages and cues the road users exchanged and how these differ between traffic scenarios. Chi-Square tests of independence were conducted to investigate the relationships between *Traffic Scenario* and (1) *Interaction Frequency*, (2) *Exchanged Messages*, (3) *Driver Social Cues, On-Vehicle Signals and Implicit Cues*, and (4) *Cyclists' Social and Implicit Cues*. *Post hoc* analyses between each pair of *Traffic Scenario* were conducted with the Chi-Square test of independence with Bonferroni corrections. The study also analysed the interplay of social and implicit cues for each road user. Observations were grouped into three *Cue Categories* comprising the number of observations where the driver or cyclist used (1) only social cues, (2) only implicit cues and (3) a combination of both cues.

Observed Demographics

A total of 414 driver-cyclist encounters were observed. Drivers operated various vehicle types, including 57 trucks or buses, 82 lorries, 137 SUVs, and 138 sedan cars. Cyclists also used a range of bicycles: 145 rode city bikes, 132 used e-bikes, 74 road bikes, 62 used mountain bikes, and one used a recumbent bicycle. 202 cyclists had helmets, and 79 had a smartphone or bike computer mounted on the bicycle handlebar. These data are critical to quantifying the likelihood of using smart devices while navigating mixed traffic and indicating whether these could be repurposed as acceptable AV-cyclist interfaces.

Interaction Frequency

In total, 231 of the 414 encounters (55.8%) resulted in interaction. This means that interaction was necessary in the majority of encounters. Table 3.2 shows the number of observations and frequency of interaction in each *Traffic Scenario*.

There was a significant relationship between *Traffic Scenario* and *Interaction Frequency* ($\chi^2(4, 414) = 71.96$, $P < .001$). This means drivers and cyclists were more likely to interact in some scenarios than others. *Post hoc* comparisons showed that interactions were significantly less likely in *Controlled Intersection* than all other scenarios ($P < .0001$ for all). Therefore, traffic lights effectively determined right-of-way and reduced the need for interaction.

Exchanged Messages

There was a significant association between *Traffic Scenario* and *Exchanged Messages* ($\chi^2(32, 351) = 176.23$, $P < .001$). Therefore, road users did not exchange the same messages across all scenarios. *Post hoc* comparisons revealed that drivers and cyclists were significantly more likely to negotiate the right-of-way and provide positive and negative feedback at *Uncontrolled Intersection* than *Controlled Intersection*, *Roundabout*, and *Lane Merging* ($P < .0001$ for all).

Traffic Scenario	*N* No Interaction	*N* Interactions	Total *N* Observations	Interaction Frequency (%)
Controlled Intersection	93	31	124	25
Roundabout	13	39	52	75
Uncontrolled Intersection	39	81	120	67.5
Ending Cycle Lane	4	20	24	83.3
Lane Merging	34	60	94	63.8
Total	183	231	414	**55.8**

Table 3.2: Number of observed driver-cyclist encounters and interactions in each *Traffic Scenario* (N = Number of).

	Message								
	ROW Negotiation	*C-Intentions*	*C-Awareness*	*C-Positive*	*C-Negative*	*D-Intentions*	*D-Awareness*	*D-Positive*	*D-Negative*
Controlled Intersection	6	10	16	1	2	7	2	0	0
Roundabout	13	10	14	1	0	14	7	1	1
Uncontrolled Intersection	44	6	14	27	9	15	16	7	1
Ending Cycle Lane	9	1	12	4	0	11	2	2	0
Lane Merging	0	23	41	0	0	0	2	0	0

Table 3.3: The exchanged messages in each traffic scenario. The table is populated with the number of times each message was communicated. Messages were most expressive in Uncontrolled Intersection; road users frequently negotiated the right of way and communicated positive or negative feedback. They were least expressive in Lane Merging. ROW stands for Right of Way; C-*Message* means the message is from the cyclist, and D-*Message* means the message is from the driver.

Interactions were mostly one-way at *Controlled Intersection* and *Lane Merging* compared to *Uncontrolled Intersection*; cyclists were significantly more likely to communicate their intentions and awareness at the former scenarios without receiving a response from drivers.

Driver Interaction Behaviour

This section reports how drivers interacted with cyclists. Table 3.4 shows the number of times drivers used each social and implicit cue in each *Traffic Scenario*.

Cue Categories There was a significant association between *Traffic Scenario* and *Cue Category* (χ^2(8, 179) = 58.43, $P < .001$). This means drivers did not consistently use the same types of cues across all scenarios; they were more likely to prioritise implicit cues in some scenarios and social cues in others. *Post hoc* comparisons showed that drivers were significantly less likely to use social cues when cyclists were *Lane Merging* compared to *Roundabout*, *Uncontrolled Intersection* and *Ending Bicycle Lane* ($P < .001$ for all). Drivers were more likely to use a combination of social and implicit cues at *Roundabout* and *Ending Bicycle Lane*. They mostly used social cues in *Uncontrolled Intersection*.

Social Cues There was no significant association between *Traffic Scenario* and *Social Cues* (χ^2 (9, 89) = 7.68, $P = .6$). Driver social cues did not significantly differ between scenarios.

	Social Cues					**Implicit Cues**			
	Hand Gesture	*Nodding*	*Facial Expression*	*Head Toward Cyclist*	*Vocal Expression*	*Acceleration*	*Maintain Speed*	*Deceleration*	*Stop*
Controlled Intersection	0	0	0	13	0	1	13	4	1
Roundabout	3	2	1	13	0	4	4	10	16
Uncontrolled Intersection	21	2	1	2	0	18	2	4	50
Ending Cycle Lane	4	2	0	8	0	7	7	1	10
Lane Merging	0	0	0	0	0	1	17	13	1

Table 3.4: The number of times drivers used each Social and Implicit cue in each Traffic Scenario. They were most expressive in Uncontrolled Intersection where they used hand gestures and commonly came to a complete stop to yield to cyclists. They were least expressive during Lane Merging where they rarely used social cues for interaction.

Implicit cues There was a significant association between *Traffic Scenario* and *Implicit Cues* (χ^2 (16, 184) = 113.83, $P < .001$). Therefore, drivers did not consistently use the same implicit cues between scenarios.*Post hoc* comparisons showed that drivers were significantly more likely to maintain their speed in *Controlled Intersection* than *Roundabout* ($P = .006$) and *Uncontrolled Intersection* ($P < .001$). This shows that traffic lights assured drivers of their right of way, so they did not need to change their behaviours.

Drivers also used significantly different implicit cues in *Uncontrolled Intersection* compared to *Roundabout* ($P = .002$) and the *Ending Cycle Lane* ($P = .003$). They were significantly more likely to accelerate or come to a complete stop at *Uncontrolled Intersection*. They were more likely to decelerate at *Roundabout* and maintain their speed in the *Ending Cycle Lane*. Finally, drivers were significantly less likely to come to a complete stop when cyclists performed *Lane Merging* manoeuvres compared to *Uncontrolled Intersection* and *Roundabout* ($P < .001$ for both). This is likely due to a lack of stop lines or give-way road markings during lane merging manoeuvres, which are dynamic scenarios that can occur anywhere in traffic.

On-vehicle signals There was a significant relationship between *Traffic Scenario* and *On-Vehicle Signals* (χ^2 (12,50) = 52.13, $P < .001$). Therefore, drivers used different signals, such as directional indicators or hazard lights, depending on the scenario.*Post hoc* comparisons showed that drivers were significantly less likely to use directional indicators when cyclists performed *Lane Merging* manoeuvres, compared to when encountering cyclists at *Roundabout* ($P = .003$), *Uncontrolled Intersection* ($P = .004$) and *Ending Cycle Lane* ($P = .02$). This is due to drivers navigating a straight road during lane merging manoeuvres, so they did not need to indicate a change in direction.

Cyclist Interaction Behaviours

This section reports how cyclists interacted with drivers. Table 3.5 shows the number of times cyclists used each social and implicit cue in each *Traffic Scenario*.

	Social Cues					Implicit Cues			
	Hand Gesture	*Nodding*	*Facial Expression*	*Head Toward Driver*	*Vocal Expression*	*Acceleration*	*Maintain Speed*	*Deceleration*	*Stop*
Controlled Intersection	11	0	1	13	1	4	2	4	6
Roundabout	10	3	2	24	1	13	15	4	4
Uncontrolled Intersection	29	13	7	31	5	28	18	5	23
Ending Cycle Lane	6	1	0	17	0	5	1	5	14
Lane Merging	21	0	0	45	0	9	10	11	2

Table 3.5: The number of times cyclists used each Social and Implicit cue in each Traffic Scenario. Cyclists frequently used social cues when Lane Merging to communicate their awareness and intentions to drivers. They commonly accelerated or maintained their speed at Uncontrolled Intersection to assert their right of way.

Cue Categories There was a significant association between *Traffic Scenario* and *Cue Category* (χ^2(8, 228)=36.04, $P < .001$). Therefore, cyclists were more likely to use implicit cues in some scenarios but social cues in others. *Post hoc* comparisons showed that cyclists were significantly less likely to use implicit cues in *Controlled Intersection* compared to *Roundabout* ($P = .005$) and *Ending Cycle Lane* ($P = .009$), where they were significantly more likely to use a combination of both cues. This is likely because drivers maintained their speed in the controlled intersection as the right of way was clear. Responding through implicit cues would be risky for cyclists, so they communicated with drivers explicitly to avoid their signals being misinterpreted. In contrast, the roundabout and ending cycle lane welcome negotiation as they feature give-way lines.

The cue categories used during *Lane Merging* were also significantly different to those used in *Controlled Intersection* ($P = .02$), *Roundabout* ($P = .01$), *Uncontrolled Intersection* ($P = .005$) and *Ending Cycle Lane* ($P = .009$). Cyclists were more likely to only use social cues during the lane merging scenario. This is because both road users were moving during lane merging; riders had to clearly communicate their intentions and inform drivers to slow down without making risky manoeuvres through implicit communication. The other scenarios were likely to have one of the road users in a stationary position, so there was more room for cyclists to speed up to assert their right of way or slow down to yield.

Social cues There was a significant association between *Traffic Scenario* and *Social Cues* (χ^2 $(16, 241)$ = 38.38, $P = .001$). Cyclists' choice of social cues differed between scenarios. *Post hoc* comparisons showed significant differences between *Uncontrolled Intersection* and *Lane Merging* ($P < .001$). Cyclists were more likely to use multiple social cues, including hand gestures and facial and vocal expressions, to negotiate their right of way at the uncontrolled intersection. They mostly used hand gestures and turned their heads toward the driver when lane merging. This is because one of the road users was likely stationary at the uncontrolled intersection, so there was more room for expressive right-of-way negotiation. They were both moving during lane merging, so interactions were more brief.

Implicit cues There was a significant association between *Traffic Scenario* and *Implicit Cues* (χ^2 $(12, 183)$ = 42.27, $P < .001$). This means cyclists used different implicit cues between scenarios. *Post hoc* comparisons showed that cyclists were significantly more likely to come to a complete stop at the *Ending Cycle Lane* compared to at *Roundabout* ($P = .02$), where they were more likely to accelerate or maintain their speed. This may be due to the roundabout having clearer road rules than the ending cycle lane, which was more abrupt for riders, forcing them to yield and maintain their safety. Similarly, cyclists were significantly less likely to come to a complete stop when *Lane Merging* than *Uncontrolled Intersection* ($P = .004$) and *Ending Cycle Lane* ($P = .03$). This is because lane merging is a dynamic manoeuvre, where interaction happens with both road users moving, so there is little room for stopping.

3.2.6 Discussion

This study contributed to interface acceptability by demonstrating the messages and cues that would help interfaces maintain familiarity and impose a minimal learning curve for AV-cyclist interaction. The study further contributes to acceptability by illustrating that driver-cyclist interaction is two-way. AVs should not only communicate intentions to cyclists but also recognise their cues and negotiate the right of way when necessary to maintain clear communication. The observations also confirmed that versatility is a key design challenge for AV-cyclist interfaces, showing that drivers and cyclists interact differently between scenarios.

Interaction Across Traffic Scenarios

The likelihood and complexity of interactions were significantly reduced at the controlled intersection, where traffic lights were used to determine the right of way. Traffic lights are enforced by law [128], but this still shows that cyclists could interpret light-based or colour-coded signals from AV-cyclist interfaces. For example, many AV-pedestrian eHMIs use light-based signals on the AV [37], and cyclists may also be able to process these if adjusted to their requirements. Traffic lights did not completely rule out the chance for interaction. Cyclists still used arm gestures to signal their intentions to turn once a light turned green and turned their heads to a driver to confirm awareness. However, drivers rarely responded through social cues and mostly maintained their right-of-way as determined by traffic lights. This poses the question of how AVs should behave in such situations and whether they should replicate human drivers or respond to cyclists. AV driving behaviours should ensure predictability for cyclists [82], and providing an explicit response to cyclists' social signals through an interface may improve future road interactions at controlled intersections. This motivated further exploration of controlled intersections in upcoming thesis chapters.

Roundabouts are stationary infrastructure with give-way lines to help determine right-of-way and encourage approaching road users to decelerate or stop [128]. The UK Highway Code recommends drivers use direction indicators to communicate their intentions at roundabouts [128]. This was also observed in this study and resulted in different interaction behaviours from the ones at the uncontrolled intersection. Drivers communicated their awareness through head movements toward the cyclist and intentions through on-vehicle signals. Cyclists often communicated their intentions through arm gestures, suggesting that right-of-way negotiations were more straightforward than at uncontrolled intersections, which involved many different social and implicit cue combinations. Interactions at the roundabout also resulted in less drastic speed changes from cyclists, who were most likely to maintain their speed or accelerate. Roundabouts have more traffic control than uncontrolled intersections [128], and road markings were present at all four corners. This suggests that the level of traffic control is correlated with the expressiveness of AV-cyclist interaction at traffic infrastructure. It highlights the challenge of AV-cyclist interface versatility and points to whether AVs should communicate the same signals between scenarios or specific ones depending on where the interaction occurs to be acceptable for cyclists.

Ultimately, interactions at the roundabout showed that intentions and awareness are key messages exchanged during interaction [82]. This aligns with prior work with pedestrians, showing these messages to be essential for communication at crossings [38, 83]. AVs can already partly communicate their intentions through direction indicators at roundabouts. It may be more challenging to compensate for the loss of eye contact and communication of awareness [80]. It is also unknown how communicating intentions and awareness across other scenarios would help cyclists navigate traffic. For example, the ending cycle lane was clearly challenging, and drivers rarely communicated these messages there. Therefore, AVs may improve interactions in these settings by reusing the messages communicated to resolve space-sharing conflicts at roundabouts.

Interactions were similar between the uncontrolled intersection and the ending cycle lane. Drivers and cyclists had to negotiate their right of way using various social and implicit cues, and one of the road users was likely stationary behind a giveaway line. This aligns with prior work prioritising uncontrolled intersections for AV-cyclist interface design due to the urgency to facilitate interaction in these settings [88, 140]. However, the findings from this study show that while uncontrolled intersections are key areas for interaction, there are other scenarios to consider, and it is insufficient for an interface to solely operate in a single scenario. This emphasises that versatility goes hand-in-hand with acceptability.

There were more drastic speed changes in the ending cycle lane, with road users accelerating or coming to a complete stop. This suggests that the road users were unsure how to proceed, and this aligns with the findings of the online survey, which shows the scenario as very challenging. Similarly, Ryerson et al. [111] identified ending cycle lanes as interaction triggers. This is attributed to its more abrupt nature and is less common than uncontrolled intersections, so neither drivers nor cyclists are particularly accustomed to it. The ending cycle lane scenario is specific for cyclists but is rarely explored in the AV-cyclist interaction domain. Previous work has recommended cycle lanes as a potential solution to segregate cyclists from motorised vehicles and prevent space-sharing conflicts [18]. However, this scenario shows that this is not practical for all parts of the journey. It motivated the remainder of the thesis to investigate clear AV-cyclist interaction further and ensure that vehicles can assist cyclists in transitioning from segregated to mixed traffic.

Similar to uncontrolled intersections, lane merging is a popular scenario in the AV-cyclist interaction domain [67]. The online survey showed it to be challenging with human drivers, and Hou et al. [67] showed that riders preferred having an interface when lane merging around AVs. This study explored lane merging in detail to understand the types of messages AVs should exchange with cyclists in these encounters. Cyclists used arm gestures and shoulder checks to communicate their intentions and awareness to drivers in this scenario. However, these interactions were brief and fast-paced, as both road users moved at higher speeds than in the other scenarios. Drivers did not respond to them through social cues. This suggests that even though cyclists prefer having an interface in lane merging scenarios [67], they may not be essential and could be optional, similar to how rearview radars are used today to warn cyclists of approaching AVs from behind.

Designers could still develop and assess interfaces that explicitly respond to cyclists' messages when lane merging. However, they should avoid overwhelming cyclists accustomed to brief, fast-paced interactions during this scenario. Some observations featured drivers flashing their headlights or using hazard lights to respond to cyclists. It remains unclear whether responding to lane merging cyclists should be through AV-cyclist interfaces or traditional vehicle signals. The emphasis on cyclists' social cues, including hand gestures and shoulder checks, shows that AVs must detect social cues rather than just the overall presence of cyclists. More advanced sensing is required, as these social cues are subtle [119].

Overall Contributions of the Study

This study showed the range of messages exchanged by drivers and cyclists. The findings inform the design of acceptable AV-cyclist interfaces that recognise cues from cyclists and respond appropriately, with minimal changes to the current cycling setup. Having AVs communicate similar messages to human drivers could simplify their integration into mixed traffic, as they will impose a minimal transition from current social norms. It remains unclear whether AVs should mimic cues from human drivers. Pokorny et al. [101] and Pelikan's [97] observations of real AV-cyclist encounters showed that AVs should mimic human drivers for implicit communication to be more predictable. However, there was no clear understanding of how human drivers implicitly communicate with cyclists, particularly across different traffic scenarios, and this study filled the research gap. For example, AVs should decelerate when they intend to yield during lane merging manoeuvres or accelerate to preserve their right of way at uncontrolled intersections. The study also identified the social cues that drivers use. AVs do not necessarily need to mimic these to present messages. For example, eHMIs do not need to be waving hands to mimic hand gestures [80]. However, they should communicate appropriate messages in a manner that is clear and predictable for cyclists. This could be done through new types of signals, such as lights or projections from the vehicle, which were found to be acceptable for pedestrians [37].

This study identified how interactions currently happen but did not directly inform how these messages should be presented in future interactions, including the optimal placements for AV-cyclist interfaces. The next study measures cyclist gaze behaviour when encountering drivers to consider these details and inform the design of acceptable interfaces.

3.3 Study 3: Eye-Tracking in Real Traffic

The observations provided insights into the types of messages and cues that AVs should recognise from cyclists and display in response. However, they did not inform the design of AV-cyclist interfaces, such as the placements they should use. Therefore, this study investigated the nuances of driver-cyclist interaction to inform the design of acceptable AV-cyclist interfaces that adhere to the natural behaviours of cyclists. Commuter cyclists were instrumented with eye-tracking glasses and tasked with recording two home-office commutes using their regular routes. This identified areas on which cyclists naturally focus, allowing for the placement of interfaces that do not disrupt reflexive cycling behaviours. This would significantly enhance interface acceptability.

3.3.1 Study Design

This was a naturalistic cycling study with *Traffic Scenario* as an independent variable and cyclist *Gaze Behaviour* as a dependent variable. Participants were instrumented with eye-tracking glasses and a bike computer to record their commutes in real traffic.

Study setup

Participants recorded two cycling commutes, one from their office to their home and the other on their journey back. The study did not include a predefined route, so participants took their usual commuting routes. Participants were asked to behave as they normally would, preserving ecological validity. All recordings were in the city of Glasgow, UK. Participants disclosed their usual commuting routes prior to taking part. Routes were at least 5 kilometres long and included a minimum of three types of road infrastructure, such as controlled intersections or roundabouts. This was to increase the likelihood of driver-cyclist encounters across multiple traffic scenarios. It also helped identify spontaneous and dynamic scenarios that may not have appeared if the route was predefined [1], such as being overtaken by a vehicle. This was critical for informing

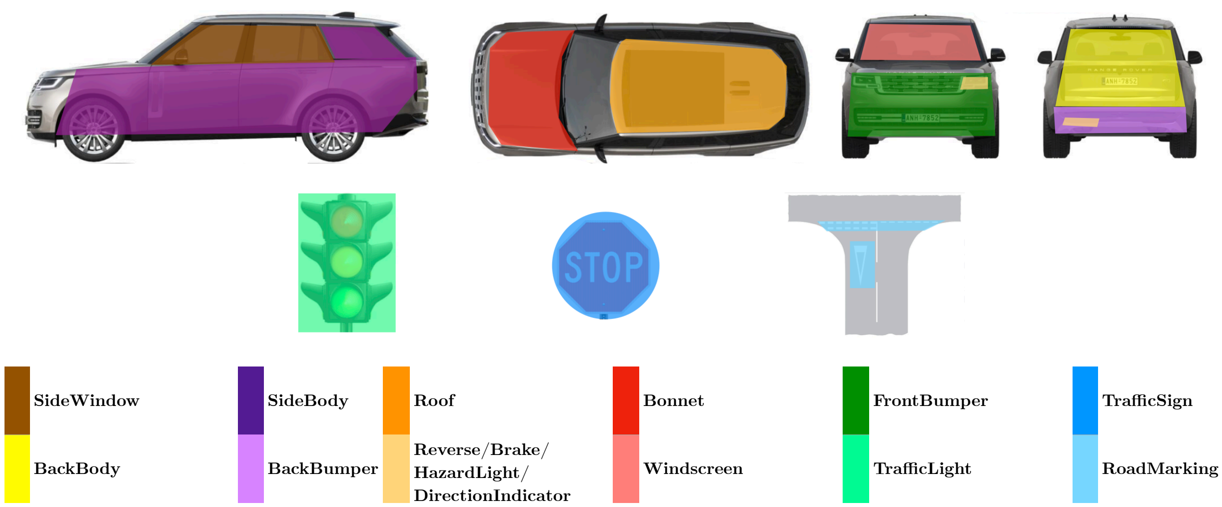

Figure 3.6: The defined Areas of Interest (AOIs) to map cyclist gaze fixations. These were different vehicle features (overlaying the vehicle on the top row), and traffic control features (overlaying the features on the bottom row).

follow-up studies investigating versatility, as any traffic scenarios to test interfaces would be derived from real cycling commutes.

Study scope

The study focused on identifying where participants look when encountering drivers across different *Traffic Scenarios*. This would show the features (e.g., traffic lights, social cues or implicit cues) that cyclists rely on to navigate space-sharing conflicts in each scenario. This approach is critical to place AV-cyclist interfaces in areas that do not disrupt the reflexive behaviours of cyclists [49]. Therefore, traffic scenarios involving a driver-cyclist encounter were labelled in the collected data. Participant gaze fixations in each scenario were then mapped to Areas of Interest (AOIs) on vehicle and traffic control features; AOIs are shown in Figure 3.6.

The vehicle AOIs were adapted from Dey et al.'s [48] study with pedestrians but extended to a 3D vehicle model to include the sides and rear of vehicles, not just the front. This was crucial as the study was conducted in the wild, and cyclists could be anywhere around a vehicle. Traffic control AOIs were derived from the UK Highway Code [128]. This included traffic lights, road works signs, signs giving orders (e.g. stop signs), across-the-carriageway road markings (e.g. stop lines) and warning road markings (e.g., 'give way ahead' markings). It was important to map participant fixations on traffic control AOIs to understand how much cyclists rely on traffic control versus social interaction in each traffic scenario. It would also show the differences in what cyclists rely on between highly controlled traffic scenarios and those without any traffic control.

Measures

The study collected the following data from each commute for analysis:

- **Route GPS data:** to visualise the route taken on the day, as participants may have taken detours due to road repairs or other factors;
- **First-person video footage:** of cyclists riding in real traffic to classify the type of traffic scenario and whether there was an encounter with a driver;
- **Cyclist gaze fixations:** throughout the commute as logged by the eye-tracker.

3.3.2 Apparatus

Participants used RideWithGPS[4] to plot and disclose their cycling routes prior to taking part. They were instrumented with a Tobii Pro Glasses 2[5] eye-tracker to record gaze fixations and video footage at a frame rate of 100 Hz with a resolution of 1920 × 1080 pixels. These glasses are portable and easy to calibrate [111]. They feature a separate recording unit attached to the glasses by a cable, so the glasses are light and comfortable to wear while cycling. Participants were also equipped with a Dell XPS 13 9300 laptop running Tobii Pro Glasses Controller[6] software. The software was necessary to calibrate the eye-tracker and manage the start and end of each recording session.

They were also given a Garmin Edge 530 bike computer, which collected GPS data to visualise and confirm their routes on the day of the recording. Each participant used their own bicycle for the study. They were provided a bicycle helmet and front/rear lights for safety if they did not already have them. Additionally, all participants received a copy of the UK Highway Code's rules for cyclists [128] to familiarise themselves with relevant guidelines. Figure 3.7 illustrates an instrumented commuter cyclist.

3.3.3 Participants

The study involved 12 commuter cyclists recruited through the University's internal social networking platform. They were all affiliated with the University for ease of communication, primarily due to the requirement of handling expensive hardware.

All participants had been cycling to work multiple days a week for at least six months. Their demographics were: $M_{\text{age}} = 32.5$, $SD = 9.1$; $Male = 8$, $Female = 4$. All had normal to corrected vision. None wore eyeglasses during the study. One participant wore contact lenses.

[4]Ride With GPS: `ridewithgps.com` ; Accessed 01/04/2025
[5]Tobii Pro Glasses 2: `shorturl.at/PD6xH` ; Accessed 01/04/2025
[6]Tobii Pro Glasses Controller Software: `shorturl.at/IFXO1` ; Accessed 01/04/2025

Figure 3.7: An instrumented cyclist. They were given Tobii Pro Glasses 2 eye-tracking glasses, which also featured a recording unit connected via cable. Cyclists also had a bike computer to log their commutes.

3.3.4 Procedure

Each participant signed up for the experiment through an online survey, which also featured the study information sheet and consent form; all initial/demographics surveys in this thesis' studies had an information sheet and consent form, and examples of these are in Appendix A. Participants provided their demographics, cycling experience, and cycling routes. An experimenter reviewed each submitted route to ensure it met the predefined requirements. Participants who met the study requirements scheduled a briefing session where they were trained to use the eye tracker and its associated software. During the session, the participant was shown sample footage from a pilot study to familiarise them with the data being collected. The footage showed a video of a cyclist's point of view (POV) in real traffic overlaid with a red dot representing the cyclist's gaze fixation; see Figure 3.8.

The participant was also instructed on operating the bike computer and was asked to press the *lap* button whenever they encountered an event they perceived relevant to the study. This recorded a timestamp in the event log file so researchers could easily locate and analyse these events later. The participant could ask questions during the briefing session. Following this, they were given the necessary equipment for data collection and tasked with recording two commutes: one from their workplace to their residence and another on the return journey. Each participant kept the equipment overnight and returned it after completing their commute the following day. They were compensated with a £10 Amazon voucher for their time.

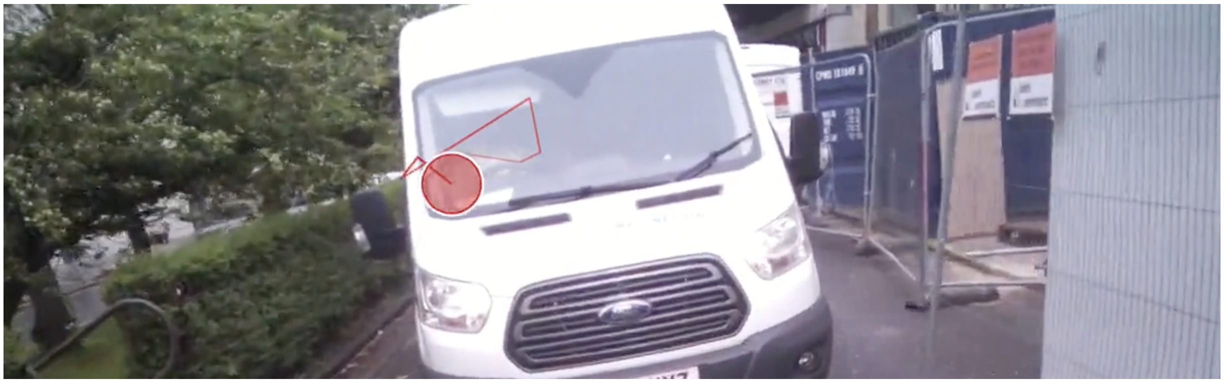

Figure 3.8: An example frame from the video shown to participants during the briefing session. It shows the cyclist's gaze fixation (red dot) in a bottleneck scenario, a narrow lane with the driver and cyclist moving toward each other.

3.3.5 Data Validation and Pre-Processing

In total, 24 video clips were collected. These had a total duration of 8 hours, 50 minutes and 25 seconds. The analysis required researchers to label any *Traffic Scenarios* that featured driver-cyclist encounters and map participant *gaze fixations* to any AOIs that appeared in each scenario. Tobii Pro Lab was used for the analysis. There was no predetermined list of scenarios to label; the only requirement was that the scenario features a potential driver-cyclist space-sharing conflict, regardless of whether there was an interaction.

Traffic Scenario Labelling in Tobii Pro Lab

The analysis was conducted by three researchers working independently to eliminate bias; These were the thesis author and two post-doctoral researchers who have published more than two research papers in HCI. All qualitative analysis in the thesis involved the thesis author and at least one post-doctoral researcher in HCI. First, one researcher ensured that all data were collected appropriately, i.e. the hardware recorded the entire commute. The researcher also checked the bike computer route to see if there were any changes to the RideWithGPS one, e.g., due to road works. After confirming the route and data quality, they played the video footage overlaid with gaze samples to familiarise themselves with the trip. The researcher then replayed the footage to label scenarios with potential space-sharing conflicts.

Scenario labels were in the form of *Times of Interest (TOI)*. This is a Tobii Pro Lab feature that allows researchers to specify a *time range* starting at the first video frame where a scenario appears in a participant's field of view and ending at the first frame where the scenario is no longer visible. The researcher labelled all 24 videos, resulting in 171 *Traffic Scenarios*. Another researcher labelled 6 videos chosen at random. Comparing the results showed no discrepancies. A third researcher labelled 3 of the 6 videos selected randomly. Comparing their results again showed no discrepancies.

Figure 3.9: A screenshot form the Tobii Pro Lab AOI tool; AOI shapes are placed on relevant areas, and dragged accordingly frame-by-frame.

AOI Mapping in Tobii Pro Lab

The three researchers then labelled the AOIs within each traffic scenario TOI. They used Tobii Pro Lab's *AOI tool*, referencing Figure 3.6 as their guide. AOIs were labelled manually frame-by-frame. This involved dragging *"AOI shapes"* to the associated area in the video frame; see Figure 3.9. Similar to the previous step, one researcher labelled AOIs within all traffic scenarios for all 24 videos. A second researcher labelled AOIs for 6 videos selected at random and found no discrepancies. A third researcher labelled AOIs for 3 of the 6 videos selected randomly and also found no discrepancies. Tobii Pro Lab automatically calculates the number of gaze fixations on each AOI within each TOI (traffic scenario). This allowed for further analysis of cyclist gaze behaviours between traffic scenarios.

Extracting Cyclist Gaze Visits

A *visit* is defined as: *"The period of time when a participant first focuses on a region until they look away from that region. A visit consists of one or more fixations"* [127]. Participant *visit counts* for each AOI in each scenario were exported as a CSV file from Tobii Pro Lab. The study analysed the number of times an AOI appeared in a cyclist's field of view, regardless of whether the participant fixated on it, and the number of visits a participant made to an AOI (visit count). This indicated how much cyclists prioritised each AOI relative to the others, which would quantify its appropriateness as a placement for AV-cyclist interfaces. It also allowed a comparison of AOI appearance between scenarios. This is especially important since cyclists may be exposed to different vehicle sides depending on the scenario, so placing an interface on an AOI that does not commonly appear between scenarios may not be appropriate.

Traffic Scenario	*N*	**AOI Distribution (%)**														
		Side Window	Side Body	Roof	Bonnet	Windscreen	Front Bumper	Back Body	Back Bumper	Direction Indicator	Hazard Light	Brake Light	Reverse Light	Traffic Light	Traffic Sign	Road Marking
Controlled Intersection	48	13.3	13.3	10	9.2	8.8	10.4	4.6	5	2.1	N/A	2.9	N/A	13.3	N/A	7.1
Controlled Crossing	19	15.9	15.9	7.9	15.9	12.7	12.7	3.2	3.2	1.6	N/A	N/A	N/A	9.5	N/A	1.6
Road Works	7	9.1	18.2	N/A	9.1	N/A	9.1	N/A	N/A	N/A	N/A	N/A	N/A	27.3	27.3	N/A
Uncontrolled Intersection	48	15.3	15.8	11.7	11.7	9.9	12.6	3.6	4.5	3.2	N/A	1.4	N/A	N/A	1.4	9
Roundabout	10	13.3	15.6	4.4	11.1	11.1	13.3	4.4	2.2	2.2	N/A	N/A	N/A	N/A	11.1	11.1
Cycle Lane into Traffic	2	14.3	14.3	7.1	14.3	14.3	14.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7.1	14.3
Lane Merging (Cyclist)	5	14.3	14.3	4.8	9.5	4.8	4.8	9.5	14.3	NA	4.8	4.8	N/A	N/A	4.8	9.5
Overtaking (Driver)	18	19.2	20.5	11.5	5.1	1.3	7.7	16.7	15.4	N/A	N/A	2.6	N/A	N/A	N/A	N/A
Parking Manoeuvre	9	18.6	18.6	14	2.3	2.3	2.3	14	14	2.3	N/A	2.3	9.3	N/A	N/A	N/A
Bottleneck	7	9.1	15.2	12.1	18.2	18.2	15.2	3	3	N/A	3	N/A	3	N/A	N/A	N/A
Total	171	14.8	15.6	10.1	10.3	8.7	6.1	5.8	6.1	1.9	0.3	1.8	0.7	5.3	1.7	6.1

Table 3.6: Labelled Traffic Scenarios and the proportion of AOIs within them. *N* = Frequency of Scenario Appearance, N/A= AOI did not appear in cyclists' field of view. Bottlenecks happen when the driver and cyclist move in the same lane in opposite directions.

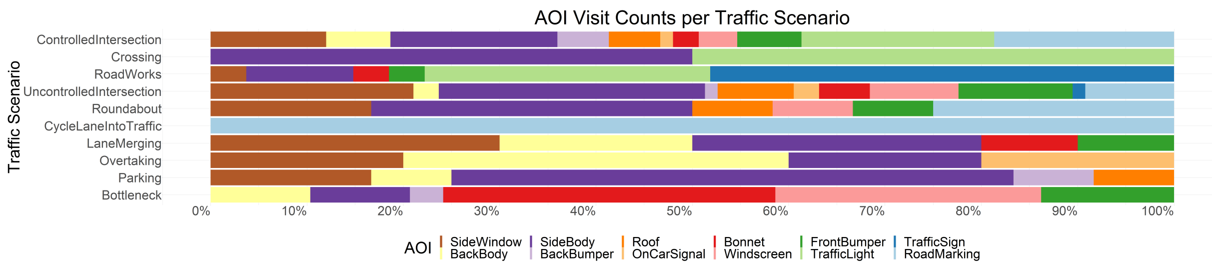

Figure 3.10: AOI visit distributions (%) in each scenario. Refer to Table 3.6 for the frequency of each scenario and the AOIs that appeared in them.

3.3.6 Results

A total of 10 types of *Traffic Scenario* were identified from cyclist commutes. Table 3.6 reports the frequency of each scenario's appearance in the collected footage, which may indicate its likelihood of occurring in traffic. Table 3.6 also presents the frequency of AOI appearances within each scenario to highlight differences in traffic control and vehicle areas visible to cyclists. Figure 3.10 shows the distribution of visits to these AOIs in each traffic scenario; this illustrates how cyclist gaze behaviours differ between scenarios. For simplicity in visualisations and data analysis, *direction indicators*, *hazard lights*, *brake lights*, and *reverse lights* were grouped into a single category: *On-vehicle signals*.

Overall Trends in Gaze Behaviour

This section uses descriptive statistics to provide an overview of how cyclist *Gaze Behaviour* differed between *Traffic Scenarios*. It shows that gaze behaviour was influenced by the availability of traffic control in traffic scenarios. Participants were less likely to look at the windscreen and other vehicle areas where the driver is visible when traffic lights are present. This suggests a lesser need for interaction in scenarios with high traffic control. The vehicle's position relative to the cyclist also influenced gaze behaviours. This has implications for interface acceptability and versatility, as AV-cyclist interfaces must be perceivable in all scenarios for cyclists to receive AV signals consistently. Figure 3.11 shows a heat map of cyclist visits on the AOIs in each traffic scenario.

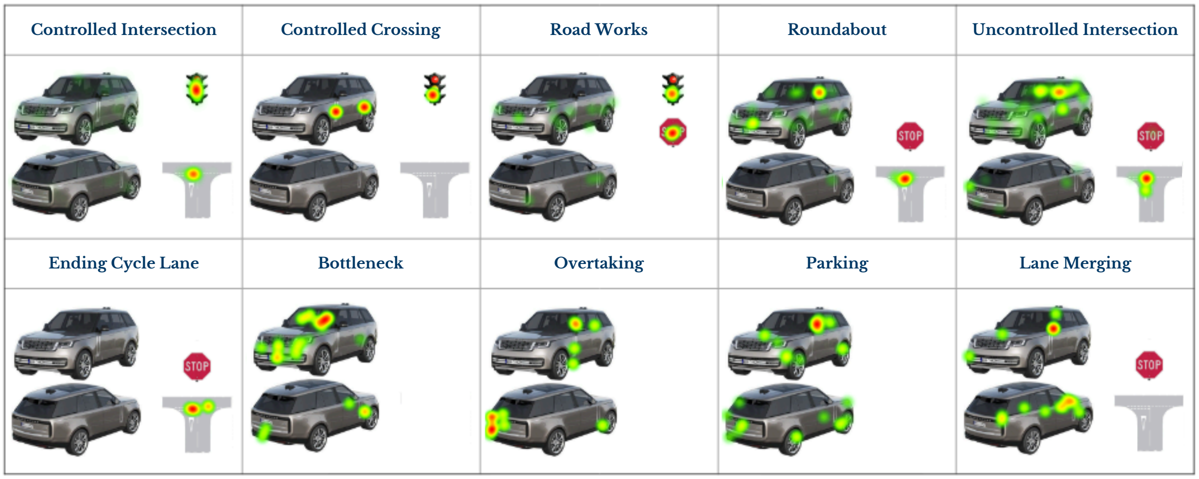

Figure 3.11: Heatmaps of cyclist visits on the AOIs in each Traffic Scenario. Green represents less frequent visits, and red most frequent. Cyclists mostly visited traffic lights when they were present. Visits were spread across the vehicle at roundabouts and uncontrolled intersections. Cyclists focused on specific vehicle areas in scenarios with no traffic control, such as bottlenecks.

Traffic Control and Gaze Behaviour Road users often visit windscreens or windows with the expectation of social interaction with the driver [48]. These AOIs were primarily visited in scenarios without traffic lights, such as *Bottleneck* (27.6%) and *Roundabout* (24.9%). In contrast, only 13.7% of visits in *Controlled Intersection* were to windscreens or windows, despite a minimal 2.3% difference in their appearance between *Controlled Intersection* and *Roundabout*.

Road markings were the most commonly visited traffic control; 25% of visits in *Roundabout* and 16% in *Controlled Intersection*. Cyclist gaze behaviour was also influenced by traffic lights, which accounted for 17.2% of visits in *Controlled Intersection* and 29.6% in *Road Works*. However, in *Road Works*, cyclists visited traffic signs (48.1%) more frequently than traffic lights.

Vehicle Position and Gaze Behaviour Cyclist gaze patterns showed variation depending on the vehicle's relative position during their commutes; different vehicle sides were visited across scenarios. For instance, 27.6% of visits in *Uncontrolled Intersection* and 58.3% in *Parking* manoeuvres were directed to vehicle side bodies, while 40% of visits in *Overtaking* manoeuvres were to the back bodies.

The front of the vehicle was most frequently visited during *Bottleneck*, where the bonnet accounted for 34.5% of visits. Although on-vehicle signals represented the smallest AOI, cyclists still fixated on them across multiple scenarios, including 2.6% of visits in *Uncontrolled Intersection*, 1.1% in *Controlled Intersection*, and 20% in *Overtaking* manoeuvres. These findings suggest that cyclists may be positioned anywhere around a vehicle. Consequently, placing displays only on the vehicle's front, as seen with pedestrian interfaces [37], is insufficient. These must also be visible from the vehicle's side or back.

Further Insights into Gaze Behaviour

This section conducts statistical tests to gain more detailed insights into the differences in cyclist gaze behaviours between traffic scenarios. Traffic scenarios were grouped into three *traffic scenario categories* to compare gaze behaviour between scenarios with similar traffic control features rather than between vastly different scenarios where differences in gaze behaviours are expected. The categories are based on the type of traffic control in these scenarios (traffic lights, road markings or no traffic control) because Table 3.6 shows that scenarios have different AOI distributions, and traffic control is a particularly distinctive feature that influenced cyclist gaze behaviour; for example, cyclists visited traffic lights more often than vehicle features when they were present. The traffic scenario categories were as follows:

1. **Controlled Scenarios:** These have high traffic control through traffic lights. This included *Controlled Intersection*, *Controlled Crossing* and *Road Works*.

2. **Uncontrolled Infrastructure:** These are physical traffic infrastructure with road markings for traffic control, but no traffic lights. This included *Uncontrolled Intersection*, *Roundabout* and *Ending Cycle Lane*.

3. **Dynamic Manoeuvres:** These scenarios lack formal traffic control and may occur anywhere on the road. This included *Bottleneck*, *Lane Merging*, *Parking* and *Overtaking*.

A Chi-Square test of independence was conducted to investigate the relationship between *Traffic Scenario* and *AOI Visit Count* within each traffic scenario category. *Post hoc* tests were performed using Chi-Square tests of independence with a Bonferroni correction.

Controlled Scenarios There was a significant association between *Traffic Scenario* and *Visit Count* (χ^2(22, 104) = 54.55, $P < .001$). This means participants did not look at the same AOIs in scenarios that share traffic lights as a common feature. *Post hoc* comparisons showed significant differences in gaze behaviour between *Controlled Intersection* and *Road Works* ($P < .001$). Cyclists were more likely to visit vehicle features in controlled intersections than in road works, where they mostly visited traffic control AOIs. This may be due to road works being more spontaneous and less familiar during daily commutes.

Uncontrolled Infrastructure No statistically significant association was found between *Traffic Scenario* and *Visit Count* (χ^2(20, 90)=17.2, $P = .6$). The gaze behaviour of participants was similar in these scenarios. They mostly visited road markings to infer the right of way, vehicle bumpers and side bodies to deduce driver intentions through implicit cues, and vehicle windscreens and windows for social interactions in these scenarios.

Dynamic Manoeuvres There was a significant association between *Traffic Scenario* and *Visit Count* (χ^2(24, 56)=50.49, P = .001). Participants looked at different AOIs between scenarios without formal traffic control. *Post hoc* comparisons showed significant differences between *Bottleneck* and *Parking* (P = .005). Cyclists were more likely to visit the vehicle's windscreen and front (e.g. bonnet and front bumper) in bottleneck scenarios, but the side and back of the vehicle in parking manoeuvres. This shows that cyclists may be anywhere around a vehicle during an interaction, influencing their behaviours.

3.3.7 Discussion

This study provided a first-person perspective of cycling in mixed traffic. It showed how cyclists' gaze behaviour changes when encountering drivers across traffic scenarios. This has direct implications for acceptable AV-cyclist interface design. The study found that traffic control and vehicle position are two primary factors that impact gaze behaviour. These are discussed below.

Traffic Control

This study was instrumental in deriving the setups of different scenarios from real traffic. This is crucial for informing studies on AV-cyclist interface versatility in the upcoming thesis chapter. Road markings were found to be a shared feature between controlled intersections and scenarios in the uncontrolled infrastructure category. Participants also frequently visited road markings. This may be due to them being directly in their line of sight and more comfortable to see, meaning they did not need to lift their heads or make uncomfortable movements to see the road markings. This finding is similar to Trefzger et al.'s [126], who found that cyclists focus more on their path ahead than the surrounding environment. This shows that cyclists may respond well to AV-cyclist interfaces placed beyond the vehicle. The road could be an acceptable placement. This is similar to Hou et al.'s [67] finding with cyclists reacting positively to road projections from the vehicle when lane merging. This study shows that road projections could also be effective in other scenarios, such as uncontrolled intersections and roundabouts, where the cyclist or AV is likely stationary and the AV is in the cyclist's view.

As in the previous study, traffic lights influenced cyclist behaviours in controlled scenarios. Cyclists had reduced visits to vehicle AOIs when traffic lights were present. AV-cyclist interfaces may be less needed here, and interface designers could focus on scenarios with more complex interactions if AVs adhere to traffic rules and drive predictably. Cyclists' reliance on traffic lights suggests they may find on-environment interfaces acceptable. Previous research found that LED lights on the other end of a crossing were useful for communicating an approaching AV's intentions to pedestrians [80], providing a potential common ground with cyclists. The effect of participants visiting traffic control features more than vehicle ones was more prominent in road works than in controlled intersections. This may be due to road works being "dynamic intersections" [6], meaning they are temporary and may be unexpected for cyclists. However, they still use components commonly seen in more controlled infrastructure, such as traffic signs. As a result, cyclists may need additional support from traffic control to navigate road works because they are less accustomed to them in their commuting routes.

Unlike permanent traffic infrastructure, road works do not feature road markings. AVs could use road projections to communicate with cyclists at road works to make interactions more familiar. Road works may also be challenging for AVs to navigate, as prior work showed that they may not be in the map database due to their dynamic nature [6]. These factors make road works a crucial scenario to explore, and this study showed the available AOIs and setups that would allow accurate recreations of this scenario in follow-up studies in the thesis. Interestingly, traffic signs were visited more frequently than traffic lights at road works. This suggests that cyclists put greater effort into processing the content of traffic signs. This could be due to traffic lights being more abstract, featuring a minimal, light-based design. AV-cyclist interfaces could be more acceptable if they use a similar approach to traffic lights, utilising minimal displays instead of complex visual signals, such as text or icons.

Vehicle features

eHMIs were shown to be the optimal solution for AV-pedestrian interaction [37]. This study suggested that they are also suitable for cyclists. The online survey found that cyclists prefer interfaces on the AV or environment to maintain the current cycling setup instead of being compelled to carry additional devices. This study and the observations demonstrated that cyclists encounter vehicles in highly diverse traffic scenarios, including dynamic manoeuvres, which can occur anywhere on the road. Placing static interfaces on the surrounding environment may not be feasible to facilitate interaction in dynamic manoeuvres. Moreover, participants frequently visited different vehicle areas throughout their commutes. This shows that eHMIs could offer a versatile and acceptable solution, as these interfaces are placed on the AV itself.

This study's findings directly inform the design of AV-cyclist eHMIs, demonstrating that real-world studies are essential for developing acceptable interfaces that adhere to the natural and reflexive behaviours of road users [49]. The study showed that cyclists may be anywhere around a vehicle during interaction. Therefore, eHMI signals must be perceivable from around the AV, and placing the eHMI on a single part of the AV could result in ambiguities due to cyclists not receiving the AV's messages. This means that eHMIs for pedestrians may not generalise to cyclists, as they are commonly placed on the vehicle's front [37]. Moreover, cyclists were most frequently exposed to and visited the vehicle's side body, its largest surface. This gives interface designers ample space to develop comprehensive displays.

Data from dynamic manoeuvres showed that the vehicle and cyclist could both be moving during the interaction. This affected cyclist gaze behaviours, as participants prioritised certain AOIs in these situations. For example, participants dedicated 27.6% of their visits to the windscreen at bottlenecks; cyclists did not have much time to visit many different features to decide on their next manoeuvre. This contrasts with their behaviours in uncontrolled infrastructure, where one of the road users is stationary, and cyclists visit a more diverse set of AOIs to form a decision. AV-cyclist interface designers should consider that the time allocated for interaction is inconsistent, and interfaces must work effectively regardless of the available time. More complex eHMIs with multiple components on the vehicle could accommodate interactions at dynamic manoeuvres by only having a specific component working at a time. Designers can refer to this study's findings to understand which components should be active in a scenario.

The previous study showed that on-vehicle signals were key to resolving interactions across multiple scenarios. Participants frequently visited these signals throughout their commutes, highlighting their importance. eHMIs must co-exist with directional indicators, hazard lights and other vehicle signals to be successful and acceptable. Replacing them could increase the learning curve for cyclists to interact with AVs. This motivated future studies in the thesis to investigate how eHMIs can work alongside traditional vehicle signals to facilitate interaction.

This study captured 171 driver-cyclist encounters across diverse traffic scenarios with different traffic control features. The study quantified the frequency of each scenario and the distribution of AOIs within them. This directly informed the investigation of versatility in the upcoming thesis chapter. The study was crucial for ensuring AV-cyclist interface acceptability. It showed that interfaces can be placed on areas that match cyclists' reflexive behaviours, so they do not need to significantly change their cycling behaviours to process interface signals. This would make AV-cyclist interfaces less intrusive. Ultimately, this study built on the online survey and observations to show that the AV and surrounding environment are suitable placements for AV-cyclist interfaces. Interfaces on the AV must be comprehensible from anywhere around the vehicle, and on-environment displays face the challenge of facilitating interaction across more dynamic situations that could happen anywhere on the road.

3.4 Overall Discussion and Design Guidelines

The studies in this chapter answered RQ1 *"How can insights from current driver-cyclist interaction inform the design of acceptable AV-cyclist interfaces?"*. Three studies were conducted to investigate how drivers and cyclists interact to produce generalisable requirements for acceptable AV-cyclist interfaces. Results showed that social interaction was necessary in most encounters, emphasising the need for AV-cyclist interfaces. Road users frequently used a mixture of social and implicit cues to resolve space-sharing conflicts. These cues were always aligned to communicate a message. For example, a driver would decelerate and use hand gestures to signal a cyclist to proceed. This impacts the design of acceptable AV-cyclist interfaces, as explicit and implicit signals must not contradict each other to avoid confusion. AVs must also use similar implicit cues to human drivers, and the studies in this chapter identified how these cues are used during interaction. This is an important contribution because previous work found that AVs driving differently from human drivers caused many issues when encountering cyclists [97].

This chapter also showed that drivers and cyclists commonly exchange their intentions and awareness of each other. These are two messages that AVs must communicate to ensure the acceptability of any interface. Cyclists may not have sufficient information to proceed in a space-sharing conflict otherwise. This aligns with previous work showing that intentions and awareness are key messages for other road users, including drivers and pedestrians [82]. Therefore, this may offer a promising common ground for more inclusive interfaces.

AV-cyclist interface placement is key for acceptability [16]. Participants from the online survey reported that using wearable or bike-mounted devices would significantly alter the current cycling setup and reduce the acceptability of interfaces. This aligns with Berge et al.'s[16] findings. The eye-tracking study showed that cyclists commonly look at the environment and vehicle; these may be acceptable placements as they match the natural behaviours of cyclists [49]. However, online survey participants did not know enough about AVs to form a clear consensus about their expectations of them. Therefore, it is critical to test any interfaces through practical user studies with cyclists directly interacting with AVs. The upcoming thesis chapters take this approach.

3.4.1 Design Guidelines for Acceptable AV-Cyclist Interfaces

The findings from the three studies presented in this chapter were used to develop a set of novel design guidelines (DGs) for acceptable AV–cyclist interfaces. These guidelines are grounded in the empirical evidence gathered throughout the chapter and serve as a foundation for further discussion, including how they align with or diverge from existing literature.

DG1: Driver-cyclist communication is two-way

Cyclists who participated in the online survey explained that interactions with drivers are not one-way, meaning they are not limited to drivers communicating messages to them. The observations also confirmed that cyclists share messages with drivers through cues such as facial expressions and hand gestures to negotiate the right of way and indicate their intentions to turn or merge lanes. AV-cyclist interface designers must accommodate the back-and-forth between drivers and cyclists. AVs should not only communicate messages to riders but also recognise their social and implicit cues and respond appropriately. Removing two-way communication and focusing on transmitting messages from the AV to the cyclist would cause a significant departure from today's interactions. It may also result in issues with AVs simply instructing cyclists to pass or not pass instead of communicating their intentions to cyclists and responding appropriately to cyclist manoeuvres [39]. Facilitating two-way communication does not necessarily mean that cyclists should use new devices to transmit messages to AVs. AVs must recognise any hand gestures cyclists use, similar to how drivers do. This may require more precise sensing than is common in most AVs, which currently only detect the presence of riders and not more subtle body movements [5].

DG2: Positive and negative feedback should not be overlooked

Driver-cyclist interactions typically involve exchanging messages critical to resolving space-sharing conflicts, such as the driver's intentions or awareness of the cyclist [82]. However, both the online survey and observations showed that natural interaction behaviour also featured the exchange of positive and negative feedback in which road users communicated their perceptions on the outcome of the interaction. For example, a cyclist may raise their hand to thank a driver, or a driver may verbally communicate a rude remark to confirm their inappreciation of a cyclist's manoeuvre. AV-cyclist interfaces could facilitate the exchange of feedback between AVs and cyclists to create more expressive AVs and avoid obstructing the current social paradigm in traffic. This could also be useful as a feedback system for AV manufacturers to assess a vehicle's performance from a cyclist's perspective.

DG3: Interfaces must not overwhelm cyclists

The observations highlighted the complexity of driver-cyclist interaction. The road users may use different cues to exchange a range of messages in a short time frame. For example, a driver and cyclist may establish their awareness of each other through eye contact, negotiate the right of way using facial expressions or hand gestures, and finally provide feedback by thanking each other using hand gestures. Each road user may also further communicate their intentions using implicit cues. The eye-tracking study also showed that cyclist attention may be distributed between the driver, vehicle and surrounding environment throughout this interaction. Such complexity could yield the design of overwhelming AV-cyclist interfaces that communicate multiple detailed messages concurrently. For the first time, this guideline shows how these complexities may be addressed. Designers must ensure that interfaces can effectively manage cyclist attention during interaction. They should avoid communicating unnecessary information in dynamic manoeuvres, where both road users are moving at higher speeds. Interfaces may work in sequence to avoid overwhelming cyclists. For example, an AV could communicate its awareness in a bottleneck scenario, followed by its intent to yield once the cyclist confirms the vehicle is aware of them.

DG4: Interfaces can communicate distinct messages between scenarios

Interestingly, the observations showed that drivers and cyclists exhibited different interaction behaviours between scenarios. For example, they used hand gestures to communicate their intentions at uncontrolled intersections but eye contact to communicate awareness during lane merging. This may extend to AV-cyclist interfaces; it shows that cyclists could process distinct signals between scenarios. However, this approach is not ideal. Social interaction with drivers utilises everyday social cues, as opposed to signals that are specific for communication in traffic [59, 82]. In contrast, AV-cyclist interfaces, such as LED lights on a vehicle [39], may not use signals cyclists are accustomed to in their everyday lives. Therefore, learning unique signals for each scenario would increase the learning curve for AV-cyclist interfaces. Further investigation is required to maximise the versatility of AV-cyclist interfaces and communicate consistent signals across traffic scenarios. The eye-tracking study showed that scenarios such as roundabouts and intersections had similar AOIs. This suggests that interfaces could still be placed on the same areas throughout traffic scenarios.

DG5: New interfaces must coexist with on-vehicle signals

In addition to social and implicit cues, drivers may also use on-vehicle signals during interaction, such as direction indicators or flashing headlights [82]. This was evident in the observations, where drivers used directional indicators to communicate their intended direction. Drivers may not manually activate on-vehicle signals; brake and reverse lights are automatically triggered by the vehicle. There was no prior knowledge of whether these signals have a role in helping cyclists resolve space-sharing conflicts. The eye-tracking study addressed the research gap by showing that cyclists place importance on manually and automatically activated signals; they often fixated on these throughout their commutes. AV-cyclist interfaces must accommodate these signals. They must work concurrently with them so cyclists can still receive their messages. Previous work did not consider the visibility of on-vehicle signals when designing eHMIs [37, 39]. However, this finding shows that eHMIs must use placements that do not obstruct existing vehicle signals. This could minimise the learning curve for AV-cyclist interfaces, as AVs could still use traditional vehicle signals in addition to novel interfaces [20], so cyclists do not need to rely on new signals entirely. It could also simplify the development of more effective interfaces, as designers can primarily focus on replacing lost social cues.

DG6: Interfaces must adapt to cyclist positions and speed

Dynamic manoeuvres pose a challenging use case for AV-cyclist interaction [67]. The online survey revealed that cyclists find these areas particularly challenging to navigate, and the observations emphasised that interaction is common in these scenarios. While dynamic manoeuvres were explored in previous research [12], prior work did not highlight the features that make them challenging for interaction. Video footage from the eye-tracking study demonstrated that both road users may be moving, there is no formal traffic control, and AVs may be anywhere around the cyclist. Cyclists must always receive an AV's messages to avoid ambiguity, regardless of these factors. Interface signals must correspond to the vehicle's position around the cyclist to ensure they receive them. For example, cyclists may not receive visual signals from an eHMI during a lane merging manoeuvre where the vehicle is behind them. Another type of signal, such as directional audio, may be more appropriate. Wearable interfaces, such as AR glasses, may also be useful to accommodate these varying positions. The timing of the messages is also critical. AVs must communicate messages without delay in dynamic manoeuvres, especially faster-paced ones. Overall, designers must consider the cyclist's position and interaction speed at an AV-cyclist encounter to develop fitting solutions.

DG7: Interfaces must incorporate and reflect implicit cues

The observations showed that drivers use explicit social cues to support their implicitly communicated messages, such as braking or acceleration. For example, they may decelerate at a roundabout to signal a cyclist to proceed and use hand gestures to reinforce this. Even though this was discussed in prior work [82], the eye-tracking study supports this with empirical evidence by showing that cyclists often fixated between a driver and the vehicle's bumper to confirm their intentions. AV-cyclist interfaces must accommodate the AV's implicit cues and not contradict them to avoid miscommunication. The AV's implicit cues must also be predictable for cyclists [97]. For example, if a cyclist gestures their intentions to merge lanes with an AV behind them, and the interface reflects an AV's intentions to yield, the AV should decelerate. Cyclists would receive contradictory messages if the AV accelerates and would be unsure how to resolve the space-sharing conflict.

DG8: eHMI messages should be perceivable anywhere around the vehicle

The online survey revealed that cyclists are not receptive to wearable or bike-mounted interfaces. eHMIs are promising as they require minimal changes to cycling setups. Cyclists do not need to carry any additional devices to interact with AVs and can maintain the simplicity of riding as it is today. The eye-tracking study also showed that cyclists commonly fixate on the vehicle, so eHMIs use a placement that is not distant from reflexive cycling behaviours. The primary challenge eHMIs face is that cyclists may be anywhere around a vehicle. They must be placed so that cyclists can receive their messages regardless of their location while still being restricted to the AV itself [15]. This may be overcome by using different modalities [45]. Visual signals may be easily obstructed if the AV is behind the cyclist, but audio signals may still reach cyclists in such cases. Visual signals must also be placed around the vehicle rather than on a specific side, such as its front. This differentiates the requirements for AV-cyclist eHMIs from those for pedestrians [37]. Placing a visual eHMI around the vehicle could cause ambiguity when there are multiple cyclists; cyclists may not know who the AV is addressing [47]. Therefore, only the parts of the eHMI in a cyclist's field of view should be used to avoid overwhelming cyclists and potentially communicating information to the wrong rider. This would require additional sensing from the vehicle to detect the position of nearby riders [5].

DG9: The road is a useful placement for AV-cyclist interfaces

The road offers ample space for displaying signals from the AV [37, 67]. Placing any interfaces on the road would allow AVs to communicate more comprehensive messages, such as right-of-way negotiations. This is useful in scenarios where AVs may be stationary, giving riders the time and space to read the messages. The eye-tracking study showed that road markings are a common feature of traffic infrastructure, such as controlled intersections and roundabouts. Cyclists frequently fixate on road markings, further motivating the use of on-road interfaces. AV-cyclist interfaces placed on the road may be augmentations through AR glasses worn by cyclists [140], road projection eHMIs [67], or road markings equipped with LED lights [125]. AR projections require cyclists to wear AR glasses and may not be accessible to all.

3.4.2 Introducing Holistic AV-Cyclist Interfaces (HACIs)

The design guidelines discuss the advantages of interfaces using different placements. For example, *DG6* explains that wearable devices are useful for communicating signals even when the AV is out of the cyclist's view, such as during lane merging. This is challenging to achieve with an eHMI on the AV [67]. However, *DG8* shows that eHMIs also have advantages because they are on the AV itself, so they do not complicate or alter the current cycling setup and align with cyclists' perceptions of acceptability [16]. Moreover, *DG9* shows that on-environment interfaces also bring advantages to interface usability. For example, placing an interface on the road allows it to be easily recognisable and aligned with cyclists' reflexive behaviours. Previous research explored AV-cyclist interfaces in isolation, such as AR displays or eHMIs working without other interfaces involved in facilitating interaction [67, 88]. These works showed that isolated interfaces have limitations. For example, not all cyclists will have access to AR glasses, so AR-based interfaces are difficult to deploy on a large scale [16, 124].

Therefore, one interpretation of the design guidelines is to utilise the advantages of each interface placement by grouping different interfaces to overcome individual limitations. For example, grouping AR glasses with eHMIs allows cyclists to receive AV signals when the AV is out of view while maintaining acceptability for cyclists without AR glasses, as they can still use the eHMI. This approach allows cyclists to incorporate multiple devices to assist them when interacting with AVs, similar to how they currently use devices such as rearview radars.

This section introduces the Holistic AV-Cyclist Interface (HACI). A HACI is defined as *"an interconnected ecosystem of AV-cyclist interfaces aware of each other's states and presence. Interfaces within a HACI work together to facilitate interaction collectively. HACIs comprise a baseline interface on the AV or environment and other devices that may use different placements"*. While prior work has explored interface groups for pedestrians [9, 80], HACIs define more precise requirements. A key requirement is for these interfaces to include a *baseline interface*. This is essential to maintain acceptability and account for cyclists who may not carry additional wearable or bike-mounted devices. This baseline can be an eHMI or on-environment interface; cyclists do not need to carry any devices to use interfaces on the AV or environment [14, 16], and the eye-tracking study showed that cyclist gaze behaviour was distributed between these areas.

Another requirement is connectivity between interfaces. This brings significant advantages. AV-cyclist interfaces communicate critical messages for cyclist safety, such as AV-yielding intentions. Using multiple interfaces that are not connected risks communicating contradictory messages that would cause confusion and unsafe situations. For example, a cyclist's AR glasses may communicate that the AV is yielding, but the AV's eHMI could display that it is not yielding. Having interfaces work together also means they could use the same *design language*. This ensures cohesion between the interfaces and would impose a lower mental effort on cyclists as they would not need to learn multiple signals communicating the same message. They could also work sequentially to facilitate interaction. This approach addresses *DG3* and avoids overwhelming cyclists.

Moreover, interconnected AV-cyclist interfaces do not need to serve the same purpose and be redundant to each other. This avoids information overload; connecting these displays allows more comprehensive information to be divided between devices. For example, AR glasses could complement eHMIs by communicating an AV's location relative to the cyclist rather than reiterating AV intentions. Similarly, HACIs can utilise wearable or bike-mounted devices to extend the reach of baseline interfaces and even make them multimodal. For example, audio from the helmet could play different sounds synchronised with an eHMI's signal on AV intentions. From a practical standpoint, these interconnected features are becoming more feasible as AVs are expected to support Vehicle-to-Everything (V2X) connectivity [65, 92, 110]. This allows AVs to connect directly with various devices, supporting interconnected HACI features.

HACIs provide designers with a large palette of devices, placements and modalities, allowing them to contribute more comprehensive AV-cyclist interfaces [80]. Baseline interfaces could compensate for human driver cues. For example, eHMIs could display the AV's awareness of the cyclist and its intentions. However, incorporating other devices allows HACIs to improve and elevate today's interactions. For example, using emerging technologies such as AR displays would reduce the need for shoulder checks and could communicate new types of messages to cyclists [67, 140]. Therefore, investigating HACIs provides the opportunity to improve interactions with cyclists and enhance the overall cycling experience instead of simply compensating for driver social cues.

Figure 3.12 illustrates an early sketch of a HACI. This was informed by the design guidelines and previous work and can be perceived as a use case for actioning the design guidelines. The design of the concept began with developing an eHMI; this is due to HACIs requiring a baseline interface to maintain acceptability, and the eye-tracking study showing that eHMIs are useful because they use the AV as a placement, meaning they match the natural gaze behaviours of

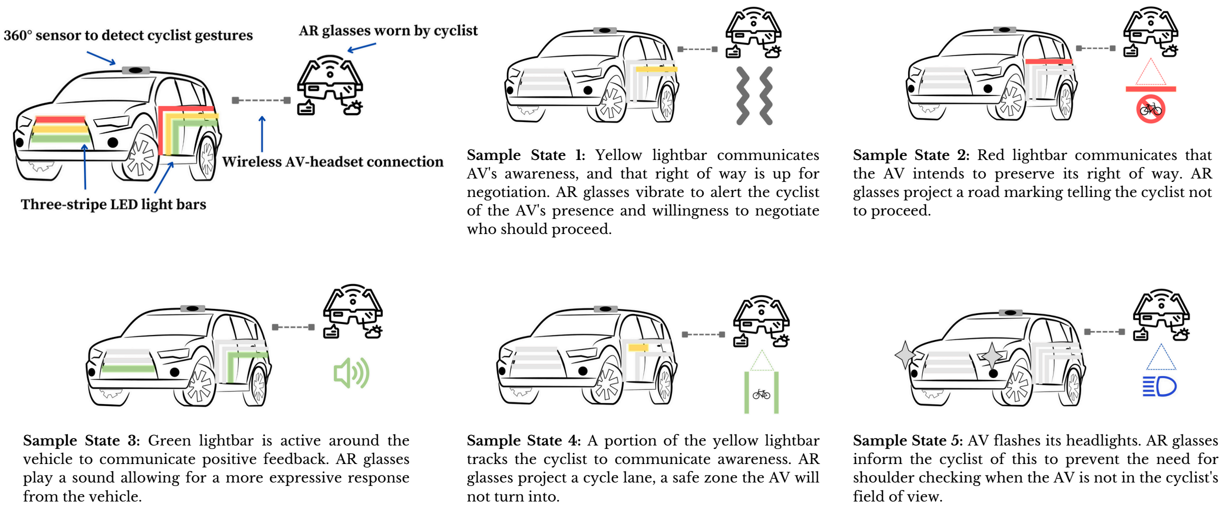

Figure 3.12: A sketch of a HACI based on the design guidelines. This features a light-based eHMI as a baseline display connected to AR glasses worn by the cyclist to communicate complementary information.

cyclists. The online survey showed that cyclists prefer some familiarity with new interfaces, e.g. communicating similar messages to human drivers or using familiar traffic features in their design. Moreover, the observations and eye-tracking study showed that traffic lights influence interaction behaviours. Therefore, the eHMI uses a similar setup to traffic lights to minimise the potential learning curve, using three rows of light bands in red, amber and green. Light bands were used due to their popularity in prior work [37] and because they are placed directly on the AV rather than using road projections, which leaves room for on-environment displays to be used in the HACI [80].

DG8 showed that eHMIs must be placed around the vehicle to account for all cyclist positions. Therefore, this light-based eHMI was placed on the front, side and back of the vehicle. This contrasts it with light-based pedestrian eHMIs, which are commonly only on the front [37]. It also does not cover the vehicle's directional indicator to align with *DG5* and allow cyclists to process traditional vehicle signals. The HACI also includes a sensor to detect cyclist cues and facilitate two-way communication, as suggested in *DG1*. A pair of AR glasses was then added for extra support. These are connected to the eHMI via V2X to avoid contradictory signals and allow comprehensive messages to be distributed between devices. AR glasses were chosen because they can be multimodal and were found to be useful for cyclists in previous research [67]; their acceptability will be enhanced due to the presence of an eHMI. *DG9* showed that the road is a useful design space for visual signals because it covers a large surface that is in the cyclist's view. Therefore, the AR glasses can display a cycle lane in green (AV is yielding) or red (AV not yielding), aligning with the AV's intentions. This can be seen in *Sample States* 2 and 4. Projecting an AR cycle lane was found to be useful in prior work [140], especially since AR displays cause less visual clutter in the environment because these displays are only visible to the cyclist wearing the glasses [123].

HACIs can communicate more comprehensive messages than single interfaces. This means that while AV intentions and awareness are key messages [82], new types of messages can be incorporated into the interface. For example, *DG2* recommended the communication of positive or negative feedback; this was incorporated into the HACI to make interactions more familiar. *Sample State 3* shows the AV thanking the cyclist using a multimodal approach. The AR glasses only use auditory cues because these messages may not be as critical as AV intentions, so cyclists will not be overwhelmed with visual signals, which prior work suggested take precedence over non-visual ones [39, 45, 67]. To further explore DG5 and promote interfaces co-existing with vehicle signals, AR glasses could warn cyclists if an AV is flashing its headlights. This could be useful to assure cyclists that the vehicle signal is targeted at them. This is shown in *Sample State 6*.

The potential for HACIs to maintain interface acceptability while enhancing the overall interaction experience motivated the upcoming studies in this thesis to explore further how HACIs can be designed for AV-cyclist interaction. One particular challenge for HACIs is managing cyclists' cognitive load, as these interface groups can be comprehensive, utilising multimodal cues to convey distinct messages. Cyclists may use HACIs in various scenarios, including lane merging, where they may be looking around them and conducting shoulder checks to locate the AV [67]. Scenarios may also feature multiple AVs, with cyclists needing to track and associate HACI signals to the correct AV [123]. These situations may be overwhelming, and HACIs must be carefully designed to manage the cognitive load, simplifying rather than complicating the interaction. This motivated the upcoming studies in the thesis to take a more practical approach, using simulators and Wizard-of-Oz setups to enable cyclists to experience interfaces while directly interacting with AVs, as opposed to relying purely on cyclist perceptions. This is especially important since the online survey showed that cyclists do not have sufficient knowledge about AVs to form clear expectations, so direct interaction experience would provide deeper insights into how HACIs affect cognitive load.

HACIs require a baseline interface to maintain acceptability and facilitate interaction with a diverse range of cyclists without imposing new types of devices. The studies in this chapter showed that versatility is a key AV-cyclist interface challenge, coupled with acceptability, as drivers interact with cyclists across diverse traffic scenarios. Therefore, the following chapter answers RQ2 and investigates how eHMIs placed on the vehicle can be versatile to act as baseline interfaces for HACIs. This would allow them to facilitate interaction with all cyclists in all scenarios without changing the current cycling setup. This is critical to ensure that AV-cyclist interfaces are usable throughout a cyclist's journey.

Chapter 4

Versatility

Figure 4.1: The three studies conducted in this chapter. First, outdoor eHMI design sessions around real vehicles. Second, evaluating the outcome designs in VR. Third, evaluating the eHMIs outdoors in a Wizard-of-Oz study.

The previous chapter showed that drivers and cyclists exchange different messages and social and implicit cues between traffic scenarios. This established versatility as a key AV-cyclist interface design challenge. Interfaces must facilitate clear communication throughout the different scenarios, regardless of the traffic control level or AV position [12].

HACIs were introduced as a promising solution for acceptability, as they use baseline interfaces on the environment or AV to ensure all cyclists can receive AV messages, but leave room for integrating other wearable or bicycle-mounted devices for added support. The additional wearable devices could be interchangeable between scenarios, removing the need for a single interface to facilitate interaction between scenarios. This is similar to how current devices, such as rearview radars, only operate when an AV is behind the cyclist.

However, it is important to consider that not all cyclists may have access to these devices [16], and some may feel overwhelmed by switching between interfaces. Therefore, the baseline interfaces in a HACI must be versatile to ensure that interaction can be facilitated with all cyclists in all scenarios. This prompted the thesis to take a ground-up approach and establish a versatile baseline in this chapter before incorporating additional devices for a final solution that goes beyond compensating for human drivers and improves upon today's interaction experiences.

Regarding whether this baseline should be on the environment or AV, eHMIs present a promising solution. These are vehicle-mounted displays, such as LED signals on the bonnet or road projections from the bumper [43]. eHMIs align with cyclists' reflexive behaviours; the eye-tracking study showed that cyclists already look at vehicles to infer driver intentions. This allows eHMIs to naturally integrate into cyclists' views without diverting their attention [49]. Unlike stationary on-environment displays, eHMIs are mounted directly on the AV, allowing them to facilitate interaction even in dynamic manoeuvres that occur anywhere on the road [67]. This makes them particularly well-suited for achieving versatility. Another key advantage of eHMIs is their proven effectiveness with pedestrians [39]. If eHMIs also succeed with cyclists, they could provide a common ground that benefits all road users.

However, there is a lack of research informing the design features that contribute to successful AV-cyclist eHMIs [14, 37]. Factors such as colour schemes and animation patterns could improve the usability of eHMIs [39], and their placement on the vehicle (e.g., roof-mounted vs. side-mounted) significantly affects the visibility of signals [67]. From a versatility perspective, it remains unclear whether eHMIs should display consistent AV signals across all scenarios or dynamically adapt their messages, similar to human drivers [14].

This chapter addresses these gaps by answering RQ2: *"How can AV-cyclist interfaces be versatile to facilitate interaction between traffic scenarios?"*. It features three studies (see Figure 4.1) investigating the features that allow eHMIs to be versatile and facilitate clear communication between AVs and cyclists across traffic scenarios with different setups:

1. **Study 4 - eHMI Design Sessions:** This study identified the design features AV-cyclist eHMIs should adopt from the perspectives of AutomotiveUI researchers and cyclists. The study used a novel method in which researchers and cyclists collaborated around real parked cars to design an eHMI for a specific traffic scenario category from Chapter 3. Participants sketched and attached their designs to relevant vehicle areas, allowing them to contemplate concepts to scale. Three new versatile eHMIs were synthesised from participant designs by combining overlapping features between concepts designed for each scenario category.

2. **Study 5 - VirtuRide eHMI Evaluation**: VirtuRide, a VR cycling simulator, was developed for this study. This allowed high-fidelity prototypes of the three eHMIs from the design sessions to be implemented in VR. Participants tested and compared each eHMI across five traffic scenarios with different levels of traffic control and vehicle positions. This provided insights into eHMI versatility and usability. The concepts were then revised according to participant feedback.

3. **Study 6 - Ghost Driver eHMI Evaluation**: Real prototypes of the revised eHMIs were built for an outdoor study using the Ghost Driver [109] approach with a hidden human

Figure 4.2: The outdoor eHMI design sessions around real vehicles. Participants used bicycles to contemplate their concepts to scale, and sketched and attached their designs to the vehicles.

driver. The study used the same structure as the VirtuRide one; participants experienced each eHMI across different traffic scenarios and provided feedback on versatility and usability. This study confirmed the most effective eHMI design features by having cyclists experience them in a representative setting.

The findings from these studies inform the design of versatile eHMIs, identifying key features. This ensures that eHMIs provide a consistent and reliable means of AV-cyclist interaction across diverse traffic scenarios, ultimately contributing to the broader development of HACIs.

4.1 Study 4: eHMI Design Sessions

The design features that allow AV-cyclist eHMIs to be usable and versatile are unknown. This study takes a participatory design approach to gain an end-user perspective on the problem, which was crucial to maintaining the acceptability of eHMIs. The study adopted a novel methodology in which AutomotiveUI researchers and cyclists collaborated to design eHMIs outdoors around real parked vehicles. They sketched and attached their concepts directly to the vehicles. Participants designed eHMIs for a specific traffic scenario category: controlled scenarios, uncontrolled infrastructure and dynamic manoeuvres, as identified in the previous chapter. Overlapping features between scenario categories were combined to create three new versatile eHMIs capable of working between scenarios. This was the first AV-cyclist interaction study exploring the design of versatile interfaces.

4.1.1 Study Design

The study was in the form of design sessions in which AutomotiveUI researchers and cyclists collaborated to design an AV-cyclist eHMI; see Figure 4.2. Transcripts of participant discussions during the design sessions and photographs of the final designs were collected for analysis.

Study scope

Participants assumed they were designing for SAE level 5 AVs; no human driver in all traffic scenarios [117]. All studies in this thesis take this assumption. They were tasked with designing an eHMI that facilitates interaction at a specific traffic scenario category, as identified in Chapter 3. These categorised traffic scenarios according to their levels of traffic control: *controlled scenarios* (traffic lights), *uncontrolled infrastructure* (no traffic lights, but may have road markings or signs determining right-of-way, e.g. roundabout) and *dynamic manoeuvres* (could happen anywhere on the road, e.g. lane merging). This avoided constraining participants to design for a specific traffic scenario and supported the versatility of eHMIs. It also avoided providing participants with a scope that was too broad, ensuring they remained focused on the task [70]. The study focused specifically on eHMI design. Participants were constrained to designing interfaces placed on the vehicle rather than exploring other potential placements, such as the bicycle. They faced no additional constraints and were free to develop eHMIs using any modality (visual, auditory or haptic) or display type.

Study setup

The study involved six teams of participants, each comprising one AutomotiveUI researcher and one cyclist. Recruiting AutomotiveUI researchers was necessary to stimulate discussions about the pragmatic qualities of the eHMIs and the feasibility of more emerging technologies [67]. Cyclists provided an end-user perspective on the designs. Their inclusion was necessary to ensure the acceptability and real-world applicability of the concepts [28].

Three design sessions were conducted, each featuring two teams working in parallel around two parked vehicles. Each design session focused on one traffic scenario category. Figure 4.3 visualises the study setup. Vehicles were parked 150 metres apart to prevent overlapping ideas. Having two teams per session allowed for cross-team discussions and feedback at later stages of the sessions once teams had a complete design [70]. This prompted discussions on design decisions and the acceptability of eHMIs. Each team was moderated by an experimenter who briefed participants and ensured they stayed focused on the task. Experimenters had at least one year of AutomotiveUI research experience, which allowed them to answer any questions about eHMIs and their purpose [28]. They also managed the data collection by video-recording the sessions and photographing the final designs.

The study was conducted in an outdoor car park with a flat, paved surface, and the vehicles were parallel parked. This allowed participants to move around them easily, which was especially useful for contemplating all vehicle sides and accounting for encounters featuring different AV positions. This is critical for versatility. Teams were also provided bicycles to immerse them further into the design process and act out scenarios at the scale of real vehicles. This supported realistic considerations of how participant designs would function in practice [115].

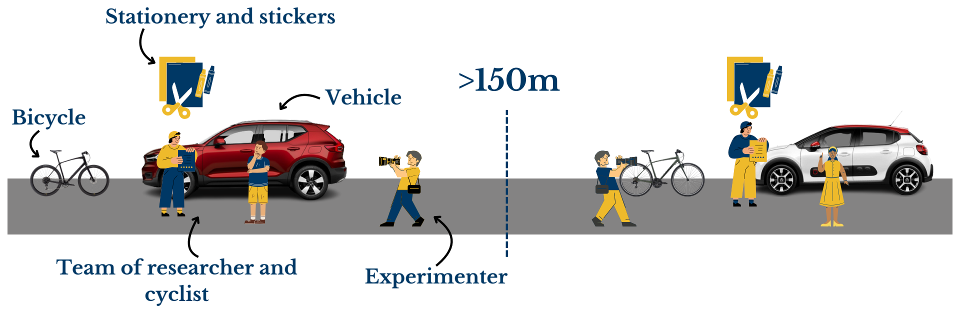

Figure 4.3: The study setup: Two teams worked in parallel around two vehicles, 150 metres apart. Each team was moderated by an experimenter who recorded the sessions for analysis.

Study structure

Design sessions were 45 minutes long. They were split into (1) 30 minutes of ideation with team members collaborating to design an eHMI and (2) 15 minutes of feedback where cyclists switched teams to provide feedback on the other team's design.

The ideation phase was modelled after the Map-it participatory design method [70]. Map-it was useful for designing cycling displays in prior work [28]. It provides equal collaboration between experts and end-users. There were no rigid roles assigned to team members: cyclists could propose ideas while researchers advised on practical considerations, and researchers could suggest concepts while cyclists reflected on their real-world applicability. This stimulated discussions between team members and provided a richer dialogue of design decisions rather than simple design generation.

During ideation, participants discussed the traffic scenario category they were assigned. They sketched their designs and placed them on relevant vehicle areas to visualise and discuss eHMI features, e.g., the icons a display should use. Participants also used whiteboard markers to draw directly on the vehicle. They were encouraged to think aloud as they worked. This provided insights into their thought processes and the context for their design choices. Teams were given *lock stickers* to place on features they felt should remain unchanged, which helped participants form strong opinions about their designs and justify their decisions [28]. During the feedback phase, cyclists switched teams to evaluate and provide feedback on the other team's design. Cyclists were given *like* and *bomb stickers* to place on features they liked or disliked in the other team's design. This promoted cross-team discussions and provided additional end-user perspectives to enhance the acceptability of the designs [70].

Measures

The study collected the following data to understand the design features that enable versatile and usable eHMIs:

- **Photographs of participant designs:** These identified the components eHMIs should use to operate in the assigned traffic scenario category. The photographs showed any overlapping features between eHMIs for different scenario categories, allowing the creation of new, versatile eHMIs after the study;

- **Video footage of the design sessions:** These videos were useful for contextualising participant design decisions and gaining detailed end-user perspectives on the problem.

4.1.2 Apparatus

Two cars were used per design session. These were a 2019 Citroën C3 (light grey, used in all three sessions) and either a 2010 Volkswagen Eos (navy blue, used in two sessions) or a 2023 Volvo XC40 (red, used in one session), depending on availability. All vehicles were right-hand drive, as the study was conducted in Glasgow, UK. Each team had either a Giant Escape 3 or Specialized Sirrus X bicycle. These are hybrid bicycles commonly used for commuting.

Teams were provided stationery and adhesives to sketch and stick their designs on the vehicles. These included A3 and A4 paper, sticky notes, laminate sheets, markers, Blu-Tack and Sellotape. They were also given stickers with a like, bomb or lock icon to place on design features they liked or disliked. Experimenters used their smartphones to record the sessions and photograph the final designs for analysis.

4.1.3 Participants

Six AutomotiveUI researchers were recruited through personal contacts. They were PhD students, postdoctoral researchers, and lecturers with at least one year of experience in AutomotiveUI research. Their demographics were: $M_{\text{age}} = 38.7$, $SD = 5.5$; $Male = 5$, $Female = 1$.

Six cyclists were recruited through social media advertising. All had at least one year of experience cycling in mixed traffic in Glasgow multiple days per week. Their demographics were: $M_{\text{age}} = 27$, $SD = 5$; $Male = 3$, $Female = 2$, $Prefer\ not\ to\ say = 1$.

4.1.4 Procedure

Participants signed up for the study through an online survey. They provided their demographic information and details about their cycling/AutomotiveUI experience, and cyclists ranked the traffic scenario categories from most to least dangerous to be assigned to one they perceived as challenging. Participants who met the recruitment criteria were assigned to a team and sent an eHMI information sheet two days before the session. This document included introductory information about the AV-cyclist interaction problem, the purpose of eHMIs and the participant's assigned scenario category.

On the study day, participants met their teammate and the experimenter at the car park where the sessions were conducted. Experimenters briefed teams about the task, provided the necessary apparatus, and answered any questions. Participants were then encouraged to familiarise themselves with the parked vehicle, using the bicycle for increased immersion. Experimenters then started the video recording, and the ideation phase began. Team members ideated, sketched and placed lock stickers on their designs for 30 minutes. The feedback phase then began; cyclists switched teams, and researchers presented their concepts. Cyclists then evaluated the designs by placing like or bomb stickers on specific eHMI features. The study concluded after 15 minutes of feedback, and experimenters ended the video recordings. They took photographs of the final designs for analysis. Participants were compensated for their time with £5 Amazon vouchers.

4.1.5 Analysis

The analysis was divided into two parts. First, the six designs were organised into a taxonomy of eHMI features. This includes their placements, modalities, and the messages they should convey. Second, a thematic analysis was conducted on the design session footage. This extracted themes representing researcher and cyclist expectations of eHMIs.

Data preparation

One researcher sketched each team's design on a Citroën C3 model using Canva[1] to achieve a consistent representation of the results. A second researcher compared the sketches with the photographs of the designs to ensure accuracy and found no discrepancies. Subsequently, one researcher manually transcribed the video footage to become familiar with the data. A second researcher reviewed the transcripts against the video footage and found no discrepancies.

Taxonomy development

A taxonomy of eHMI features was developed to visualise the design features participants used and the relationships between them. For example, the *modality* that should be used to communicate a specific *message*. This taxonomy was also useful for identifying overlapping features between participant designs, allowing for the creation of new versatile concepts capable of working across traffic scenario categories.

Each taxonomy layer represents a category of eHMI feature, e.g. *modality* or *placement*. Layers were ordered into a hierarchy that captures participants' overall thought process when selecting a feature. This required a deductive thematic analysis [19] of the video transcripts with the research question, *"What eHMI features did participants prioritise and discuss during the design process?"*. Video transcripts were imported into NVivo[2] for analysis. One researcher identified 35 unique codes related to eHMI features, e.g., 'visual cue' or 'bumper (placement)'. Two researchers independently organised these into higher-level themes based on code similarities, e.g., 'visual cue' would go under 'modality', and 'bumper' would go under 'placement'.

[1]Canva visualisation tool: `canva.com` ; Accessed 01/04/2025
[2]NVivo qualitative analysis software: `lumivero.com/products/nvivo/` ; Accessed 01/04/2025

This was iterative; disagreements were discussed, and themes were revised until resolved. Five themes were extracted. These themes represented eHMI features discussed in the study, such as *message*, *modality* or *placement*.

The most prominent order in which participants discussed the features (i.e., *design decision sequence*) was deduced to capture the participants' overall thought process and develop the taxonomy's hierarchy. 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 researcher relabelled the codes in the transcripts with the higher level themes they were mapped to (e.g. 'visual cue' would be relabelled to 'modality'). Two researchers then independently counted the frequency in which each theme appeared in a sequence of 1-5 or less, as five themes were identified in the previous step. No discrepancies were found. Each feature was placed in the taxonomy hierarchy depending on its most common appearance in the *design decision sequence*. It is critical to mention that participants were free to follow their own design process/sequence. The think-aloud nature of the study and mapping of the codes to higher-level themes allowed a clear identification of the most common design decision sequence, and for the taxonomy to have a hierarchical structure.

Populating the Taxonomy

One researcher used the Canva design sketches to classify each team's design within the taxonomy, populating each layer with corresponding features. For example, if an eHMI featured speakers on the bonnet, 'audio' would be categorised under the 'modality' layer and 'bonnet' under the 'placement' layer. Additionally, the researcher recorded the frequency of appearance for each feature across the designs, indicating their popularity. This made it straightforward to identify prominent and overlapping features between eHMIs designed to operate in different scenario categories.

Thematic Analysis

An inductive, data-driven thematic analysis [19] was conducted on the video transcripts. The transcripts were then imported NVivo for coding. One researcher (the thesis author) identified 92 unique codes from the data. Following this, two researchers (the thesis author and Post-Doctoral Researcher in AutoUI) collaboratively sorted these codes into three overarching themes based on their similarities. This process was iterative; disagreements were discussed and resolved, with codes being remapped as necessary. Themes containing two or more overlapping codes were reassessed and combined where appropriate.

4.1.6 Results

This section presents the taxonomy of eHMI features. It also summarises participant designs to provide context for the taxonomy. The Canva drawings of the designs are shown in Figure 4.4. A tree diagram of the taxonomy is shown in Figure 4.5. A total of 32 eHMI components were identified from participant designs and organised into the taxonomy. Lastly, this section reports the themes that reflect researcher and cyclist perspectives and expectations of the eHMIs.

Designs and taxonomy

The taxonomy follows the following hierarchy, which represents the sequence of participant design decisions:

1. **Traffic Scenario Category:** The category of traffic scenario for which it was designed. These were identified in Chapter 3: controlled scenarios, uncontrolled infrastructure, or dynamic manoeuvres;

2. **Message Type:** The message the eHMI component displays, including an AV's awareness of the cyclist or its intentions;

3. **Familiarity Level:** How familiar the component is in traffic from the cyclist's perspective. This could replicate human social cues, use traffic signals such as a stop sign or introduce a new concept entirely, such as a lightning bolt display to indicate acceleration;

4. **Modality:** The modality used to convey the message. These were visual, auditory or sensing/V2X;

5. **Technology:** The specific device or mechanism used (e.g., speakers, road projections, LED strips);

6. **Placement:** The location of the eHMI component on the vehicle, classified using Areas of Interest (AOIs) from the previous chapter (e.g., bonnet or windscreen).

This taxonomy provides a structured understanding of how eHMIs were designed, showing trends in placement, modality, and message type across different traffic scenarios. Overall, the taxonomy shows that participants mostly designed eHMIs that communicate the AV's awareness of the cyclist and its intentions. Participants mostly used visual cues to display these messages. They rarely used components that replicate driver social cues. They opted for features that are either new to traffic, such as a lightning bolt icon to indicate acceleration, or signals familiar in traffic, such as red and green lights communicating yielding intentions. Participants mostly used LED lights and road projections, and these were mostly placed around the vehicle.

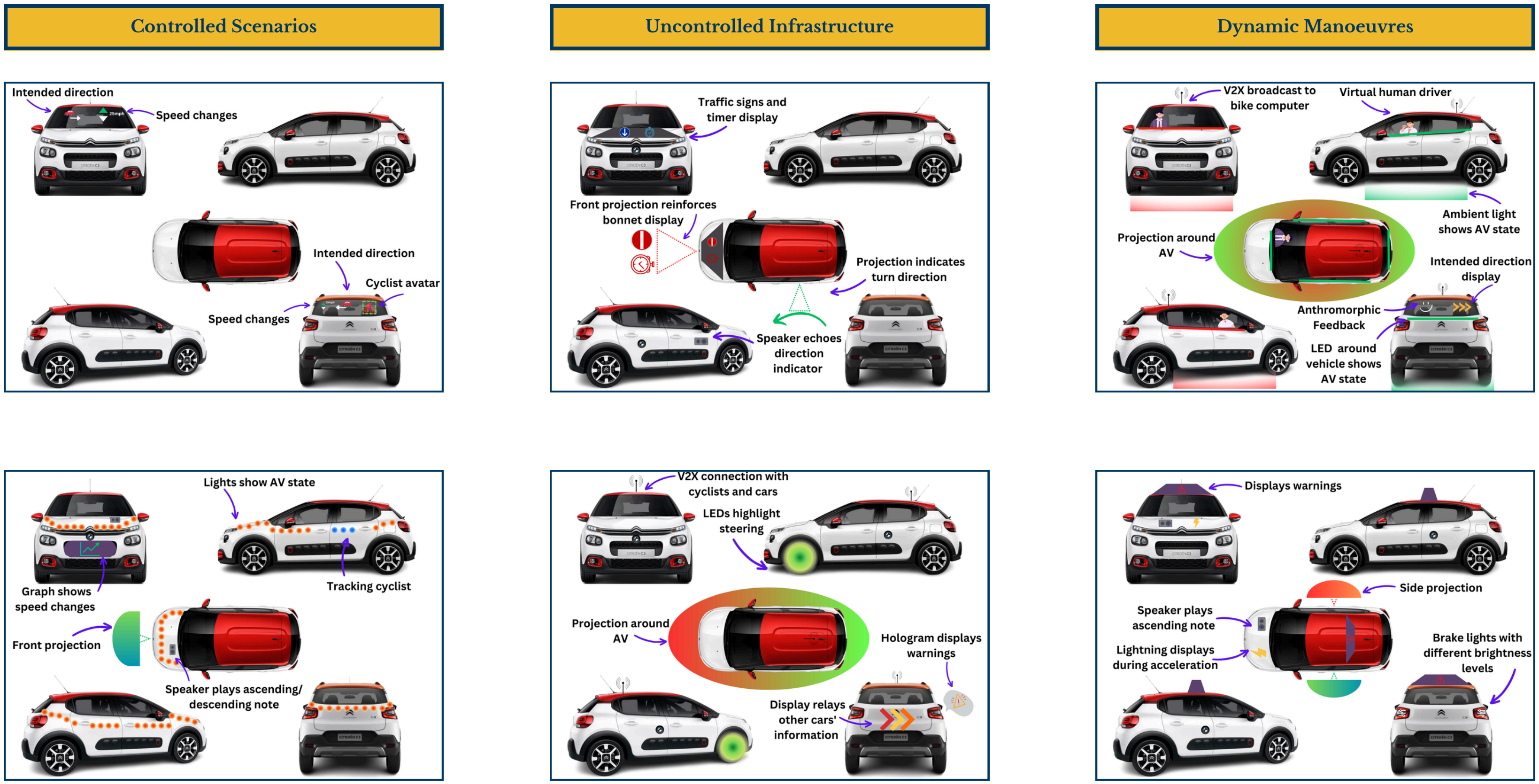

Figure 4.4: Sketches of participant designs. The first row shows designs for Controlled Scenarios, the second row for Uncontrolled Infrastructure, and the third row for Dynamic Manoeuvres. From left to right, the top row shows the designs of teams 1, 3 and 5. The bottom shows the designs of teams 2, 4, and 6.

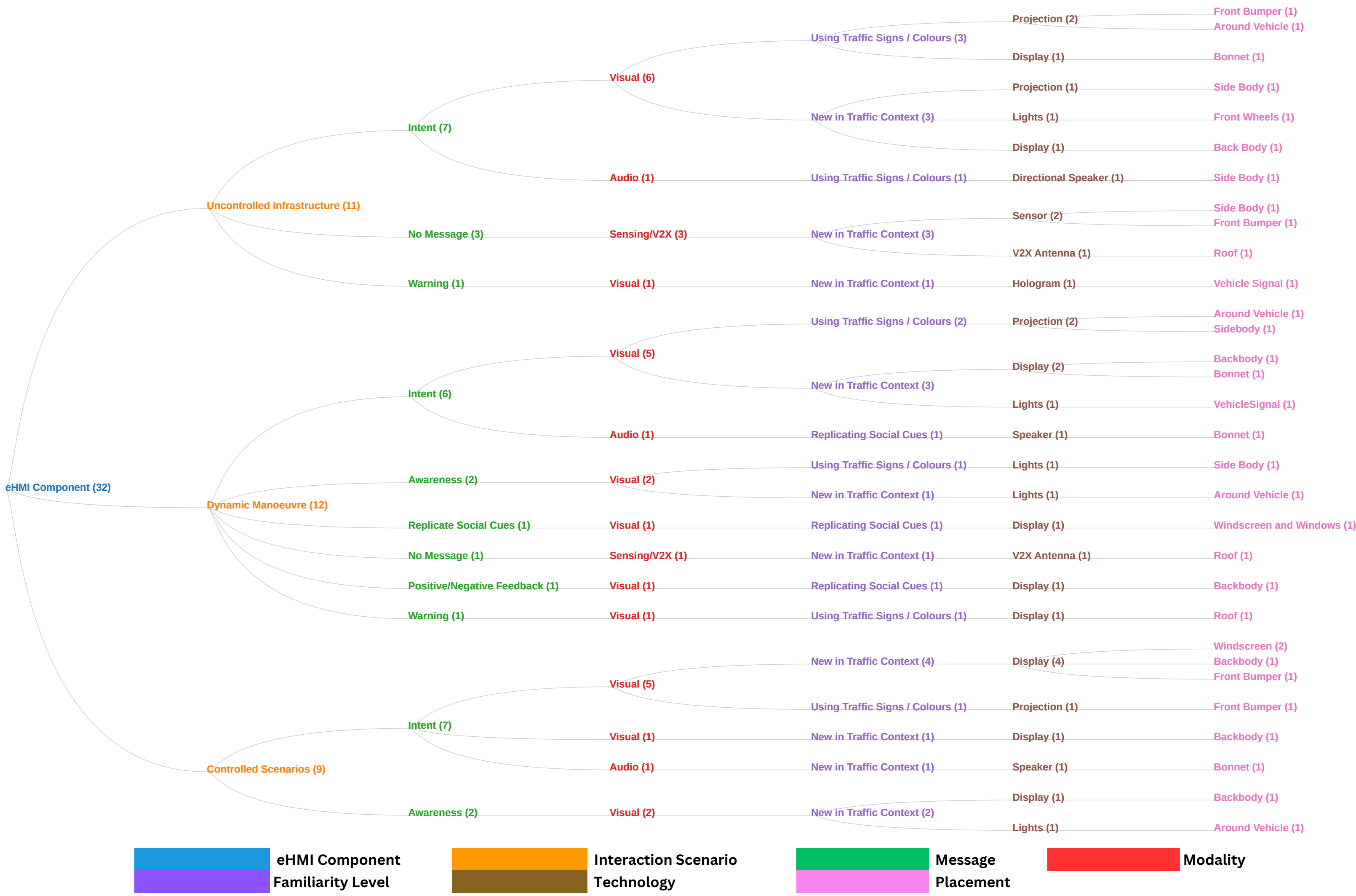

Figure 4.5: The taxonomy of eHMI features populated with participant designs. Each branch is labelled with: *eHMI feature (frequency of appearance)*

Team 1 - Controlled Scenarios This featured two displays on the vehicle's windscreen, both communicating the AV's intentions. One display showed a car icon with an arrow indicating the vehicle's intended direction. The other displayed the current speed alongside an upward or downward-facing arrow to signal acceleration or deceleration, reiterating its implicit cues. The same displays were also placed on the vehicle's back body, with an additional display tracking the cyclist and mirroring their movements to indicate the AV's awareness of them. Not all displays may be active at the same time. This prevented information overload and ensured cyclists received only the most relevant information for each interaction.

Team 2 - Controlled Scenarios This used always-on amber LED lights surrounding the vehicle to indicate that it was in autonomous mode with all sensors functioning correctly. These lights responded dynamically to nearby cyclists, with a blue light widening as a cyclist moved closer to signal the AV's awareness of their presence. Additionally, the design incorporated road projections from the front bumper to communicate intentions to cyclists ahead. A green projection indicated that the AV would yield, while a red projection signalled that it would not. Speed changes were communicated through a *graph* displayed on the bumper, where the line rose as the vehicle accelerated and lowered as it decelerated. Additionally, the eHMI incorporated a multimodal approach by integrating a speaker system using a Doppler effect to warn cyclists that the AV will overtake them. This played an ascending note as the AV approached and a descending note as it moved away. This auditory signal was activated at controlled intersections when the traffic light turned green, where multiple vehicles might be behind the cyclist and accelerating to overtake.

Team 3 - Uncontrolled Infrastructure This included a display on the bonnet and a front projector, both using stop/go traffic signs to communicate the AV's intentions; stop means the AV will not yield, and go means the AV will yield. The displays also showed a timer near the signs to facilitate some right-of-way negotiation. The design was multimodal. A directional indicator sound played whenever the AV activated its turn signal, reinforcing its intended change in direction. This design also helped cyclists avoid left-hook turns by incorporating a sensor that detected riders on the vehicle's left side. A left-facing arrow was projected onto the road when a cyclist was present to warn them of the vehicle's intentions to turn.

Team 4 - Uncontrolled Infrastructure This design used road projections to communicate the AV's intentions, displaying signals only on the side where the cyclist was present. Green projections indicated that the AV was yielding, while red projections signalled that it was not. The eHMI also included LED lights on the front wheels, which activated when the AV turned to reinforce its implicit cues and clarify its intended direction. The eHMI also featured a hologram projection from the rear lights to provide further situational awareness, displaying warnings such as *"road works ahead"*. Finally, a display on the back body communicated the status of other vehicles in front of the AV, such as *"the vehicle ahead is turning"*. This information was retrieved through a V2X antenna connected to nearby vehicles.

Team 5 - Dynamic Manoeuvres This featured screens on the windscreen and side windows displaying a virtual human driver, replicating familiar social cues to minimise the learning curve. Further anthropomorphic feedback was provided through a smiley or sad face displayed on the vehicle's back body, reacting to a cyclist's manoeuvre. Additionally, the back body display included arrows that communicated the AV's intended direction, synchronised with its directional indicators to reinforce its turning intentions. The design also incorporated road projections to communicate AV intentions to cyclists from any position around the vehicle; green projections signalled that the AV was yielding, while red projections indicated it was not. Additionally, an LED strip surrounding the vehicle's body and green ambient lights placed under the vehicle confirmed that the AV was in autonomous mode and that all sensors were functioning correctly. The eHMI incorporated a V2X antenna that broadcasts information to cyclists with other interfaces like AR glasses. This integration enables the design to function as part of a HACI.

Team 6 - Dynamic Manoeuvres This featured a taxi-like display on the roof to warn cyclists of potential hazards, such as road works. It also incorporated road projections from the vehicle's sides to communicate AV intentions: green indicating the AV is yielding and red indicating it is not. The eHMI reinforced AV implicit cues by displaying a lightning bolt on the bonnet and playing a revving sound when the AV accelerates. Additionally, it modified existing vehicle signals by using variable brake light brightness levels to convey the intensity of braking.

Themes

This section reports the outcomes of the thematic analysis of the video transcripts. The identified themes provide insights into participant design choices. These themes are supported by participant quotes from the design sessions.

Theme 1: Messages Exchanged Between AVs and Cyclists

This theme describes the messages that participants anticipate from AVs and the different approaches to displaying these messages.

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

- ***Awareness and intentions:*** Messages about AV awareness of cyclists and intentions are *"basic information coming from the AV"* - Cyclist 5 (C5). Participants explained the benefits of communicating awareness: *"[awareness] is useful. It lets me know that the car* *is making eye contact with me"* - C6. This increases perceived safety and trust in AVs: *"you could be confident that you're currently being taken into account based on what it's doing"* - C6. Participants explained that AV intention messages take two forms: (1) directional intent (e.g. *"it's all about where the car is going to go"* - C4) and (2) speed changes (e.g. *"it should communicate accelerating, decelerating and holding steady states"* - C6). Intention signals help riders determine their next manoeuvre: *"I would want to know what the car would do next. So, I can plan around what would happen"* - C5. AVs should communicate both awareness and intentions 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. Therefore, communicating awareness and intentions 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): *"It's nice to show that the car is not dead"* - C3. This would make them confident that the vehicle is functioning appropriately. For example, when talking about an always-on lightband, Researcher 6 (R6) explained, *"The light ring is always on, so you'd know if there's something wrong when it is off"*. Therefore, communicating the vehicle state could be a failsafe for eHMIs.

- ***Instruction:*** Cyclists were not welcoming of instructions from the AV: *"The AV is not the boss of the road"* - C2. Cyclists will likely make their next manoeuvre based on the AV's intentions and awareness rather than following its instructions: *"I don't want a car to suggest that I turn or do a certain thing, because I make these decisions, not the car"* - C5. Therefore, awareness and intentions give cyclists more autonomy than instruction, helping them make more informed decisions.

eHMIs, driving behaviour and vehicle signals Driving behaviour plays a significant role in cyclists' decision-making: *"If it were a nice car, it wouldn't need a display – just slow down"* - R1. eHMIs must align with the AV's driving behaviour to avoid contradicting implicit cues: *"If it 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"* - C5. Moreover, cyclists currently depend on on-vehicle signals, such as directional indicators. eHMIs should not replace these signals: *"if the indicators would change a lot, it would need a Master's for a cyclist!"* - C3. eHMIs may reiterate on-vehicle signals but should not alter them: *"when the blinker is on, it [projects] the arrow [on the road]"* - C1. Therefore, eHMIs could introduce some novelty to traffic, but it is important to integrate these interfaces with more traditional signals.

Familiarity of eHMI messages Participant designs featured 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 to indicate awareness. This could overcome some issues in today's interactions: *"AVs can signal more actively than drivers who do their thing until you meet their eyes or wave at them"* - C5. However, too much deviation from today's signals may challenge cyclists: *"We need to make indicators simple without much deviation from the general understanding"* - C3.

- ***Level 2: Reusing traffic control features:*** This involves 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: *"Is it red for you to stop or the AV to stop? Also, people who are colour blind won't know"* - R1. This may also cause confusion as to whether the AV is instructing the cyclist or communicating its intentions: *"If we use a stop sign to say the AV is speeding up, will that confuse cyclists into thinking the car is instructing them?"* - R3.

- ***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: *"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?"* - E3.

Theme 2: Challenges for AV-Cyclist eHMIs

This theme provides an overview of the challenges AV-cyclist eHMIs must overcome to be usable on real roads. Many of these challenges relate to the four key AV-cyclist design challenges explored in this thesis, including versatility, scalability and cultural inclusivity.

Adhering to cycling behaviour eHMIs must adhere to the unique requirements of cyclists. 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: *"if I don't need to take my eyes off my path, it's better"* - C2. They should also communicate messages, even when the AV is not in a cyclist's field of view, e.g., behind them: *"[I should receive messages from] anywhere I am around the vehicle"* - C3. eHMIs must be inclusive to support a diverse range of cyclists. 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: *"to adopt traditional signals, you need to adopt ones in that cultural context"* - R3. eHMIs must communicate understandable messages to a broad range of cyclists without significantly affecting their road behaviours.

Ambiguity R6 mentioned, *"the challenge is ambiguity; knowing what that represents"*. Using icons instead of colours could make messages more understandable: *"who is it red for? An icon is colour independent"* - R1. 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.

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: *"use the same colour scheme etc., across interfaces and scenarios"* - R6; *"they can have the same symbols to get consistency in meaning"* - R4. This reiterates that eHMIs must function across different road scenarios to avoid the need to learn multiple interaction techniques.

Scalability Cyclists must know the communicated message is for them: *"we need to indicate to the cyclist that if we had a sound, it is for them"* - C1. eHMI messages must still be comprehensible in busy environments, allowing cyclists to associate eHMI signals with the AV with minimal effort: *"in busy roads where every car has LED strips... Is that going to impact visibility?"* - R3. Therefore, eHMIs must function appropriately in one-to-one, one-to-many and many-to-many interaction scenarios.

Varying road conditions eHMIs should function effectively, regardless of weather or other external factors. Participants considered adding failsafes for their designs to function in changing road and weather conditions: *"We need something other than visual if the road conditions aren't great"* - R3. Failsafes should not distract riders: *"you shouldn't create something super distracting or harder to see at night"* - R3. For weather conditions, participants suggested solutions that communicate a message from multiple vehicle areas: *"having it in two places is good because if you look on the ground, it might be difficult on a really snowy day"* - R1. Another approach is to avoid placements and display types that are easily affected by weather changes, such as road projections: *"maybe there will be something preventing us from seeing the projection"* - C1, or windows: *"it might be tinted, tilted or have some reflection from the sun"* - C6. Therefore, designers must consider the factors that may affect the receptivity of eHMI messages in the design process.

Theme 3: AV-Cyclist eHMI Specifications

This theme explains specific features that eHMIs should adopt to be successful. This includes the modalities and advanced sensing AVs should use to improve the interaction experience.

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: *"Audio is the first way you know there's something behind you"* - R1. 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' " - R2*. However, audio may not be scalable enough: *"if all the cars start playing a sound that's going to be bad"* - C1. Audio also has some inclusivity issues: *"what about people wearing headphones?"* - C2. Some teams suggested sounds already used in traffic: *"speakers to sound like a direction indicator"* - C1. Others opted for new sounds: *"I'd prefer a new type of sound, perhaps just because a continuous tone may not give you a sense of distance"* - C5. Participants did not use horns as they may be culture dependent: *"in the UK, it's a sign of annoyance"* - R4. Some designs were multimodal, combining visual and auditory cues: *"that's only a visual cue; it's easy to miss"* - R2. Multimodality could provide eHMIs with redundancy, helping riders receive messages across modalities. Individual components in multimodal eHMIs could operate sequentially: *"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"* - R1. Visual and auditory modalities may also operate simultaneously: *"sound to indicate the action of speeding up, with visual signs to indicate the details of the speed change"* - R6. Overall, participants saw value in multimodal eHMIs but explained that auditory signals have issues with scalability and inclusivity and may be lost with environmental noise.

Sensing and V2X Participants suggested more complex feedback from eHMIs: *"a graphic that moves the way I move"* - C5. This involves more advanced vehicle sensors tracking the cyclist with eHMIs reacting to movements. Moreover, some participants used V2X to improve interaction: *"we extend the 'eyes' of all vehicles for the benefit of cyclists"* - C2. This took two forms: (1) AVs communicating the state of other vehicles: *"what if the car could tell me what the car behind it is going to do"* - C6; and (2) a direct connection between the AV and the cyclist: *"I think communication between the AV and bike computer is really important"* - C5. Therefore, this theme shows that cyclists are open to HACIs.

4.1.7 Discussion and Design Synthesis

This study identified the design features that AV-cyclist eHMIs should adopt from the perspective of researchers and cyclists. Participants were welcoming of eHMIs, as they use a familiar placement for interaction and address a clear problem: communicating explicit signals from AVs. They explained that relying solely on AV implicit cues would be insufficient, which aligns with the previous chapter's findings. This study used a novel methodology in which participants collaborated around real parked cars to develop their concepts. This method was effective, as the concepts aligned with the findings from the previous chapter, even though they were designed through the perceptions of participants. For example, all designs accounted for cyclists being anywhere around the vehicle, so messages are perceivable from all vehicle sides. Similarly, most designs communicated AV awareness and intentions; the observations in the previous chapter showed that these are key messages exchanged during interaction.

The emphasis on awareness and intentions also aligns with previous eHMIs designed for drivers and pedestrians [37]. These messages are key for AV-HRU interaction [82]. In contrast, participants were not welcoming of AVs instructing cyclists and needed greater autonomy to make decisions based on AV intentions. This aligns with previous work with pedestrians, showing that AVs should negotiate with road users rather than enforce their right of way [39]. It also shows that AVs must behave similarly to human drivers; the previous chapter showed that drivers use social and implicit cues to negotiate rather than instruct cyclists. Participants also accommodated this in their designs; they incorporated more advanced sensors to detect their subtle cues, and this was partly to prepare AVs for negotiation rather than limiting eHMIs to display instruction signals. This aligns with the *"driver-cyclist communication is two-way"* design guideline from the previous chapter and shows that this guideline generalises to AVs.

Participants deduced various ways to communicate AV intentions, either through new types of signals, such as a lightning bolt icon for not-yielding, or more familiar signals, such as traffic signs and red and green colour schemes. However, participants raised the issue of traffic features in eHMIs being associated with instruction signals, as these features are currently used to instruct cyclists on the right of way. Previous AV-HRU research has not provided a clear consensus on this issue. Some research has found that using red and green in eHMIs could be associated with instructing pedestrians to cross [39], while other works showed that red and green signals are highly effective and usable as intention messages because they are quick to recognise and distinguish [58]. The upcoming studies in this chapter explore this issue further.

Participants also incorporated V2X antennas into their designs to allow cyclists to receive signals through wearable devices. Therefore, participants from this study also saw value in eHMIs being incorporated into HACIs, and this further emphasises the acceptability of HACIs. Interestingly, participants discussed the four key AV-cyclist interface design challenges this thesis investigates without being prompted by experimenters. This shows that acceptability, versatility, scalability, and cultural inclusivity are issues researchers and cyclists acknowledge should be resolved before interfaces can be used on real roads. This further motivated the studies conducted in this thesis.

Regarding versatility, there were some subtle differences between eHMIs designed for each scenario category. For example, participants were mostly concerned about AVs overtaking them once traffic lights turn green in controlled scenarios and designed their eHMIs accordingly; they included cues such as Doppler effect audio to communicate the relative distance of the AV behind the cyclist. In contrast, participants designing for uncontrolled infrastructure designed eHMIs that communicate messages to overcome many issues observed in today's traffic. For example, they incorporated features to warn cyclists of left-hook turns or used V2X to also

	Message	Modality	Familiarity Level	Technology	Placement
Safe Zone	AV Intentions	Visual	Traffic Signs/Colours	Display	Bonnet
	AV Intentions	Visual	Traffic Signs/Colours	Road Projection	Around Vehicle
Emoji-Car	AV Intentions	Visual	New to Traffic	Display	Roof
	Vehicle State	Visual	New to Traffic	Lights	Roof
LightRing	AV Intentions + Awareness	Visual	New to Traffic	Lights	Around Vehicle

Table 4.1: The three new eHMIs classified according to the eHMI taxonomy.

display the intentions of other vehicles in congested areas. This is likely due to at least one road user being stationary in these scenarios, and this allows for the communication of more detailed signals. However, it also shows that eHMIs are not restricted to compensating human drivers and can be used to improve the overall interaction experience through emerging technologies. Designs for dynamic manoeuvres all used red/green projections around the vehicle to communicate AV intentions. These signals may align with the fast-paced interactions in these scenarios as they are simpler than more complex animations in other designs. Previous work on AV-cyclist interaction during lane merging found red/green projections to be highly usable [67], and the previous chapter showed that this is a large surface that allows cyclists to recognise signals while maintaining their riding behaviours.

Design Synthesis

Participants designed for individual traffic scenario categories. It was critical to synthesise new versatile eHMIs for evaluation in follow-up studies. This section uses the taxonomy to identify overlapping features between designs for different scenario categories, suggesting that these features work across scenarios. Three new concepts were developed, each capturing a distinct aspect of the results. All new concepts used only visual cues because the eHMIs in this chapter were developed to be baseline interfaces for HACIs, and participants in this study highlighted many issues with auditory signals. For example, they may get lost in the environment or be difficult to map to the correct AV when there are multiple vehicles around the cyclist. Previous work has also found similar issues with auditory eHMIs [37, 123]. Moreover, previous research on cyclists showed that they prefer clear, visual signals as the primary source of information in eHMIs [67]. This leaves room for auditory and haptic modalities to be incorporated through other devices in a HACI. Table 4.1 classifies the three new eHMIs according to the taxonomy. The eHMIs are discussed below.

Concept 1: Safe Zone

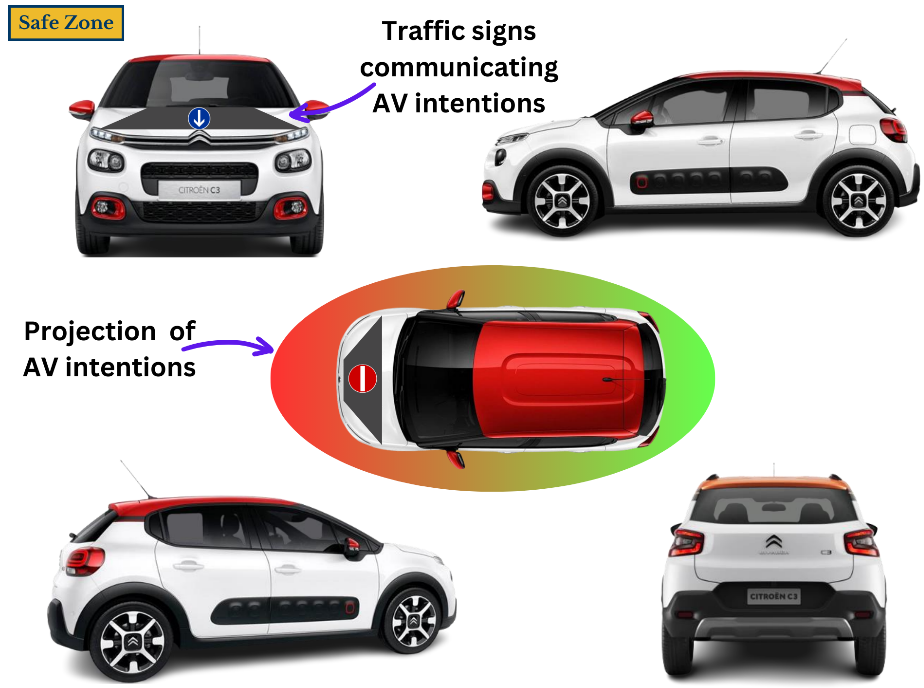

Figure 4.6: Safe Zone: Uses road projections and a bonnet display to communicate with cyclists using traffic signs and colours.

Safe Zone is visualised in Figure 4.6. This design uses red and green road projections and a bonnet display showing traffic signs to communicate AV intentions to cyclists. This allowed an exploration of the *"Familiarity of eHMI messages"* subtheme as it reuses traffic control features for eHMI signals. The taxonomy showed that cyclists must know AV intentions to resolve space-sharing conflicts, and road projections were a particularly popular approach for displaying these signals. Therefore, road projections were incorporated into this design by drawing from Teams 3, 4, 5 and 6. These road projections were red if the AV was not yielding and green if it was. Red/green projections were repurposed from Teams 5 and 6's designs to allow cyclists to differentiate between AV intentions through contrasting colours, which was effective with pedestrians [39].

The *"Varying road conditions"* subtheme suggests that road projections may not be effective across road textures and weather conditions, so it was critical to incorporate a failsafe. Therefore, a bonnet display was added; this drew from Team 3. It displayed a *stop* sign if the AV was not yielding and a *go* sign in the form of a white arrow with a blue background if the AV was yielding. This allowed further exploration of reusing traffic control features for eHMI signals, which was particularly important to understand whether cyclists perceive these signals as intentions or instructions from the AV. Safe Zone may be effective as it uses the road as a design space. Cyclists may prefer signals that reuse traffic control features, as this would require a smaller learning curve than introducing new signals to eHMIs. This was critical to evaluate in the following study.

Concept 2: Emoji-Car

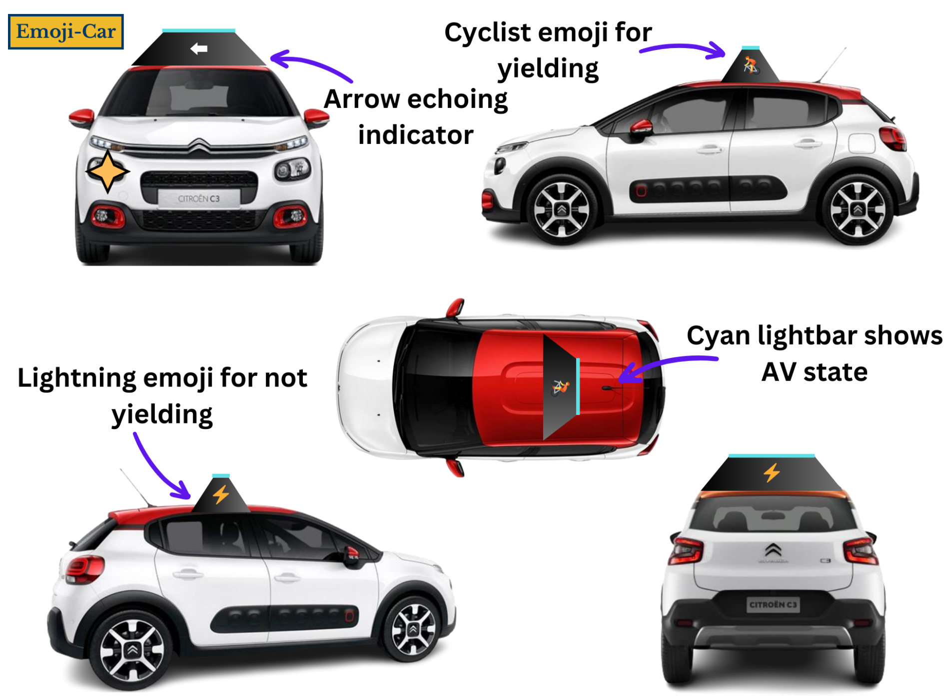

Figure 4.7: Emoji-Car: A display on the roof; this uses emojis to communicate with cyclists.

Emoji-Car is visualised in Figure 4.7. This eHMI features a display on the roof that communicates AV intentions through emojis. The majority of participant designs were placed on large surfaces on the vehicle, such as its side and back body. This aligns with the results from the eye-tracking study, as cyclists naturally fixate on these areas. However, it was also critical to explore other placements that allow messages to be perceived from anywhere around the vehicle. The roof is a promising possibility as it allows eHMIs to be perceivable from different vehicle sides without taking up much vehicle space. This was evident in Team 6's design. It was critical to further explore the roof as an eHMI placement. Therefore, Emoji-Car was a roof display with screens on all four sides. The roof currently has no signals that are critical for interaction, so cyclists may need more time to get accustomed to the roof placement.

The use of emojis was drawn from Team 5, who used a smiley face to provide feedback to cyclists, and Team 6, who used a lightning bolt to convey that the AV was not yielding. Emoji-Car displayed a lightning bolt on the side the cyclist was on when the AV did not yield, and a cyclist emoji when the AV yielded. The cyclist emoji could also implicitly communicate the AV's awareness of the cyclist. Cyclists may be familiar with emojis as these symbols are already used, e.g. in smartphones [10]. Emojis are also used in traffic; for example, some roadside displays show a smiley face when drivers are within the speed limit [95]. Therefore, these are not entirely new symbols specific to the eHMI.

The *"Essential messages to communicate"* subtheme showed that cyclists could benefit from knowing the vehicle's state: autonomous mode with all sensors functioning correctly. Team 2 also included a light bar around the AV to communicate this. Emoji-Car features an always-on cyan light bar on top of the display to communicate the AV state. Having the display 'always-on' in cyan was useful for communicating that the vehicle is in autonomous mode with all sensors functioning correctly. This was first introduced in Dey et al.'s [39] light-band design, but has appeared in real traffic. For example, the 2024 Mercedes S Class uses cyan lights when it is in autonomous mode [132]. This could be a useful transitional feature to inform cyclists riding in mixed traffic with AVs and manually driven vehicles that the vehicle is autonomous, and they should expect signals from the eHMI rather than a human driver. It could also improve perceived safety, as riders will know that all sensors in the AV are functioning.

The interplay of eHMIs and on-vehicle signals is a compelling feature to explore. The design guidelines from the previous chapter emphasised that eHMIs must coexist with more traditional signals, and the *"eHMIs, driving behaviour and vehicle signals"* theme from this study reiterated this. Some participants echoed vehicle signals through eHMIs to improve cyclist situational awareness. For example, Team 3 played a directional indicator sound to alert cyclists of left-hook turns. Therefore, Emoji-Car displayed a blinking arrow emoji on the front screen that was synchronised with the directional indicator.

Concept 3: LightRing

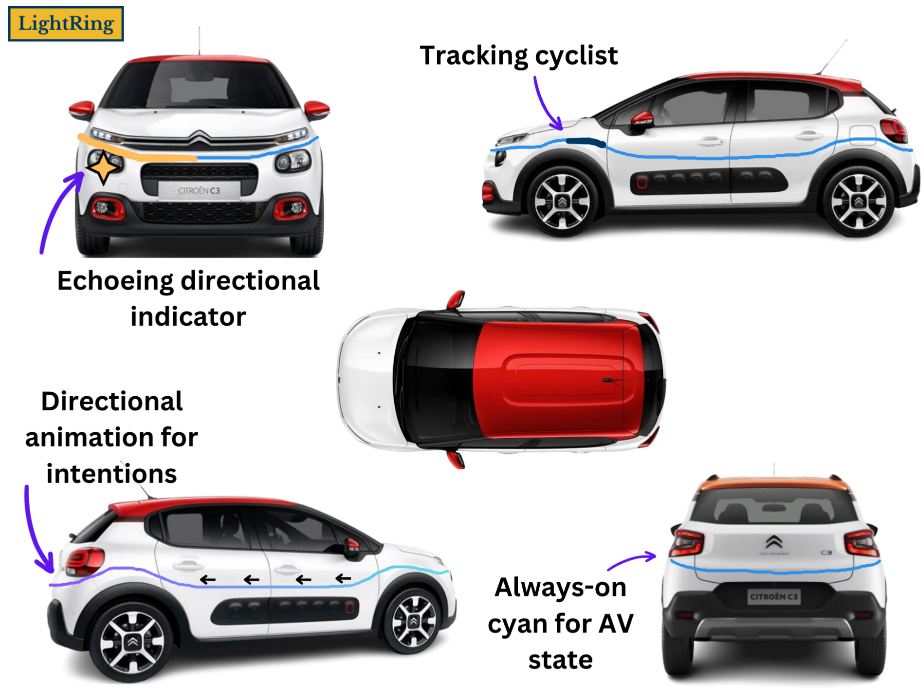

Figure 4.8: LightRing: A cyan LED light strip around the vehicle that uses animations to communicate with cyclists.

LightRing is visualised in Figure 4.8. This concept is based on Dey et al.'s [39] light-band design for pedestrians, readjusted also to address cyclists' needs. This is beneficial, as the design may be inclusive enough to work with other road users, such as pedestrians. Similar to the cyan display in Emoji-Car, LightRing uses an always-on cyan lightbar to communicate the AV state. However, this is around the vehicle rather than on the roof, which could improve visibility as it allows the signals to be viewable on a large surface from anywhere around the AV. This also differentiates it from Dey et al.'s [39] light-band design, which was only placed on the vehicle's bumper. Placing displays around the vehicle was a popular approach in the taxonomy, and many designs used larger surfaces, such as the side body. Similar to Dey et al.'s [39] approach, all signals are displayed on the lightbar. This contrasts LightRing from Emoji-Car, which used a separate display from the cyan light bar to display AV intentions.

In contrast to the previous designs, LightRing directly adheres to the *"Essential messages to communicate"* subtheme to explicitly display AV awareness. Similar to Team 2's design, the cyclist is tracked using a visible sensor on the AV's roof, and LightRing displays a navy blue colour, reacting to the cyclist and getting wider as the cyclist moves closer. AV intentions are communicated through animations, as in Dey et al.'s [39] light-band. The cyan lights are animated by stroking apart from the front centre (on the front bumper) when the vehicle is not yielding and moving toward the front centre when the AV is yielding at one stroke per second.

Therefore, LightRing contrasts with Safe Zone and uses signals that are entirely new to traffic to communicate AV intentions. LightRing also echoes directional indicators by having the relevant side blinking in amber in sync with the vehicle's indicators.

Overall, three new eHMIs were synthesised for evaluation in follow-up studies. Safe Zone used red/green road projections and traffic signs on a bonnet display to communicate AV intentions. Investigating this was critical to assess the usability of road projections across multiple traffic scenarios and uncover any ambiguity issues associated with using traffic features in eHMIs. Emoji-Car used a roof display to communicate AV intentions through emojis. This facilitated an exploration of using vehicle areas that do not currently display any critical signals for interaction. Finally, LightRing adapted Dey et al.'s [39] light-band eHMI for cyclists. This would further highlight any similarities and contrasts between pedestrians and cyclists. Investigating LightRing could help contribute to more inclusive eHMIs. These designs were implemented and tested in VR in the following study.

4.2 Study 5: VirtuRide eHMI Evaluation

The versatility and usability of Safe Zone, Emoji-Car and LightRing were unconfirmed. The designs were conceptual and not tested in practice. This study evaluated the eHMIs (and a baseline condition with no eHMI) across five traffic scenarios. Scenarios featured varying levels of traffic control and AV positions relative to the cyclist to maximise their differences. VirtuRide, a VR cycling simulator, was developed for the study. Participants wore a VR headset and used a stationary bicycle to navigate a virtual environment. They interacted with virtual AVs equipped with each eHMI across the five scenarios. Participants provided feedback on the eHMIs after each scenario, and VirtuRide logged key cyclist behaviours, including gaze patterns, speed, and shoulder checks. This allowed for a comprehensive comparison of the eHMI usability and versatility. This was the first AV-cyclist interaction study focusing on assessing interface versatility.

4.2.1 Experiment Design

This was a within-subjects study with two independent variables: *eHMI* and *Traffic Scenario*. The dependent variables were cyclist *perceptions* and *behaviours* toward each eHMI in each scenario. Participants used VirtuRide to navigate a virtual urban environment. They encountered AVs using each eHMI across different traffic scenarios. Participants indicated their perceptions of the eHMIs through questionnaires, and VirtuRide logged their behaviours.

Figure 4.9: The evaluated eHMIs as implemented in VirtuRide. The photos on the left show Safe Zone; the middle show Emoji-Car; the right show LightRing.

Study scope

The eHMIs tested in this study were synthesised from the previous design sessions and included *Safe Zone*, *Emoji-Car*, and *LightRing*; Figure 4.9 shows how these were implemented in VirtuRide. Additionally, a baseline *No eHMI* condition was included; no display was present on the vehicle, meaning participants did not receive any explicit signals from the AV.

The *Traffic Scenarios* were adapted from the eye-tracking study in Chapter 3; vehicle driving behaviours and obstacles were modelled after the video footage collected in that study. Scenarios featured distinct levels of traffic control and AV positions relative to the cyclist. This maximised the contrast between them and supported the exploration of eHMI versatility. Traffic scenarios are visualised in Figure 4.10 They were:

- **Controlled Intersection:** The controlled intersection had four arms. Each arm had stop lines and traffic lights to determine the right of way. The AV approached from the cyclist's left. It accelerated to 50 kilometres per hour (km/h) when the cyclist was 50 metres away. The AV yielded and stopped 0.5 metres behind the stop line if the traffic lights dictating its behaviour were red. It maintained its speed and continued straight if the lights were green. Traffic lights dictating the cyclist's behaviour were red for 30 seconds before changing state.

- **Roundabout:** This had four arms, with give-way lines on each arm. The AV approached from the cyclist's left. It accelerated to 50 km/h when 50 metres from the cyclist and stopped 0.5 metres behind the give-way line if yielding. It maintained its speed and

Figure 4.10: The traffic scenario setup in VirtuRide. The top photo shows a track featuring seven scenarios. The second and third rows show the setup of each traffic scenario. The right photo on the third row shows a cyclist's POV when encountering an AV using Emoji-Car in a Bottleneck.

continued straight (taking the second exit) when not yielding. The vehicle used its left direction indicator before taking the second exit as observed in Chapter 3.

- **Uncontrolled Intersection:** This was a four-way intersection; it had four arms. There were give-way lines on each arm. The AV approached from the cyclist's left. It accelerated to 50 km/h when 50 metres from the cyclist and stopped 0.5 metres behind the give-way line if yielding. It maintained its speed and continued straight when not yielding.

- **Bottleneck:** This was a narrow lane with parked cars on both sides. The AV approached from opposite the cyclist. One road user had to steer away. The AV drove at 25 km/h, steered left (with the direction indicator active), and stopped between two parked cars when yielding. It continued straight and maintained speed when not yielding.

- **Lane Merging:** Road repairs obstructed the cyclist's path, forcing them to move to the other lane with an AV approaching from behind. Therefore, cyclists had to merge lanes with this AV. The AV drove at 40 km/h and decelerated to 15 km/h when yielding. It maintained its speed when not yielding.

Study setup

Scenarios were organised into four *tracks*, each representing a specific eHMI condition, meaning all AVs within a track used the same eHMI. Each track was a 1 kilometre straight, two-lane road. Participants cycled in the left lane and had the right-of-way at intersections and roundabouts in line with UK traffic regulations [128].

Each track included the five scenarios where the AV yielded to the cyclist and two additional non-yielding scenarios. The non-yielding scenarios were randomly selected and excluded from the analysis. They were used to minimise learning effects and maintain participant attentiveness. Traffic scenarios were presented in random order within each track and were spaced 100 metres apart. Participants cycled through all seven scenarios to complete a track. The order of eHMI conditions was counterbalanced using a Latin square design to reduce potential biases.

Measures

The following data were collected:

- **Post-Scenario Questionnaire:** This was answered after each *Traffic Scenario* to measure versatility. The questionnaire featured the NASA Task Load Index (NASA-TLX) [61] to measure the interaction workload. It also featured two five-point Likert scale (strongly disagree-strongly agree) questions to measure participant confidence in the AV's awareness of them and its intentions, as these were shown to be essential messages in prior work [82] and the previous design sessions. The questions were: *"The AV was aware of my presence"* and *"I was confident in the AV's next manoeuvre"*. The tabular format of the questionnaire is in Appendix B.2;

- **Post-Track Questionnaire:** This was answered after each group of *Traffic Scenarios* (track) to provide an overall assessment of the eHMI and its usability. The questionnaire featured the Anxiety and Perceived Performance dimensions of the Car Technology Acceptance Model (CTAM) [94] adapted for cyclists. It also included a five-point Likert scale question to assess perceived safety (strongly disagree-strongly agree): *"I felt safe using the interface while riding"*. The questionnaire assessed usability with the User Experience Questionnaire - Short Version (UEQ-S) [114]. These questions were previously used to evaluate cycling interfaces and AV-pedestrian eHMIs [40, 140]. The tabular format of the questionnaire is in Appendix B.3;

- **Cycling Behaviour:** VirtuRide logged key cyclist behaviours when using each *eHMI* in each *Traffic Scenario*. Cycling speed in metres per second (m/s) was logged every second. The number of shoulder checks conducted was also logged; a shoulder check occurred when the Unity camera (participant's head) Y-axis rotation > 45°, as determined through eight pilot tests. VirtuRide also logged any collisions that occurred between the participant

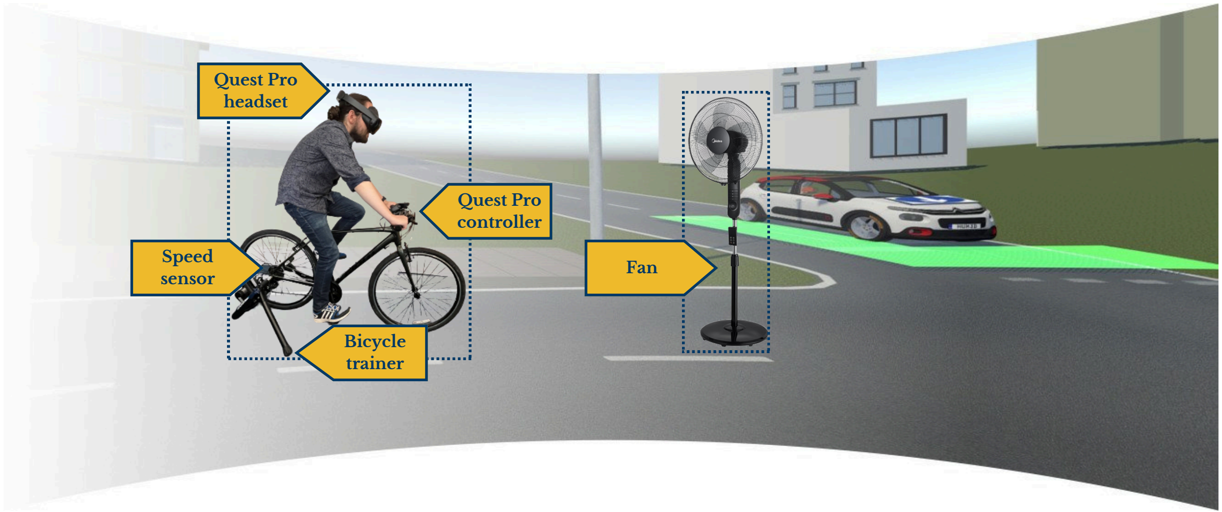

Figure 4.11: VirtuRide's hardware setup. This featured a VR headset and a stationary bicycle mounted on an indoor trainer. A speed sensor was attached to the bike's back wheel hub, and a headset controller was attached to the handlebar to translate speed and steering in VR. The setup also included a fan to simulate headwind.

and an AV. Finally, VirtuRide also logged the number of *gaze visits* on an AOI. AOIs were adapted from the eye-tracking cycling study in Chapter 3. They covered vehicle (e.g., windscreen) and traffic control features (e.g., traffic lights);

- **Qualitative Data:** Post-study semi-structured interviews were used to contextualise the findings. Participants discussed and ranked each eHMI. They highlighted any points for improvement, discussed the different scenarios and identified ones that they felt needed/did not need eHMIs.

4.2.2 VirtuRide Components and Apparatus

VirtuRide (see Figure 4.11) was developed in Unity using the EasyRoads3D package[3]. This was chosen for its realistic road textures and assets resembling UK road infrastructure, enabling an accurate recreation of the traffic scenarios explored in the study. All virtual AVs were 3D models of a 2019 Citroen C3 to maintain consistency with the real vehicle used in the previous design sessions and the remaining studies in the thesis. AV movements were pre-recorded animations that triggered depending on the cyclist's position.

The simulator comprised a Giant Escape 3 hybrid bicycle[4] mounted on a Wahoo Kickr Snap smart trainer[5]. Similar to a previous VR simulator setup from Hou et al. [67], the wheel-on trainer allowed participants to use the bike's rear brake in the virtual environment without mod-

[3]EasyRoads3D Unity Package: `easyroads3d.com` ; Accessed 01/04/2025
[4]Giant Escape 3 bicycle: `giant-bicycles.com/gb/escape-3` ; Accessed 01/04/2025
[5]Wahoo Kickr Snap Bicycle Trainer: `https://shorturl.at/2t98P` ; Accessed 01/04/2025

ifying the bicycle. A Coospo Bluetooth speed sensor[6] was attached to the rear wheel hub to control speed in VR. VirtuRide used a Meta Quest Pro headset[7] to display the virtual environment and measure gaze behaviour using its integrated eye-tracker. As in Hou et al.'s [67] VR simulator, the headset's left controller was attached to the handlebar centre to translate turn angles into the virtual world based on controller rotation. A fan was placed 60 centimetres in front of participants to simulate headwind. This enhanced immersion and mitigated simulator sickness [89].

VirtuRide was particularly useful for displaying high-fidelity eHMI prototypes without needing much real-world apparatus or space restrictions [67, 89]. This was helpful as the follow-up study required real eHMI prototypes, so any feedback and design revisions would be incorporated before building the real prototypes. VirtuRide also allowed factors such as lighting and weather to be fully controlled [140]. It helped participants to experience accurate and detailed representations of the traffic scenarios, such as placing a statue on the roundabout or traffic lights on the controlled intersection.

4.2.3 Participants

The study included 20 participants recruited through social media advertising. This sample size was chosen because it is considered standard in HCI [22] and the AV interaction domain [14, 37], so it aligns with similar studies in the field [47, 67, 84, 125, 137, 146]. This also enabled five complete repetitions of the Latin Square design, helping to mitigate potential ordering effects. All participants had experience riding in the UK, which was the basis for the VR environment used in the study. Their demographics were: $M_{\text{age}} = 29$, $SD = 6.6$; $Male = 16$, $Female = 4$.

Participants were a mix of beginners and regular cyclists. This was important as not all cyclists encountering AVs will be expert riders. Ten participants cycled at least once a week, two at least once a month, five multiple times a year, and three once a year or less.

4.2.4 Procedure

Each participant answered a survey on their demographics and cycling experience. The experimenter then briefed them about the study and showed videos of the eHMIs to familiarise them with the signals. They were then familiarised with the simulator; the experimenter ensured the participant was comfortable with the bike gear and saddle height by riding for three minutes with no headset; adjustments were made when needed. The participant then put on the headset and practised between 7 and 15 minutes of virtual cycling in a car park environment to become familiar with the VR setup and reduce novelty effects.

[6]Coospo Cycling Speed Sensor: `shorturl.at/T7GNU` ; Accessed 01/04/2025
[7]Meta Quest Pro: `meta.com/gb/quest/quest-pro/` ; Accessed 01/04/2025

	eHMI				Scenario				
	Safe Zone	*Emoji-Car*	*LightRing*	*No eHMI*	*C-Intersection*	*Roundabout*	*U-Intersection*	*Bottleneck*	*L-Merging*
Workload	3.10 ± 3.20	5.08 ± 4.10	5.73 ± 4.25	5.75 4.14	3.90 ± 3.55	4.79 ± 3.70	4.67 ± 3.85	5.62 ± 4.34	5.66 ± 3.55
Awareness Confidence	4.26 ± 1.0	4.02 ± 1.24	3.73 ± 1.10	2.91 1.51	3.47 ± 1.36	3.81 ± 1.21	3.87 ± 1.25	3.85 ± 1.29	3.64 ± 1.46
Intention Confidence	4.31 ± 0.91	3.65 ± 1.39	3.16 ± 1.40	2.65 1.47	3.49 ± 1.41	3.50 ± 1.37	3.53 ± 1.43	3.61 ± 1.43	3.05 ± 1.54
Cycling Speed	5.31 ± 1.44	5.23 ± 1.48	4.85 ± 1.33	5.08 1.44	5.41 ± 1.41	5.12 ± 1.43	5.14 ± 1.44	4.73 ± 1.35	5.27 ± 1.45

Table 4.2: Mean ± Standard Deviation (SD) of each Post-Scenario Questionnaire subscale for each eHMI and Traffic Scenario condition.

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 and turned on the fan. The participant started cycling to navigate the track. 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 experienced all eHMI conditions. A semi-structured interview followed the experiment. The study took approximately 90 minutes. Participants were compensated for their time with £10 Amazon vouchers.

4.2.5 Results

This section reports cyclist perceptions and behaviours toward each eHMI in each traffic scenario. It starts by reporting the Post-Scenario Questionnaire results, followed by the Post-Track Questionnaire and insights into Cycling Behaviour. These findings are contextualised with themes resulting from post-study interviews.

Post-Scenario Questionnaire

The data were not normally distributed; a two-way Aligned Rank Transform (ART) ANOVA [147] was conducted to examine the fixed effects of *eHMI*, *Traffic Scenario* and their interactions on each Post-Scenario Questionnaire subscale. The model included a random intercept for *Participant* to account for individual variability. *Post hoc* tests between *Traffic Scenario* and *eHMI* pairs were performed using the ART-C method [51]. Mean values are in Table 4.2. These are also visualised as box plots in Figure 4.12.

The overall results show that all eHMIs were versatile and performed consistently between traffic scenarios. The *No eHMI* condition consistently underperformed, so cyclists needed an interface to navigate space-sharing conflicts without ambiguity. *Safe Zone* was the best performing display as participants experienced a lower workload and were confident in the AV's awareness and intentions when it was used. Results also showed that *Lane Merging* was a challenging scenario as the AV was behind the cyclist and out of view.

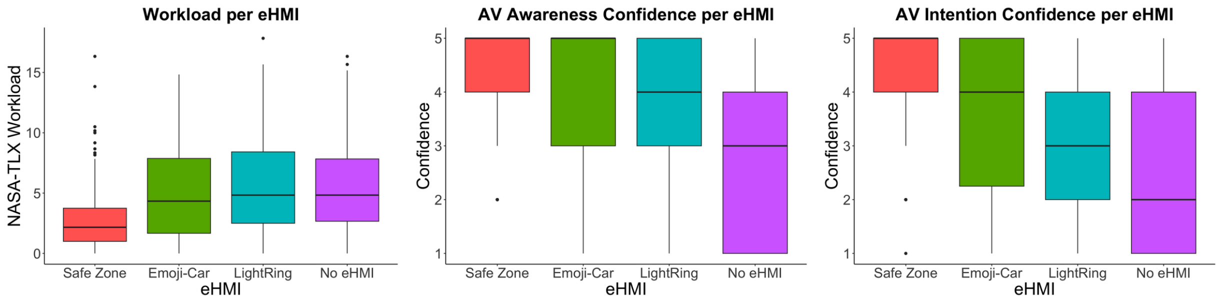

Figure 4.12: Mean ± SD of each Post-Scenario Questionnaire subscale per eHMI. Left for Workload, middle for confidence in AV awareness, and right for confidence in AV intentions. Safe Zone consistently outperformed the other conditions.

Workload (overall NASA-TLX score) There were significant effects of *eHMI* (F(3, 349.78) = 23.49, $P < .001$; $\eta^2 = 0.17$) and *Traffic Scenario* (F(4, 349.68) = 4.92, $P < .001$; $\eta^2 = 0.05$). This means the workload differed depending on the eHMI, and not all traffic scenarios required the same workload. However, there was no interaction between them (F(12, 349.77) = 0.96, $P = .5$). This suggests that each eHMI imposed a similar workload across the scenarios, meaning the eHMIs performed consistently and were versatile in this context.

Post hoc comparisons between *eHMI*s showed that *Safe Zone* significantly lowered the workload compared to all other conditions ($P < .0001$ for all). *Emoji-Car* also significantly lowered workload compared to *No eHMI* ($P = .03$). Therefore, explicit signals about AV intentions significantly reduced the interaction workload. However, these must be distinguishable through colour changes or icons to be effective. *Post hoc* comparisons between *Traffic Scenarios* showed that *Controlled Interaction* required a significantly lower workload than *Bottleneck* ($P = .003$) and *Lane Merging* ($P = .001$). Therefore, the workload was significantly reduced when traffic lights were present.

Confidence in AV Awareness There were significant effects of *eHMI* (F(3, 350.19) = 32.48, $P < .001$; $\eta^2 = 0.22$) and *Traffic Scenario* (F(4, 349.95) = 2.64, $P < .05$; $\eta^2 = 0.03$). This means that each factor influenced cyclists' confidence in AV awareness. However, they had no interaction (F(12, 350.11) = 0.93, $P = .5$). Therefore, eHMIs were versatile and performed consistently between traffic scenarios.

Post hoc comparisons between *eHMIs* showed that participants were significantly more confident in the AV's awareness when using *Safe Zone* than *LightRing* and *No eHMI* ($P < .0001$ for both). Similarly, participants were significantly more confident when using *Emoji-Car* than *LightRing* ($P = .008$) and *No eHMI* ($P < .0001$). Therefore, LightRing underperformed despite explicitly communicating awareness through colour changes. No significant differences were found between *Traffic Scenarios*.

	eHMI			
	Safe Zone	*Emoji-Car*	*LightRing*	*No eHMI*
Cycling Performance	4.50 ± 1.25	3.88 ± 1.13	3.25 ± 2.06	2.50 ± 1.81
Anxiety	2.58 ± 1.38	2.83 ± 1.54	3.25 ± 1.21	3.33 ± 1.00
Perceived Safety	4.00 ± 2.00	3.00 ± 2.00	2.00 ± 2.25	2.00 ± 1.00
Usability	1.38 ± 1.50	0.69 ± 1.49	-0.06 ± 1.53	-0.75 ± 1.28

Table 4.3: Median ± Interquartile Range (IQR) of each Post-Track Questionnaire subscale for each eHMI.

Confidence in AV Intentions There were significant effects of *eHMI* (F(3, 350.38) = 36.17, $P < .001$; $\eta^2 = 0.24$) and *Traffic Scenario* (F(4, 350.03) = 3.79, $P < .005$; $\eta^2 = 0.04$). They had no interaction (F(12, 350.23) = 0.83, $P = .6$). Similar to the previous results, the eHMI and the traffic scenario they navigated influenced cyclist confidence in AV intentions. However, eHMIs were versatile and performed consistently between scenarios.

Post hoc comparisons between *eHMI*s showed that participants were significantly more confident when using *Safe Zone* than *Emoji-Car* ($P = .0008$), *LightRing* ($P < .0001$), and *No eHMI* ($P < .0001$). This suggests that projecting AV intentions onto the road is an effective approach. Participants were significantly less confident when there was *No eHMI* compared to *Emoji-Car* ($P < .0001$) and *LightRing* ($P = .007$). This shows that cyclists need explicit signals to interpret AV intentions confidently. *Post hoc* comparisons between *Traffic Scenario*s showed that they were significantly more confident when navigating *Bottleneck* than *Lane Merging* ($P = .002$). Therefore, confidence was reduced when the eHMI was behind the cyclist and out of their view.

Post-Track Questionnaire

The data were not normally distributed; a Friedman's test was conducted to examine the effect of *eHMI* on each *Post-Track Questionnaire* subscale. *Participant* was treated as a blocking factor to account for individual variability. *Post hoc* comparisons between eHMI pairs were performed using the Nemenyi test. Results are in Table 4.4. Median values are in Table 4.3. Figure 4.13 visualises these as box plots.

The overall results showed that Safe Zone is the best performing eHMI. Participants felt safer and less anxious when it was used. The No eHMI condition consistently underperformed. LightRing also did not perform well, as participants felt unsafe and gave it a low usability score; this could be due to its animations being more challenging to differentiate than Safe Zone's colour-coded signals.

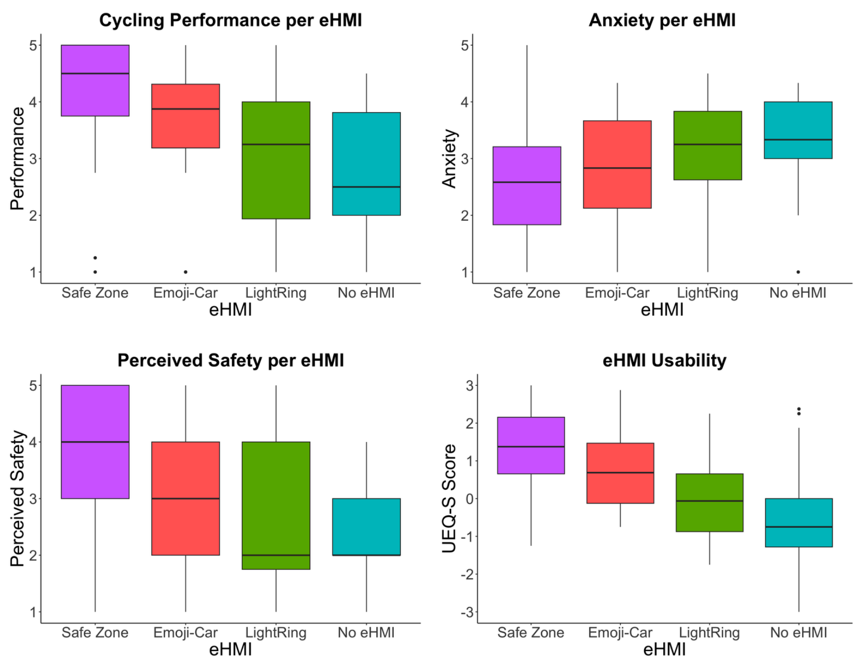

Figure 4.13: Median ± IQR of each Post-Track Questionnaire subscale per eHMI. Safe Zone consistently outperformed the other conditions, and No eHMI consistently underperformed.

Measure	**Friedman's Test**	**Significant *Post Hocs***	**Takeaway**
Cycling Performance	$\chi^2 = 24.934$, df = 3, $P < .001$; $\eta^2 = 0.29$	*Safe Zone* > *LightRing* ($P = .002$) *Safe Zone* > *No eHMI* ($P = .0001$) *Emoji-Car* > *No eHMI* ($P = .03$)	Cycling performance was increased when communicating explicit signals that were quick to recognise and distinguish.
Anxiety	$\chi^2 = 12.094$, df = 3, $P < .01$; $\eta^2 = 0.12$	*Safe Zone* < *LightRing* ($P = .04$) *Safe Zone* < *No eHMI* ($P = .02$)	Road projections were most effective for reducing anxiety as cyclists did not have to shift their attention significantly.
Perceived Safety	$\chi^2 = 17.981$, df = 3, $P < .001$; $\eta^2 = 0.2$	*Safe Zone* > *LightRing* ($P = .01$) *Safe Zone* > *No eHMI* ($P = .005$)	Participants felt safer when AV intentions were easy to confirm on a large surface.
Usability (UEQ-S Score)	$\chi^2 = 29.793$, df = 3, $P < .001$; $\eta^2 = 0.35$	*Safe Zone* > *No eHMI* ($P < .0001$) *Safe Zone* > *LightRing* ($P = .003$) *Emoji-Car* > *No eHMI* ($P = .002$)	eHMIs improved usability, but their signals must be easy to comprehend while moving.

Table 4.4: Friedman's test results for each Post-Track Questionnaire subscale. Safe Zone consistently outperformed the other conditions, while LightRing and No eHMI underperformed.

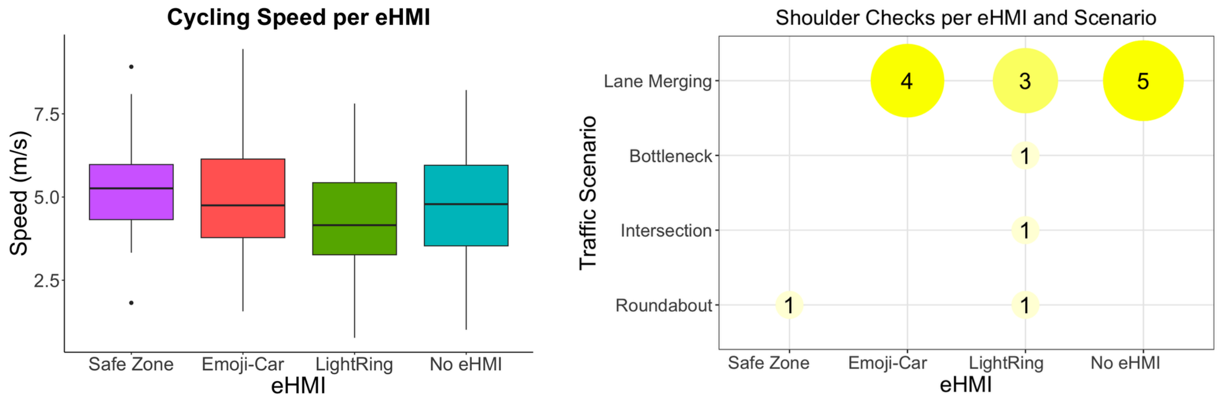

Figure 4.14: Cycling behaviours logged by VirtuRide. Left: shows a box plot of the mean ± SD Cycling Speed per eHMI. Right: shows a dot plot of the number of shoulder checks conducted per eHMI and Traffic Scenario. LightRing caused the most cumbersome behaviours, as participants cycled slower and conducted shoulder checks more frequently.

Cycling Behaviour

This section reports cyclist behaviours when using each *eHMI*. The overall trend shows that *Safe Zone* outperformed the other eHMIs even in cycling behaviour; participants were more comfortable to cycle faster and conduct fewer shoulder checks. There were also no collisions when *Safe Zone* was used. *Safe Zone* also required less attention according to gaze data. In contrast, *LightRing* underperformed, causing participants to cycle more slowly and resulting in more collisions. Figure 4.14 shows speed and shoulder checking behaviours for each *eHMI*.

Cycling Speed The data were not normally distributed, so speed was analysed using the same approach as the Post-Scenario Questionnaire. There was a significant effect of *eHMI* (F(3, 361) = 11.92, $P < .001$; $\eta^2 = 0.09$) and a significant effect of *Traffic Scenario* (F(4, 361) = 19.33, $P < .001$; $\eta^2 = 0.18$). However, there was no interaction (F(12, 361) = 0.64, $P = .8$). Therefore, eHMIs remained versatile even in cycling behaviours. *Post hoc* comparisons between *eHMI*s showed that participants were significantly faster when using *Safe Zone* than *Emoji-Car* ($P = .05$), *LightRing* ($P < .0001$) and *No eHMI* ($P = .003$). Therefore, participants could quickly process colour-coded AV intention signals while riding at higher speeds. In contrast, participants were significantly slower around *LightRing* than *Emoji-Car* ($P = .0053$). They had to slow down to differentiate between eHMI animation patterns. *Post hoc* between *Traffic Scenarios* showed that participants were significantly faster at *Controlled Intersection* than *Roundabout* ($P = .03$), *Uncontrolled Intersection* ($P = .01$) and *Bottleneck* ($P < .0001$). Traffic lights eliminated the need for right-of-way negotiation, allowing cyclists to maintain a consistent speed. They were significantly slower at *Bottleneck* than all other scenarios ($P < .0001$ for all). This is because they had to slowly ride in a narrow lane while avoiding an AV ahead.

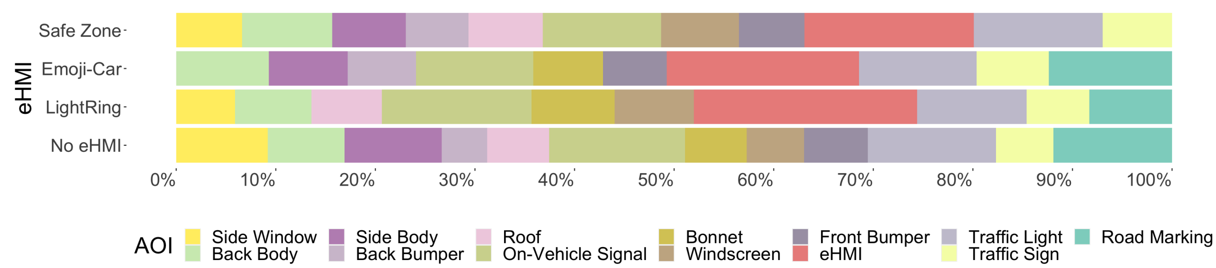

Figure 4.15: The distribution (%) of cyclist gaze visits on each AOI per eHMI condition.

Shoulder Checking A Chi-Square test of Independence was conducted to deduce the relationship between the *eHMI* and *Traffic Scenario*. No significant association was found (χ^2(9, 16) = 12.67, $P = .2$). However, Figure 4.14 shows that shoulder checks were unlikely when *Safe Zone* was used and most likely during *Lane Merging*.

Collisions VirtuRide logged 6 collisions; three occurred during *Lane Merging* when there was *No eHMI*, 2 during *Lane Merging* when *LightRing* was used, and 1 collision during the *Bottleneck* scenario when *LightRing* was used. Therefore, cyclists needed an eHMI to avoid collisions. However, these should use signals that are more straightforward to differentiate, such as colours or icons, rather than animations.

Gaze Behaviour Figure 4.15 shows the distribution of gaze visits to each AOI for each eHMI condition. A Chi-square test of independence was conducted to investigate the relationship between *eHMI* and *Visit Counts*. *Post hoc* tests were performed using a Chi-Square test of independence with a Bonferroni correction.

There was a significant association between the variables (χ^2(36, 10970) = 2187.8, $P <$ .001). *Post hoc* comparisons showed that participants relied significantly more on traffic control with *No eHMI* as they visited traffic signs/lights and road markings more often than in all other conditions ($P < .0001$ for all). Therefore, implicit cues were not enough for participants to make decisions. They had to distribute their attention between traffic control features and the vehicle. *Safe Zone* required significantly less visual attention (fewer visits to the eHMI display) than *Emoji-Car* and *LightRing* ($P < .0001$ for both). Therefore, *Safe Zone*'s signals were quick to differentiate and comprehend.

Qualitative Results

This section reports themes based on the post-study interviews. Interviews were auto-transcribed by otter.ai and corrected by a researcher. An inductive, data-driven, thematic analysis [19] was conducted on the transcripts. Transcripts were imported into NVivo for coding. One researcher extracted 42 unique codes from the data. Two researchers sorted these into three themes based

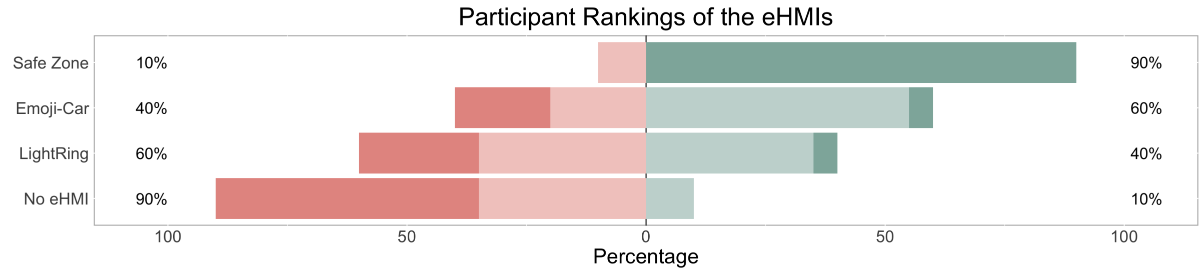

Figure 4.16: Participant rankings of the eHMI conditions. Left in red are lower ranks, and right in green are higher ranks. Safe Zone was the most favoured eHMI, and No eHMI was the lowest ranking condition.

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. Participants also ranked the eHMIs from best to worst. These rankings are visualised in Figure 4.16; *Safe Zone* was ranked as the best and *No eHMI* as the worst.

Theme 1: Safe Zone's colours were easy to recognise Participants were particularly comfortable with Safe Zone's red and green signals for AV intentions: *"I would go with conventional colours [...] They are easy to understand. I felt safer"* - P14. Red and green were perceived as clear and unambiguous: *"Red and green. Super, super intuitive. I understood very quickly what was going on"* - P2. Participants also preferred colour changes over animation, as they found them easier to process while cycling: *"LightRing would be my favourite if it used Safe Zone's colours"* - P16.

Theme 2: LightRing's animations were hard to distinguish LightRing used animations to communicate AV intentions, but these proved difficult to distinguish while cycling: *"I didn't have time to concentrate on [the animation] while cycling"* - P20. Some participants still appreciated animations but felt they should complement other, more distinguishable signals rather than serve as the primary source of information: *"I think it's tough interpreting what the car will do through animation alone"* - P18.

Theme 3: Emoji-Car's icons were too similar Participants struggled to differentiate between Emoji-Car's emojis from a distance: *"I spent more time trying to identify the emoji"* - P21; *"Interpreting emojis from far caused a lot of ambiguity"* - P13. The similarity between emojis, particularly their shared yellow colour, further hindered distinguishability: *"There is too much detail in the emojis, so I had to concentrate more. They are very similar. They both use yellow and have a similar shape"* - P20.

4.2.6 Discussion and Design Revision

All eHMIs were versatile as there were no interaction effects between the *eHMI* and *traffic scenario* independent variables in any result. This validates the previous participatory design methodology for developing versatile eHMIs. Combining overlapping features between designs for specific traffic scenario categories yields versatile concepts. There were still areas for improving the designs after testing them in VirtuRide, and this shows that AV-cyclist interfaces must be tested as part of an iterative design process to ensure usability and acceptability [67]. Therefore, the findings from this study were used to revise each eHMI.

Controlled intersections required the lowest workload out of the scenarios. Cyclists relied on traffic lights, even when eHMIs were present. For example, P15 said *"I didn't see the eHMI, I saw a green light and went"*. This coincides with the eye-tracking study from the previous chapter, where cyclists fixated more on traffic lights than nearby vehicles. It also shows that traffic control influences cyclists' interaction with AVs, even when eHMIs are present. Similarly, participants experienced a higher workload, conducted more shoulder checks and were less confident in the AV's intentions when it was behind them during lane merging. They were more comfortable when it was opposite them at bottlenecks, which also had no traffic control. This confirms that the AV's position relative to the cyclist also influences interaction with AVs [67].

Colour-coded eHMI signals

Safe Zone's red and green colour-coded signals were positively received throughout. The colours were easy to recognise and distinguish. This study and the previous design sessions showed that distinguishability is a key AV-cyclist eHMI feature, as cyclists must quickly interpret the eHMI's signal in fast-paced scenarios [66]. However, most eHMIs use one colour and rely on animation patterns to communicate AV intentions [37]. This study showed that relying solely on animation hinders distinguishability for cyclists and is ineffective in communicating sufficient information quickly, as seen with LightRing. This finding aligns with Hou et al.'s [67] who evaluated AV-cyclist interfaces for lane merging scenarios and also found that red and green signals performed well. Similarly, even though animation patterns are the current standard for communicating messages to pedestrians, Mahadevan et al. [80] found that pedestrians are also receptive to red and green signals. This provides a common ground for eHMIs that accommodate multiple road user types, including cyclists and pedestrians.

Despite the many advantages of using red and green to communicate with cyclists, there is a risk of the colours being misinterpreted as instructions from the AV rather than yielding intentions [39]. This is due to red and green being used in traffic lights. Nevertheless, participants were consistently the most confident in the AV's intentions when red and green were used in Safe Zone. The signals also performed well in negotiation-based scenarios, including bottlenecks and lane merging. This could be due to cyclists being capable of inferring the different meanings of colours depending on context; there are cases in traffic where the same colour can convey different meanings. For example, pedestrian crossings, traffic lights, directional indicators, hazard lights, and on-car blind spot warnings all use amber differently [128].

Similarly, the previous chapter showed that human drivers also use hand gestures similar to instructive ones from traffic control offices, such as waving for 'go', to communicate their intentions rather than instruct cyclists [56]. This effect may extend to red and green. A colour's perceived meaning may depend on its source, and this was captured in this study's findings. For example, P13 said *"There is no rule telling me to stop. Even if it is red, the car will react to me if I go. A rule tells me to stop at traffic lights, and the lights communicate this rule"*. New traffic colours, such as cyan, were effective for pedestrians and may be a suitable alternative to avoid misinterpretation of red and green signals [39]. However, new colours were not positively evaluated in this study, as seen in LightRing. A longitudinal study with cyclists learning to interpret new colours may show different outcomes, but these would need suitable contrasts to be distinguishable and effective.

Design Revisions

In response to this study's findings, all revised eHMIs incorporated red and green to enhance the recognisability and distinguishability of their signals. This may be challenging for colourblind cyclists. Therefore, animations, patterns or symbols were also incorporated into each design to ensure accessibility, similar to traffic lights using light positions (red-top and green-bottom) and animations (flashing amber) to convey meaning. The revised designs are described below.

Revision 1: Safe Zone

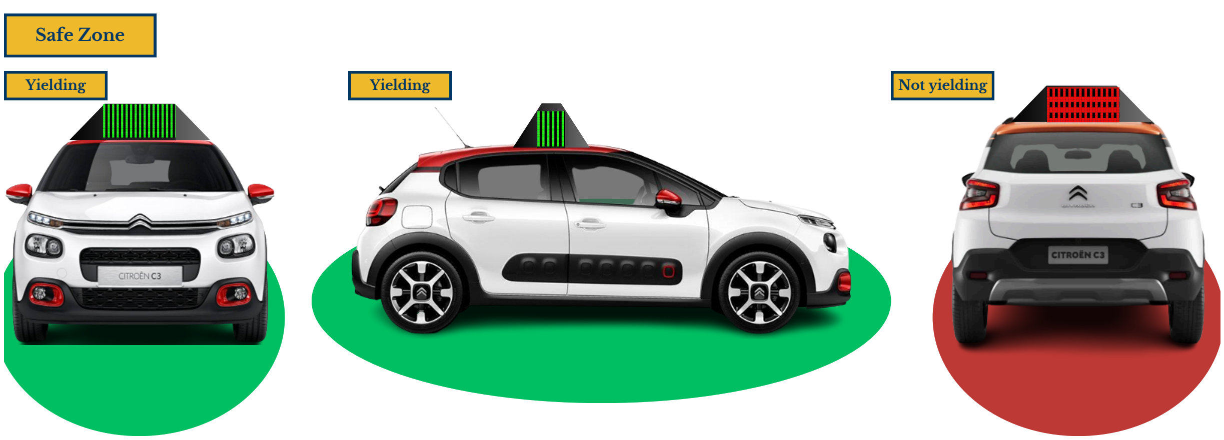

Figure 4.17: Safe Zone: Red/green road projections and a synchronised display showing red/green patterns on the roof. Patterns on the roof display were used to support colour-blind cyclists to distinguish the signals.

Safe Zone led to the fewest shoulder checks and consistently reduced anxiety and the workload to navigate each scenario. Participants were more confident in the AV's intentions as they were projected on a large surface. Eye-tracking data also showed that participants spent less time fixating on Safe Zone than the other eHMIs. This suggests that Safe Zone's signals were easy to recognise and comprehend through quick glances. However, participants paid significantly more attention to the road projections than the bonnet display. They were even sometimes unaware of the bonnet display's presence. For example, P4 said *"There was something on the bonnet? I did not know!"* This aligns with the design guidelines from the previous chapter, which recommend placing AV-cyclist interfaces on the road to enhance recognisability on a large surface. Previous work also found that road projections are highly usable for cyclists as they do not need to divert their attention from the road [67, 140].

Therefore, the bonnet display was relocated to the vehicle's roof to spread the eHMI's signals throughout the vehicle and emphasise its recognisability through peripheral vision. The display was also abstracted by replacing traffic signs with red and green colours synchronised with the road projections to reduce the potential cognitive load imposed by interpreting two different signals communicating the same message. However, colour-blind cyclists may find colour changes more challenging to distinguish than the traffic signs used in the previous bonnet display. Therefore, the updated roof display incorporated patterns using crossed lines for red and vertical lines for green. Figure 4.17 shows the revised Safe Zone.

Revision 2: Emoji-Car

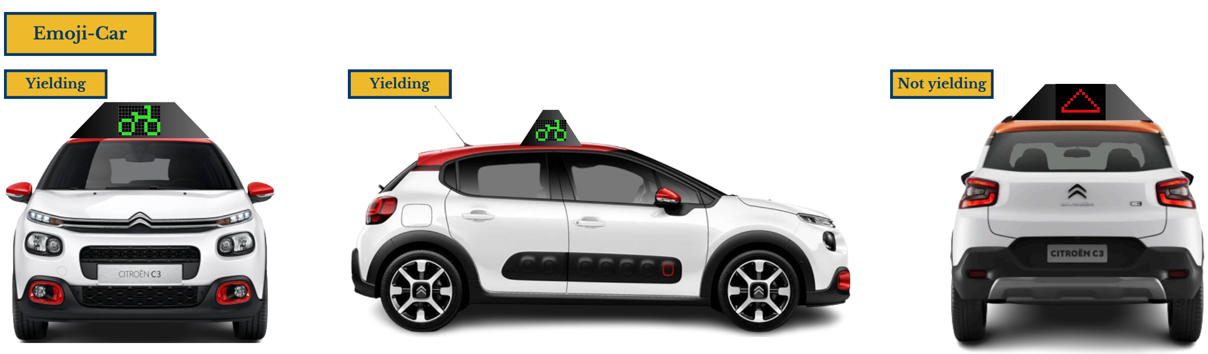

Figure 4.18: Emoji-Car: Display on the roof showing green bicycle icons for yielding, and red triangles for not yielding. The icons were used to support colour-blind cyclists to distinguish the signals.

Compared to Safe Zone, participants were slower around *Emoji-Car* and performed more shoulder checks. This could be due to the eHMI being placed solely on the vehicle's roof, which currently does not display any signals for interaction [49], so participants were not used to this.

The eye-tracking data also showed that icons in Emoji-Car required greater attention to process than Safe Zone's colours. This was partly due to the emojis being harder to differentiate while cycling, which imposed a higher workload. For example, P5 said: *"They both use yellow, so it's really hard to tell them apart"*. This further shows that eHMI signals must be distinguishable and understandable from a distance.

Participants also struggled to comprehend the meaning of the emojis and preferred that they be aligned with standard traffic symbols. P1 said *"I can't map lightning to anything meaningful"*. This relates to the theme from the previous study, which discusses the three familiarity levels of eHMI signals in traffic. It shows that novel signals to traffic may not be well received, and cyclists prefer familiar signals. Some participants incorrectly interpreted the top cyan light bar as a signal of the AV yielding, leading to potentially unsafe encounters. For instance, P3 mentioned, *"I saw the light on top and thought I could pass"*. The blinking arrow echoing directional indicators also overloaded the display. It proved redundant and ambiguous. Participants were unsure whether it instructed them to turn or displayed the AV's turn direction.

As a result, Emoji-Car was revised to focus on communicating AV intentions and awareness. The cyan light bar and blinking arrow were removed to avoid overloading the eHMI and to focus on the necessary information that cyclists can process across all scenarios. The new version of Emoji-Car used red triangles to communicate non-yielding; these are found in traffic signs, suggesting caution [128]. The red triangle replaced the lightning symbol to ensure familiarity. The eHMI also uses green bicycle symbols to communicate yielding. This may implicitly communicate the AV's awareness of the cyclist as the icon suggests the AV has detected a cyclist nearby and is yielding to them. Colour coding the icons was necessary to enhance distinguishability. Colourblind cyclists could still use icons to differentiate signals. Figure 4.18 shows the revised Emoji-Car.

Revision 3: LightRing

Figure 4.19: LightRing: Always-on cyan LED strips around the AV. They change to red (flashing quickly) or green (pulsing slowly) to communicate AV intentions. Animations were used to support colour-blind cyclists to distinguish the signals.

Despite being placed on a large vehicle surface, LightRing consistently underperformed. Participants were more anxious and felt unsafe when LightRing was used. Unlike pedestrians [39], cyclists did not respond positively to a new colour (cyan) in traffic. Similarly, animations imposed a higher workload to distinguish between AV intentions compared to colour changes in Safe Zone. For example, P9 said, *"It just did not make sense to me. I have to shoulder check and try to understand the animation direction in little time"*.

This disagrees with Dey et al.'s [39] findings, which showed that animated cyan lights were well received by pedestrians. However, pedestrians remain stationary at crossings and have more time to process signals [66]. This study shows that distinguishable signals that are easy to process on the move are key for eHMI versatility; eHMIs designed for pedestrians do not necessarily generalise to other road users [126].

LightRing was also complex and overloaded with signals. It incorporated synchronised amber lights on the car's side with directional indicators, navy blue lights to indicate awareness, and animations communicating intent. This hindered the interaction. Participants were slower around LightRing as they needed more time to process its signals. They preferred a more straightforward interface closer to *Safe Zone*. As a result, LightRing's lights were changed to slowly pulse in green (one pulse per second) when the AV detects and yields to the cyclist and flash quickly in red (two flashes per second) when not yielding.

In this case, animations complement colour changes rather than being the primary source of information. They were necessary to help colourblind cyclists differentiate between yielding conditions. These new animations are speed-based rather than directional, which could make them easier to distinguish. Cyclists may also find flashing animations more familiar as they are used in traffic. For example, some pedestrian crossing signs flash before changing state [128].

LightRing still uses ‘always-on’ cyan to communicate that the AV is in autonomous mode, with all sensors functioning correctly. As discussed in the previous study, this feature is useful because it informs cyclists that AV sensors are functioning correctly, and that the vehicle is autonomous, so they can expect to receive signals from the eHMI, rather than a human driver in case the vehicle was an SAE level 3 or 4 automated vehicle, which may feature a human driver in some cases. Here, cyan is used to communicate a new message that human drivers do not currently communicate. LightRing could retain the always-on cyan design feature because signal changes in the updated LightRing are more apparent with animations and colours. The eHMI avoids being overloaded by not displaying multiple signals simultaneously, as in the cyan light bar in the previous iteration of Emoji-Car. It causes less visual clutter than the road projections in Safe Zone, which can be overwhelming to always leave on in busy roads [37]. Figure 4.19 shows the revised LightRing.

Overall, red and 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 reiterating a directional indicator, only added to the workload of using an eHMI. All three designs were revised based on cyclist feedback and behaviours observed in VirtuRide to evaluate a second iteration in a real-world setting in the following study.

4.3 Study 6: Ghost Driver eHMI Evaluation

The revised eHMIs from the VirtuRide study all used colour-coded signals. They still warranted further comparison due to differences in their placement on the vehicle and variations in how messages were presented, such as using icons or animations alongside the colour changes. This study replicated the VirtuRide experiment outdoors. It used a *Ghost Driver* [109] setup with a human driver hidden under a car seat costume to create the illusion of an AV. Real prototypes of the revised eHMIs were built using LED strips and an LED matrix to display the signals. This was critical for collecting real cycling behaviours toward the eHMIs.

4.3.1 Study Design

The study replicated the VirtuRide experiment in an outdoor setting using a Ghost Driver [109] setup, where a human driver was hidden to create the illusion of an AV. It was a within-subjects study with two independent variables: *eHMI* and *Traffic Scenario*. The dependent variables were cyclist *perceptions* and *behaviours* toward each eHMI in each scenario. Participants encountered an “AV” using each eHMI across different traffic scenarios. They indicated their perceptions of the eHMIs through questionnaires, and various sensors logged their behaviours.

Study scope

Participants cycled outdoors to interact with a moving vehicle with a hidden human driver simulating an AV. They experienced real prototypes of each *eHMI*: *Safe Zone*, *Emoji-Car* and *LightRing*. Like the VirtuRide study, a baseline *No eHMI* condition was included; no display was present on the vehicle, meaning participants did not receive any explicit AV signals.

The eHMIs were evaluated across four of the *Traffic Scenarios* from the VirtuRide study; see Figure 4.20. *Controlled Intersection* was excluded, as results from the VirtuRide study showed that traffic lights removed the need for right-of-way negotiation or explicit AV signals. The AV always yielded to the cyclist to maintain participant safety. The driving behaviour was as follows:

- **Roundabout**: The roundabout had three arms, with giveway lines on each arm. The AV approached from the cyclist's left. It drove at 30 km/h and stopped 0.5 metres behind the giveway line.

- **Uncontrolled Intersection**: This was a three-way intersection; it had three arms. There were giveway lines on each arm, and the AV approached from the cyclist's left. It drove at 30 km/h and stopped 0.5 metres behind the giveway line.

- **Bottleneck**: This was a narrow lane with obstacles on both sides. The AV approached from opposite the cyclist. It drove at 25 km/h, decelerating as needed to yield according to the cyclist's speed. The AV used its left directional indicator and steered left to stop between two obstacles.

- **Lane Merging**: An obstacle obstructed the cyclist's path, forcing them to merge lanes with an AV approaching from behind. The AV was driving at 25 km/h and decelerated as needed to yield according to the cyclist's speed.

Study setup

The study occurred in a coned-off outdoor area at the University. This featured a 60 metre straight road intersecting with a 50 metre side road on the left. Lane-dividing lines were drawn onto the roads to replicate the two-lane layout from the VirtuRide study. Give-way lines were drawn on both sides of the intersection to accurately represent the layouts for the *Roundabout* and *Uncontrolled Intersection* scenarios. Participants navigated all scenarios by cycling along the 60 metre road until they reached the endpoint, which was located 5 metres after the intersection, except in the *Roundabout* scenario, where they performed a U-turn before returning to the start point. As in the VirtuRide study, scenarios were grouped into tracks, with the scenario order randomised within each track. The AV used the same *eHMI* throughout a track, and the *eHMI* sequence was counterbalanced using a Latin Square design.

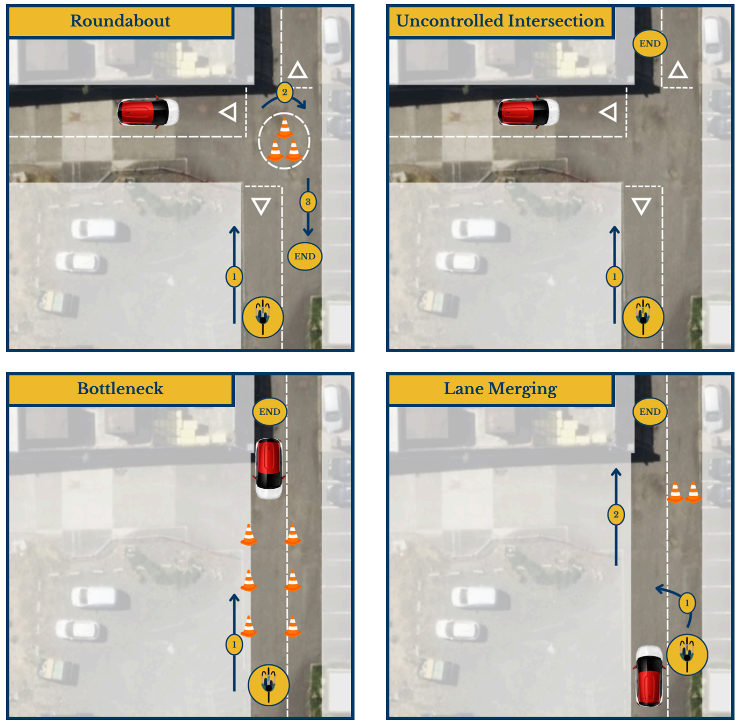

Figure 4.20: The traffic scenario setups in the study. Left to right: Roundabout, Uncontrolled Intersection, Bottleneck and Lane Merging. Traffic cones were used to simulate obstacles and mark start and end points for participants. Traffic cones in the roundabout scenario had a circle around them that was drawn using chalk.

The AV always yielded to ensure participant safety, but participants were shown both yielding states before each track and were told that the AV might not yield during the scenarios. A single driver was used for all sessions to maintain consistency across trials. The driver ensured a minimum distance of 1 metre from the cyclist as advised in the UK Highway Code [128].

Measures

Participants wore a pair of Tobii Pro Glasses 2 to record their gaze behaviour, and a smartphone was mounted on the bike's handlebar to log their speed. The study measured the same dependent variables as in the VirtuRide experiment:

- **Questionnaires:** Participants completed the same *Post-Scenario* and *Post-Track* questionnaires as in the VirtuRide study;
- **Cycling Behaviours:** Cycling speed (m/s) was logged every second. The Tobii Pro Glasses' gyroscope logged shoulder-checks. This was Y-axis rotation exceeding 90°, as established through 10 pilot tests. Gaze fixations were mapped to the predefined AOIs from the eye-tracking study in Chapter 3 to analyse *gaze visit counts*;
- **Post-Study Interview:** Interviews were conducted after the study. Participants discussed and ranked their experiences with the different eHMIs.

Figure 4.21: Real prototypes of the eHMIs. These were built using LED strips and an LED matrix. The top row shows photographs of Safe Zone. The left photo on the bottom shows Emoji-Car, and the right photo shows LightRing.

4.3.2 Apparatus and eHMI Implementation

Participants were given a Giant Escape 3 bicycle and a helmet if they did not bring their own. They wore a pair of Tobii Pro Glasses 2 to record their gaze behaviour, and an iPhone 12 mini was mounted on the bicycle's handlebars to record speed using the Cyclemetre app[8]. White chalk was used to draw road markings on the ground, and traffic cones were placed in the outdoor space to represent obstacles (see Figure 4.20).

The study used a grey 2019 Citroën C3. The driver wore sunglasses, black gloves and a car seat cover with holes for eyes and arms (see Figure 4.23). Participants never saw the driver, creating the illusion that the vehicle was an SAE level 5 AV [109]. The eHMIs were constructed using LED strips and an LED matrix (see Figure 4.21). They were powered via the vehicle's USB port and controlled remotely by an experimenter using an iPad over Bluetooth. The LED matrix was mounted on the roof using a custom-built panel attached to a removable roof rack[9]. The rack was present in all conditions and described to participants as part of the AV's sensors. Participants only encountered the vehicle's front or left side, so the eHMIs were designed to be primarily visible from these directions. Velcro was used to attach and detach the eHMIs to the vehicle body between conditions.

[8]Cyclemetre iOS application: `https://shorturl.at/GRcME` ; Accessed 01/04/2025
[9]HandiWorld removable roof rack: `handiworld.com/handirack/` ; Accessed 01/04/2025

Figure 4.22: Photograph from a pilot study comparing the visibility of LED lights and road projections. Road projections were barely visible in sunny conditions.

eHMI Implementation

Real prototypes of the eHMIs were built for this study. These are in Figure 4.21. All eHMIs were 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:** This study did not use road projections. It was conducted outdoors during daylight, and pilot tests comparing the visibility of the LED matrix, LED strip, and projections (see Figure 4.22) showed that projections were barely visible. Various projectors with high lumen values (>11,000) were tested, but they remained indistinguishable in daylight. Pilot tests also explored red/green ambient lighting using 15,000-lumen LED torches mounted under the bumper, but these also had minimal visibility. Therefore, an LED strip was attached around the bottom of the vehicle's front half using velcro. This approach positioned the lights closer to the road surface while emphasising that Safe Zone is in the cyclist's peripheral vision, particularly when combined with a roof display. The roof display was an LED matrix showing the green pattern synchronised with green LED lights when the AV was yielding. It displayed the red pattern, synchronised with red lights from the LED strip, when the AV was not yielding.
- **Emoji-Car:** The LED matrix on the vehicle's roof was folded on the left, allowing cyclists to receive messages when they are on the vehicle's left side. The matrix displayed three green bicycle icons (one on each side) when the AV was yielding. It showed three red triangles, resembling warning signs, when the AV was not yielding.
- **LightRing:** LED strips were attached to the vehicle's left side (2 metres long) and front (1 metre long) using velcro. The LEDs were always on in cyan, indicating that the car was autonomous and not reacting to the cyclist. The colour changed to green, pulsing slowly (one pulse per second) when the AV was yielding, and red, flashing quickly (two flashes per second) when the AV was not yielding.

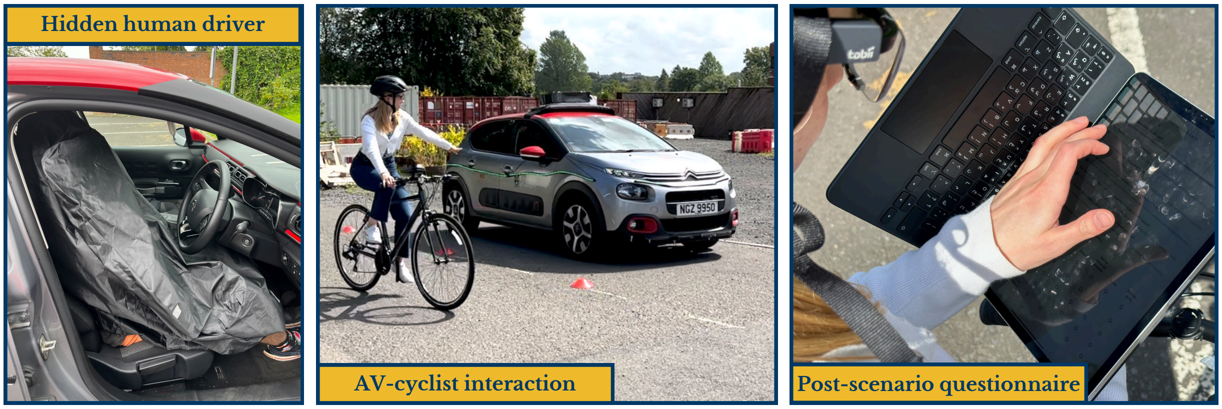

Figure 4.23: The study process: Left: A human driver was hidden in a car-seat costume. Middle: Participants interacted with a simulated AV. Right: Participants answered questionnaires to provide feedback.

- **No eHMI:** This was a baseline condition with no eHMI display. Any LED strips were removed from the vehicle, and the LED matrix on the roof was switched off.

4.3.3 Participants

The experiment involved 20 participants recruited through social media. Their demographics were: $M_{\text{age}} = 20.4$, $SD = 5.9$; $Male = 12$, $Female = 7$, $Non\ Binary = 1$. All participants had experience riding in the UK. Eleven cycled at least once a week, three at least once a month, two multiple times a year, and four cycled once a year or less. Thirteen participants used their own bikes during the study.

4.3.4 Procedure

The procedure is in Figure 4.23. The participant met the experimenter in the outdoor space and answered a questionnaire on their demographics and cycling experience. The experimenter also briefed them about the study and showed them the start and endpoints for the scenarios. Those who did not bring their own bikes ensured they were comfortable with the study bicycle and saddle height; adjustments were made where needed. The participant then cycled from the start to the endpoint and back for 3 minutes to familiarise themselves with the study's route.

Before each track, the experimenter showed the participant how the eHMI worked by controlling the lights on the vehicle so that they were familiar with the signals before interaction. The participant then moved to the starting point to experience the scenarios. The participant started cycling, and the driver started driving once they saw a thumbs-up from the experimenter. The experimenter controlled the eHMI to react to the participant at the appropriate moment, depending on their cycling speed and location. After each scenario, the participant returned to their starting point and answered the post-scenario questionnaire while the experimenter placed

	eHMI				Scenario			
	Safe Zone	*Emoji-Car*	*LightRing*	*No eHMI*	*Roundabout*	*U-Intersection*	*Bottleneck*	*L-Merging*
Workload	6.23 ± 2.30	6.50 ± 2.36	5.85 ± 2.46	9.18 3.86	6.22 ± 2.57	6.28 ± 2.89	6.70 ± 2.78	7.64 ± 3.20
Awareness Confidence	4.21 ± 0.75	4.24 ± 0.72	4.31 ± 0.66	2.56 1.18	4.03 ± 0.97	4.07 ± 1.01	4.05 ± 1.00	3.70 ± 1.12
Intention Confidence	4.01 ± 0.86	3.99 ± 0.90	4.00 ± 0.85	2.39 1.32	3.87 ± 1.04	3.84 ± 1.21	3.75 ± 1.11	3.43 ± 1.14
Cycling Speed	6.85 ± 3.11	7.17 ± 3.00	7.35 ± 2.77	6.02 2.30	7.05 ± 2.80	7.60 ± 3.24	6.39 ± 2.70	6.60 ± 2.70

Table 4.5: Mean ± SD of each Post-Scenario Questionnaire subscale for each eHMI and Traffic Scenario condition.

the next scenario's obstacles on the road. The experimenter changed the eHMI after each track while the participant answered the post-track questionnaire. The post-study interview was conducted to conclude the study after the participant had navigated all four tracks and experienced all eHMI conditions. The experiment took approximately 90 minutes. Participants were compensated for their time with a £10 Amazon voucher.

4.3.5 Results

This section reports cyclist perceptions and behaviours toward each eHMI in each traffic scenario. It starts by reporting the *Post-Scenario Questionnaire* results, followed by the *Post-Track Questionnaire* and insights into *Cycling Behaviour*. These findings are contextualised with themes resulting from post-study interviews.

Post-Scenario Questionnaire

This used the same analysis as the previous study. Data were not normally distributed; a two-way ART ANOVA was conducted to examine the fixed effects of *eHMI*, *Traffic Scenario* and their interactions on each Post-Scenario Questionnaire subscale. The model included a random intercept for *Participant* to account for individual variability. *Post hoc* tests between *Traffic Scenario* and *eHMI* pairs were performed using the ART-C method. Mean values are in Table 4.5. These are visualised as box plots in Figure 4.24.

The overall results show that the *No eHMI* condition significantly underperformed, reiterating that AV-cyclist interfaces are critical. The *Lane Merging* scenario was also considered to be more challenging than the others, which is due to the AV being out of the cyclist's view.

Workload There were significant effects of *eHMI* (F(3, 207.09) = 26.52, $P < .001$; η^2 = 0.28) and *Traffic Scenario* (F(3, 206.22) = 9.25, $P < .001$; η^2 = 0.12). However, they had no interaction (F(9, 206.15) = 1.02, $P = .4$). This means that the eHMIs remained versatile in the outdoor setting.

Post hoc comparisons of *eHMI* pairs showed that *No eHMI* imposed a significantly higher workload than all other conditions ($P < .0001$ for all). Therefore, cyclists need explicit signals about AV intentions to lower the interaction workload. Comparing *Traffic Scenario* pairs showed

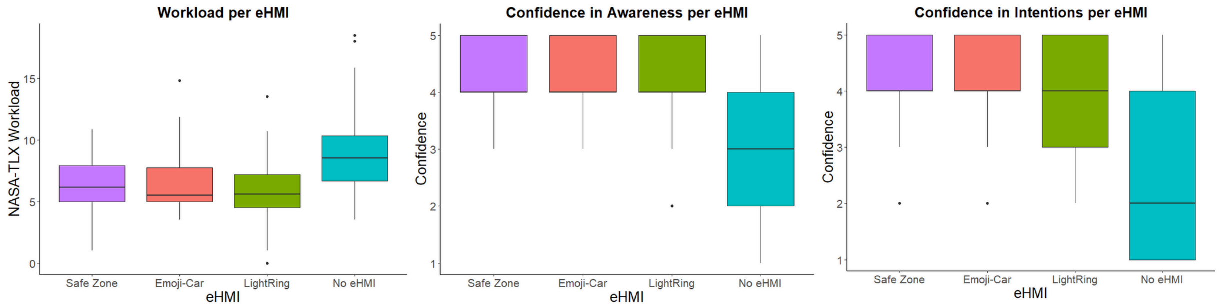

Figure 4.24: Box plots showing the mean ± SD of each Post-Scenario Questionnaire per eHMI condition. Left: Workload; Middle: Confidence in AV Awareness; Right: Confidence in AV Intentions. The No eHMI condition consistently underperformed.

that *Lane Merging* caused a significantly higher workload than *Roundabout* ($P < .0001$), *Uncontrolled Intersection* ($P = .0001$) and *Bottleneck* ($P = .002$). Consistent with the previous study, participants found it more demanding to interact with an AV out of their view.

Confidence in AV Awareness There were significant effects of *eHMI* (F(3, 209.86) = 30.16, $P < .001$; $\eta^2 = 0.3$) and *Traffic Scenario* (F(3, 206.84) = 2.74, $P < .05$; $\eta^2 = 0.04$). There was no interaction (F(9, 206.6) = 0.54, $P = .9$). Therefore, eHMIs and traffic scenarios influenced cyclists' confidence in the AV's awareness, but eHMIs were versatile and performed consistently between the scenarios.

Post hoc comparisons between *eHMI* pairs showed that participants were significantly less confident when there was *No eHMI* compared to all other conditions ($P < .0001$ for all). Therefore, changing the eHMI's state to display the vehicle's intentions as it approaches also assured cyclists that the AV had detected them. *Post hoc* comparisons between *Traffic Scenario* pairs showed that participants were significantly more confident in the AV's awareness when navigating *Roundabout* than *Lane Merging* ($P = .05$). Therefore, confidence in AV awareness was increased when the AV was in the cyclist's view with traffic control regulating right of way.

Confidence in AV Intentions There was a significant effect of *eHMI* (F(3, 209.22) = 23.21, $P < .001$; $\eta^2 = 0.25$). However, there was no effect of *Traffic Scenario* (F(3, 206.71) = 2.04, $P = .1$), and no interaction (F(9, 206.53) = 0.90, $P = .5$). Therefore, the eHMI influenced cyclists' confidence in AV intentions and was versatile throughout the scenarios. However, the traffic scenario did not meaningfully influence confidence.

Post hoc comparisons between *eHMI* pairs showed that confidence was significantly lower when there was *No eHMI* compared to all other conditions($P < .0001$ for all). Therefore, explicit signals communicating AV intentions were more effective than implicit ones.

	eHMI			
	Safe Zone	*Emoji-Car*	*LightRing*	*No eHMI*
Cycling Performance	4.25 ± 1.06	4.00 ± 0.63	4.25 ± 0.81	2.25 ± 1.38
Anxiety	2.33 ± 0.25	2.50 ± 0.63	2.20 ± 0.71	3.50 ± 0.50
Perceived Safety	4.00 ± 0.00	4.00 ± 1.00	4.00 ± 0.25	2.00 ± 1.25
Usability	1.50 ± 1.31	1.38 ± 1.75	1.81 ± 0.94	-1.06 ± 1.31

Table 4.6: Median ± IQR values for each Post-Track Questionnaire subscale per eHMI.

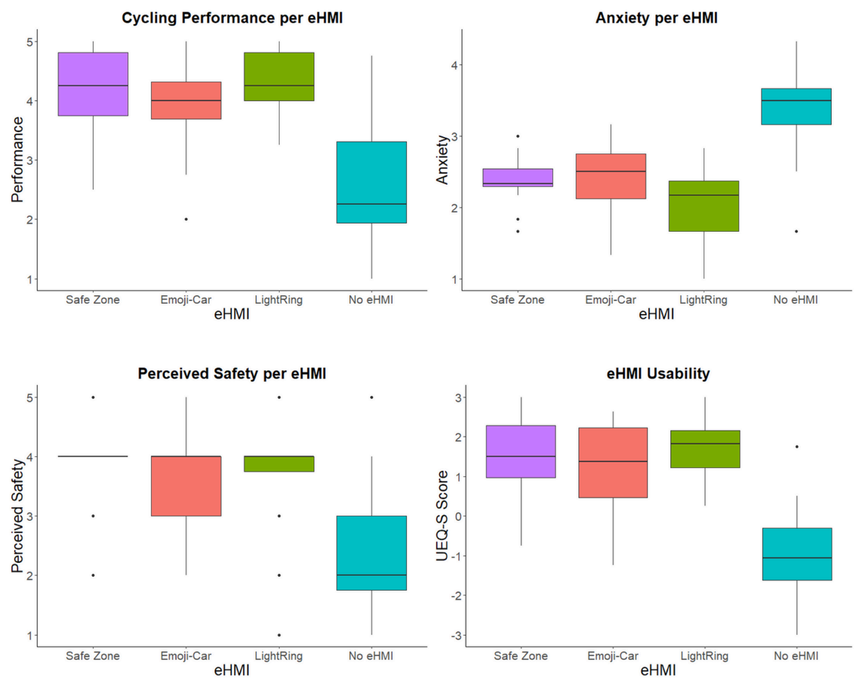

Figure 4.25: Box plots showing the median ± IQR values for each Post-Track Questionnaire subscale per eHMI condition. Results show that the No eHMI condition underperformed; LightRing outperformed the others in some metrics, including Cycling Performance and Usability.

Post-Track Questionnaire

Like in the previous study, the data were not normally distributed. Therefore, a Friedman's test was conducted to examine the effect of *eHMI* on each Post-Track Questionnaire subscale. *Participant* was treated as a blocking factor to account for individual variability. Post hoc comparisons between eHMI pairs were performed using the Nemenyi test. Results are in Table 4.7. Median values are in Table 4.6. These are also visualised as box plots in Figure 4.25. The overall results show that the *No eHMI* condition consistently underperformed. *LightRing* was the best performing *eHMI* in some metrics, including *Anxiety* and *Usability*.

Cycling Behaviour

This section reports cycling speed, shoulder checking, and gaze behaviours when using each *eHMI*. These data are critical to provide insights into the impact of eHMIs on real cycling behaviours. Figure 4.26 shows speed and shoulder checking behaviours when using each *eHMI*.

Measure	Friedman's Test	Significant *Post Hoc*s	Takeaway
Cycling Performance	χ^2 = 32.29, df = 3, $P < .001$; $\eta^2 = 0.39$	*Safe Zone* > *No eHMI* ($P = .0004$) *Emoji-Car* > *No eHMI* ($P = .006$) *LightRing* > *No eHMI* ($P < .0001$)	Signals perceivable from anywhere around the vehicle enhanced performance.
Anxiety	χ^2 = 35.3, df = 3, $P < .001$; $\eta^2 = 0.43$	*Safe Zone* < *No eHMI* ($P = .0002$) *Emoji-Car* < *No eHMI* ($P < .0001$) *LightRing* < *No eHMI* ($P < .0001$)	Having explicit signals about AV intentions reduced anxiety.
Perceived Safety	χ^2 = 19.72, df = 3, $P < .001$; $\eta^2 = 0.22$	*Safe Zone* > *No eHMI* ($P = .008$) *Emoji-Car* > *No eHMI* ($P = .02$) *LightRing* > *No eHMI* ($P = .006$)	Participants felt safer when there was an eHMI.
Usability	χ^2 = 34.5, df = 3, $P < .001$; $\eta^2 = 0.41$	*Safe Zone* < *No eHMI* ($P < .0001$) *Emoji-Car* < *No eHMI* ($P = .001$) *LightRing* < *No eHMI* ($P < .0001$)	eHMIs improved usability, especially when signals were on a large surface.

Table 4.7: Friedman's test results for the Post-Track Questionnaire results. The No eHMI condition significantly underperformed in all metrics.

The overall results show that cyclists were slower and conducted more shoulder checks when using *No eHMI*. Their gaze behaviours were also more distributed between the AV's driving behaviours and traffic control features. This shows the positive impact eHMIs have on cycling behaviours.

Cycling Speed The data were not normally distributed, so speed was analysed using the same approach as the Post-Scenario Questionnaire analysis. There were significant effects of *eHMI* (F(3, 252.71) = 4.21, $P < .01$; $\eta^2 = 0.05$) and *Traffic Scenario* (F(3, 252.43) = 3.61, $P < .05$; $\eta^2 = 0.04$). There was no interaction (F(9, 252.59) = 1.35, $P = .2$). Therefore, eHMIs remained versatile, even for cycling behaviour. *Post hoc* comparisons of *eHMI* pairs showed that participants were significantly slower when there was *No eHMI* than when *Safe Zone* ($P = .02$) and *LightRing* ($P = .009$) were used. Therefore, while an eHMI helped participants cycle faster, the signals needed to be more abstract and displayed on a larger surface than in *Emoji-Car*. *Post hoc* comparisons between *Traffic Scenario* pairs howed that participants were significantly faster at *Uncontrolled Intersection* than *Bottleneck* ($P = .04$). This may be due to participants being constrained in a narrow lane, with a slow-moving AV approaching in a *Bottleneck*.

Shoulder Checking A Chi-Square test of Independence was conducted to deduce the relationship between *eHMI* and *Traffic Scenario*; *post hoc* tests were conducted using the Chi-Square test of Independence with a Bonferroni correction. There was a significant association between the variables (χ^2(9, 348) = 132.07, $P < .001$). *Post hoc* tests for *eHMI* showed that participants were significantly less likely to shoulder check in the *No eHMI* condition than all others ($P < .001$ for all). For *Traffic Scenarios*, shoulder checks were significantly less likely in *Bottleneck* than all others ($P < .001$ for all). They were significantly more likely during *Lane Merging* than in all other scenarios ($P < .001$ for all).

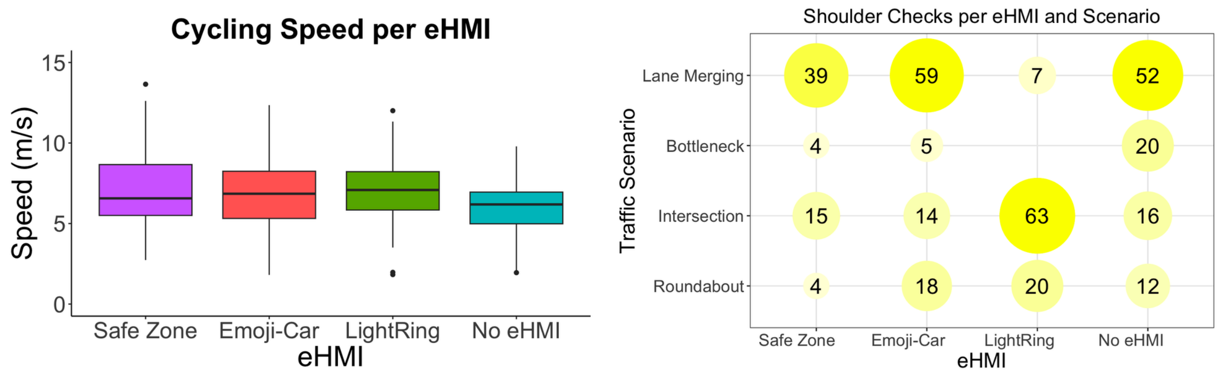

Figure 4.26: Cycling behaviours logged in the study. The left graph shows a box plot of the mean ± SD cycling speed per eHMI. The right graph shows the number of shoulder checks conducted when each eHMI was used in each Traffic Scenario.

Figure 4.27: Heatmap showing cyclist gaze behaviours in each eHMI condition. Gaze visits were more distributed in the Safe Zone condition, suggesting that the eHMI was viewable through peripheral vision. Visits were most distributed across vehicle and traffic control features in the No eHMI condition.

Gaze Behaviour Figure 4.27 shows a heatmap of cyclist visits on the AOIs for each eHMI. As in the eye-tracking study from Chapter 3, Tobii Pro Lab was used to map participant fixations to AOIs. These were then exported as *visit counts* to each AOI. A Chi-square test of independence was conducted to investigate the relationship between *eHMI* and *AOI visit counts*. *Post hoc* tests were performed using a Chi-Square test of independence with a Bonferroni correction.

There was a significant association between the variables ($\chi^2(30, 9263) = 2158.2$, $P < .001$). Participants were significantly more likely to fixate on the AV's bumper, direction indicators and road markings when there was *No eHMI* compared to all other conditions ($P < .0001$ for all). This suggests that participants relied more on the AV's implicit signals and traffic control when there was *No eHMI*. Moreover, participants were significantly less likely to fixate on the light displays when *Safe Zone* was used than *Emoji-Car* and *LightRing* ($P < .0001$ for both). This suggests that *Safe Zone*'s signals were still viewable through peripheral vision, even when projections were not used. Similarly, *LightRing* also required significantly fewer fixations than

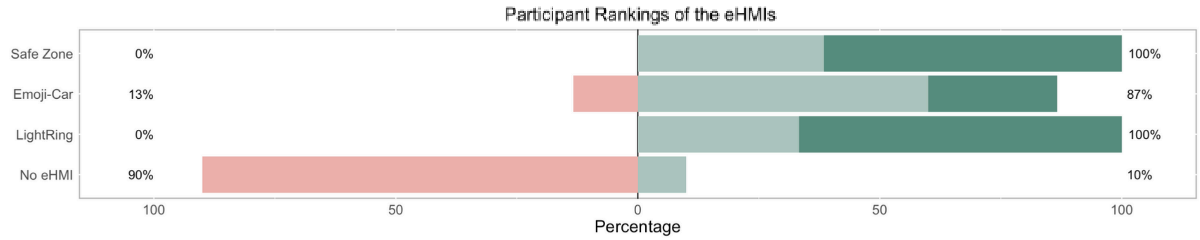

Figure 4.28: Participant rankings of the eHMIs. Left in red are lower ranks, and right in green are higher ranks. No eHMI was ranked as the worst condition; LightRing was the best.

Emoji-Car ($P < .0001$); *Emoji-Car's* roof display required greater attention to comprehend.

Qualitative Findings

The same inductive thematic analysis as in the VirtuRide study was conducted on the post-study interview transcripts. One researcher extracted 31 unique codes from the data. Two researchers sorted these into three themes based on code similarity. eHMI rankings are visualised in Figure 4.28. Participants ranked *LightRing* as the best *eHMI* and *No eHMI* as the worst.

Theme 1: LightRing's placement improved message recognisability Participants highlighted the effectiveness of *LightRing*'s placement on the AV body: *"You see better because you can kind of see the edge of the LED strip from wherever"* - P8. In contrast, *Emoji-Car*, positioned on the roof, was more difficult to spot: *"Compared to LightRing, then you have to really look at the roof to see the emoji"* - P18. This emphasises that placement is a crucial eHMI feature that significantly affects interface visibility.

Theme 2: eHMI redundancy was effective The VirtuRide study showed cyclists want simple signals on AV intentions communicated through colour changes. This study showed that pulsing animations in *LightRing* successfully reinforced these colour changes: *"LightRing flashing drew attention to itself and different flashing speeds were easy to spot"* - P4. This suggests that more subtle redundancy complementing colour changes was useful for cyclists.

Redundant messages presented on the top and bottom of the AV in *Safe Zone* were also well received. For example, P20 said, *"Always redundancy is better. The top and bottom displays accommodated that"*. Therefore, participants were not overwhelmed by receiving the same message from different vehicle areas. Redundancy was useful when used in the same eHMI display and across displays on different vehicle areas.

Theme 3: eHMIs were useful throughout traffic scenarios Participants found eHMIs most valuable in scenarios where right-of-way required negotiation, and traffic control was minimal: *"It will benefit all these scenarios, but especially lane merging. I think I would say it's crucial"*

- P19. However, they still appreciated them in the Roundabout and Uncontrolled Intersection Scenarios: *"They're necessary. It adds clarity and reassurance"* - P17. This reinforces the findings that implicit cues are insufficient for cyclists.

4.3.6 Discussion

This study complemented the VirtuRide experiment by introducing real cycling in an outdoor environment. In contrast, VirtuRide provided high-fidelity eHMI prototypes that would have been challenging to construct and test outdoors [138]. VirtuRide was crucial for gathering initial feedback on interface usability and refining the eHMIs before transitioning to real-world evaluation [28]. This study was critical for identifying subtle features contributing to eHMI usability and versatility. All revised eHMIs maintained versatility in outdoor settings. The differences with the baseline condition became more apparent in this study than in previous iterations. This emphasises the importance of iterative design for AV-cyclist interfaces [28]. The baseline, no eHMI condition, consistently underperformed and received the lowest ratings across all metrics. Participants were slower and performed more shoulder checks. Their gaze behaviour was more spread out, as they relied on more AOIs to infer an AV's intentions. This could be due to the study including a real vehicle; cyclists may have felt less secure when encountering real obstacles. This study reiterates that cyclists must receive explicit signals about AV intentions in space-sharing conflicts. These signals must be recognisable, understandable, and distinguishable to improve AV-cyclist interaction. Results showed that using binary AV intention signals using a red and green colour scheme was effective in achieving these requirements.

Similar to the previous study, scenarios with more traffic control, such as the roundabout, needed lower workloads than dynamic ones without traffic control, such as *Lane Merging*. Participants also had greater confidence in the AV's intentions at the roundabout. This can be attributed to the well-defined right-of-way rules in the UK Highway Code [128], 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 of achieving eHMI versatility. Despite the differences between scenarios, this study showed that all scenarios would benefit from an eHMI, as they all required a higher workload when there was no eHMI. The study also showed that eHMIs can communicate consistent signals about AV intentions throughout the scenarios, despite their differences.

Participants could quickly infer signals from Safe Zone, despite it being more abstract and relying solely on colour changes without icons or animations. The widespread distribution of lights (roof and vehicle bottom) made them easier to locate through quick glances. This was supported by eye-tracking data, which suggested that cyclists often looked at the vehicle's centre, not just the eHMI itself. These findings show that the design changes to enhance the visibility of Safe Zone were successful, even though no road projections were used. Emoji-Car was not as well-received as the other eHMIs. Its roof placement and use of icons drew significant attention from riders, as indicated by eye-tracking and speed data. Riders were slower than the other eHMIs, suggesting they needed more time to process Emoji-Car's signals. Cyclists did not rely solely on the icon colours. Some participants interpreted Emoji-Car's messages as two separate signals, one communicating intentions and the other awareness, despite being told that bicycles are always green and triangles are always red. For example, P8 said, *"I needed to first check if it is a cyclist to confirm the car has seen me. Then, I needed to see if it was green and if it would stop."* This suggests that participants found the signals more complex than the abstract colour changes in the other designs.

Similarly, Emoji-Car was placed on the vehicle's roof, which is not as large as its main body. Even then, the icons prohibited full use of the entire LED matrix. 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 [67]; placing eHMIs on specific AV areas could divert cyclists' attention from the road, and it is better to use signals recognisable through quick glances. This also coincides with the design guidelines from the previous chapter, recommending placing AV-cyclist interfaces on large surfaces. LightRing received better feedback than the other eHMIs in some metrics. Participants expressed a greater sense of safety and ranked it as the most preferred eHMI. One contributing factor was its communication of the AV's state through cyan lights: *"I liked the cyan colour telling me everything is fine"* - P12. This suggests that new messages have a place in future traffic and can be communicated using new types of signals and colours if they do not overload or complicate a display. It also provides a common ground with pedestrians, who also prefer cyan lights to communicate the AV state [39].

LightRing covered a larger AV surface, which the previous chapter and the VirtuRide study showed is a desirable feature. Flashing and pulsing animations were also easier to distinguish than directional ones from the previous iteration. This finding contrasts with previous research with pedestrians showing directional animation to be ideal [39]. This emphasises that cyclists must process AV signals in faster-paced scenarios than pedestrians, and interfaces should be designed accordingly. The successful use of speed-based animation in LightRing shows that redundancy is effective in enhancing participant confidence in AV intentions when designed correctly to avoid overloading the display.

Overall, this study highlighted key design features for successful, versatile AV-cyclist eHMIs. They must be easy to recognise and process on large surfaces. Red and green is a useful colour scheme for communicating AV intention information that cyclists can quickly differentiate, and redundantly communicating these messages by incorporating a secondary display on the vehicle or using animations was useful.

4.4 Overall Discussion and Design Guidelines

Overall, this chapter answered RQ2: *" What features enable AV-cyclist interfaces to be versatile, supporting interaction across diverse traffic scenarios?"*. All eHMIs designed and evaluated in this chapter were versatile, working consistently across scenarios with varying levels of traffic control and vehicle positions. This is a significant finding; it ensures that cyclists can safely navigate a range of traffic scenarios without switching between interfaces [12, 16]. Moreover, the versatile eHMIs in this chapter communicated consistent signals between traffic scenarios, so cyclists do not need to learn messages unique to each scenario. This minimises the learning curve for AV-cyclist interaction and even improves today's interaction, where drivers and cyclists interact differently between traffic scenarios.

It is critical to consider the practical usability of eHMIs when riders navigate mixed traffic around multiple AVs. Here, audio-based eHMIs may not be effective, as sounds may be lost in environmental noise, or it may be challenging to distinguish between AVs. Hence, the choice of exploring visual eHMIs in this chapter. Visual eHMIs may still cause some visual clutter for cyclists and be challenging to contemplate in heavy traffic, particularly because results showed that these eHMIs should be on large surfaces to be effective. However, measures were taken to minimise this effect. For example, the eHMIs in this chapter only change state when an AV interacts with a cyclist, so not all eHMIs will necessarily be active, which could reduce visual overload [37]. This can be further enhanced by only activating the side of an eHMI where a cyclist is present [15]. For example, only showing a portion of the road projections for Safe Zone. Current traffic also shows that cyclists can process multiple on-vehicle signals being active simultaneously. For example, the eye-tracking study from Chapter 3 showed that cyclists rely on directional indicators at roundabouts, and multiple vehicles could be using these simultaneously. These issues are further explored in Chapter 6, which investigates the scalability design challenge, which could feature multiple AVs using eHMIs around a cyclist.

The potential presence of a human driver in SAE level 3 or 4 AVs could also confuse cyclists about whether they should receive signals from the driver or eHMI. It may be challenging for the vehicle to detect a driver's intentions and display them directly on the eHMI. Therefore, this issue could be mitigated by including the always-on cyan feature, as seen in LightRing. This would inform cyclists that the vehicle is autonomous and they should expect the signal from the eHMI. The cyan lights feature could be transitional until cyclists are accustomed to interacting with AVs and automated vehicles become a majority in traffic.

Ultimately, this chapter showed that eHMIs can facilitate interaction with cyclists across diverse traffic scenarios, but their design must be optimised to achieve this. They must account for varying vehicle positions and be placed around vehicles rather than on a single area, as seen with AV-pedestrian eHMIs placed on the vehicle's front [37]. This area is preferred to have a larger surface, such as the vehicle's side body, rather than a smaller surface, like the roof, to ensure that cyclists can quickly recognise these messages. This is because some scenarios are faster-paced than others [12], particularly dynamic manoeuvres that do not have formal traffic control and often feature both road users moving [67]. The studies in this chapter showed that colour changes were key to achieving this. These findings align with the design guidelines from Chapter 3, showing that Chapter 3's approach was effective in producing generalisable requirements, even though studies focused primarily on driver-cyclist interaction.

This chapter showed that AV intention signals are key for versatile eHMIs. Cyclists must know the AV's intentions in all scenarios to make informed decisions about their next manoeuvres. Previous research and the design sessions in this chapter showed that AV awareness of the cyclist is also a key message. However, the evaluation studies where cyclists directly interacted with AVs showed that intentions take precedence. This aligns with eHMIs designed for pedestrians [37] and offers a promising common ground.

4.4.1 Design Guidelines for Versatile AV-Cyclist Interfaces

The findings from the three studies in this chapter formed the basis for design guidelines (DGs) for versatile eHMIs, which are presented below and provide a foundation for further discussion.

DG1: eHMIs are key facilitators of AV-cyclist interaction

Studies from Chapter 3 showed that social cues from human drivers are crucial for cyclists to resolve space-sharing conflicts and plan their manoeuvres safely. The three studies in this chapter demonstrated that this need for explicit communication also applies to AV-cyclist interaction. Interestingly, prior research on AV-pedestrian interaction found that implicit cues, such as AV driving behaviours, were sufficient for some AV-pedestrian interactions [76]. However, this does not apply to cyclists. Participants in the design sessions identified AV intentions and awareness as critical messages, and the follow-up evaluations confirmed that cyclists consistently felt more confident in AV intentions and awareness when eHMIs were present. Cyclists conducted fewer shoulder checks and were more comfortable riding at higher speeds with an eHMI. Qualitative findings supported this; for example, P2 from the Ghost Driver study stated, *"You definitely need eHMIs. When there was no intervention, I had no idea and no control. I felt unsafe"*. Therefore, eHMIs are essential for AV-cyclist interaction. They effectively communicate key messages needed to resolve space-sharing conflicts across various traffic scenarios. They do not require cyclists to carry additional devices or modify their cycling setup. This aligns with the design guidelines from the previous chapters, describing eHMIs as a crucial *baseline* for cyclist safety that supports AV-cyclist interface acceptability.

DG2: eHMI level of detail could depend on traffic control level

This chapter examined the perceived workload of navigating different traffic scenarios with varying traffic control. Results showed a negative correlation between workload and traffic control;

workload increased as traffic control decreased. Dynamic manoeuvres were generally more demanding than controlled scenarios. This aligns with observations from Chapter 3, which found that driver-cyclist interactions were more frequent in uncontrolled infrastructure and dynamic manoeuvres. Participants designed more expressive eHMIs for uncontrolled infrastructure and dynamic manoeuvres to support negotiation and clear communication in these settings. Follow-up evaluations confirmed that eHMIs were perceived as most valuable in dynamic manoeuvres, where no traffic control regulated the right of way. However, participants still acknowledged their usefulness in all scenarios. eHMIs also consistently outperformed the baseline condition with no eHMI, regardless of the traffic scenario. This suggests that eHMIs should be present throughout a cyclist's journey to provide consistent communication. This would reinforce versatility and ensure cyclists do not have to adjust their expectations between scenarios. However, more expressive or detailed eHMIs may be overwhelming in scenarios with traffic control or could divert attention from AV driving behaviour in settings like roundabouts, where such cues are crucial. Designers should either develop minimal eHMIs, similar to LightRing, or consider adjusting the level of eHMI detail between scenarios to prevent cognitive overload. For example, eHMIs could delay message presentation in controlled scenarios, allowing cyclists to first interpret AV intentions based on driving behaviour before receiving explicit signals.

DG3: Versatile eHMIs can reuse signals between scenarios

The observations from Chapter 3 revealed that drivers and cyclists exchange different messages depending on the scenario, raising uncertainty about how this would translate to AV-cyclist interaction. The design sessions in this chapter demonstrated that participants designing for all scenario categories prioritised AV intention and awareness signals. Follow-up studies confirmed that cyclists preferred eHMIs that communicated AV intentions using abstract, binary signals (yielding/not yielding) in all traffic scenarios. This approach supports versatility because, unlike human drivers, AVs can provide consistent signals throughout. This suggests that AV-cyclist interfaces can not only compensate for the lost social cues from human drivers but also enhance current road interactions, as there would be a minimal learning curve between scenarios. Furthermore, this aligns with prior research showing that binary intention signals are also effective for pedestrians [37, 82], indicating the potential for synthesising eHMIs that accommodate multiple road users.

DG4: eHMIs should explicitly communicate intent and implicitly convey awareness

As discussed in the previous guideline, participants in the design sessions prioritised AV intentions and awareness as key messages for eHMIs to communicate. However, these messages were simplified into binary signals on AV intentions after first-hand interaction in the VirtuRide study. This does not mean that cyclists did not need to know whether the AV was aware of them. Interestingly, the evaluation studies showed that an eHMI changing its state to yielding or not yielding implicitly communicated that the AV had detected the cyclist and was displaying its intentions in response to their presence. For example, Safe Zone and the updated LightRing turned green when the AV detected the cyclist and yielded, signalling both awareness and intentions simultaneously. Separately communicating both messages proved overwhelming. For instance, the first iteration of LightRing conveyed intentions through animation and awareness through colour changes. Riders took longer to process these signals and fixated on them more than the abstract, binary ones, suggesting a higher cognitive load. Researchers must measure how cyclists interpret AV-cyclist interface messages and their confidence in those interpretations, rather than assuming cyclists will perceive signals as intended. This approach would provide insights that support versatility and avoid misinterpretation of messages.

DG4: eHMIs should be placed on large surfaces on the AV's body

The previous chapter and design sessions established that AV-cyclist interface messages must be perceivable from any angle around the vehicle, suggesting that placements such as the AV's roof could be suitable. However, while visibility from all angles is a core requirement, the evaluation studies in this chapter showed that it is not always sufficient. AV-cyclist interfaces must also be quick to recognise and process at a glance. This requires using large surfaces, such as the road or the vehicle's side body, as smaller placements like the roof do not provide the same level of visibility. This finding aligns with the eye-tracking study from the previous chapter, which showed that cyclists primarily fixated on larger surfaces like the road due to their ease of recognition. Prior work [140], the eHMI design sessions, and the VirtuRide study all highlighted road projections as a promising solution. However, the Ghost Driver study revealed significant limitations. Implementing road projections with current technology is challenging and expensive, and their effectiveness may vary across different road surfaces (e.g., gravel). In contrast, placing displays directly on the vehicle, such as LED strips, is a more practical solution. LEDs were highly visible even in sunny conditions and well received by cyclists, as demonstrated in LightRing. Ultimately, leveraging large surfaces enhances eHMI versatility, as this chapter showed that the AV's position relative to cyclists impacts workload, confidence, and cycling behaviour. However, designers should take care when choosing these large surfaces and must consider the practical aspects of their concepts.

DG5: Colour changes are crucial for message clarity and distinction

Studies in this thesis consistently showed that cyclists must recognise, distinguish, and understand AV messages while moving. The eHMI design sessions explored various approaches to achieve this, including colours, icons and animation patterns. Animations are particularly popular with pedestrians [37]. However, the VirtuRide study demonstrated that icons and animations were ineffective as primary communication methods for cyclists. The first iterations of Emoji-Car and LightRing increased workload, requiring cyclists to focus more on them to interpret yielding intentions. Icons were challenging to interpret from a distance, and directional animations were difficult to process from different angles around the vehicle. The Ghost Driver study confirmed that colour was the most effective distinguishing factor. However, designers must ensure that colour choices provide strong contrast and remain easily recognisable from a distance. This chapter showed that red and green were particularly effective. Animations or icons can complement colour to improve distinguishability and accessibility for colourblind cyclists. However, this should not come at the expense of message recognisability. For instance, the updated Emoji-Car icons limited the usable space on the LED matrix, and directional animations in LightRing's first iteration were harder to recognise than the speed-based animations in the revised version. Designers must carefully consider how to support colour changes without compromising recognisability. Some research on AV-pedestrian interaction has shown that colour takes precedence over animation as a distinguishable factor [39]. This suggests a potential overlap that designers can leverage when developing eHMIs for multiple road users.

DG6: Echoing vehicle can signals confuse cyclists

The observation and eye-tracking studies from Chapter 3 showed that cyclists rely not only on social cues from drivers but also on traditional vehicle signals, such as directional indicators. Participants in the design sessions recognised the value of these signals but raised concerns about their visibility from different vehicle angles. They suggested that eHMIs could reinforce vehicle signals to improve visibility, such as LightRing flashing amber in sync with the directional indicator or Emoji-Car displaying a blinking arrow pointing toward the vehicle's turn direction. The VirtuRide study tested these approaches, but both designs overloaded the displays. This increased cognitive workload and caused confusion. This indicates that blending eHMI signals with vehicle ones can lead to ambiguity. eHMIs should focus on communicating the AV's yielding intentions and be positioned in a way that does not obstruct the visibility of traditional signals. Cyclists must distinguish between traditional signals and eHMI messages, which could be achieved through distinct placements, colours, or animation patterns for novel eHMIs.

DG7: eHMI signals should align closely with the existing traffic vocabulary

The design session themes identified three levels of familiarity in eHMI signals: replicating driver social cues, adapting existing traffic signals, and introducing entirely new signals, such as animated cyan lights. The evaluation studies demonstrated that cyclists preferred signals with some familiarity, which minimised the learning curve and improved confidence in AV intentions. Familiarity could be incorporated through colour. Participants consistently responded positively to red and green signals for AV intentions, as these colours were familiar and required little interpretation. Similarly, animations should align with familiar traffic patterns. The Ghost Driver study showed that flashing animations, resembling those in pedestrian crossings, were easier to process than directional animations, which required more fixation time. Icons also need to be easily recognisable. The VirtuRide study revealed that cyclists struggled to associate a lightning emoji with non-yielding behaviour, leading to confusion and ambiguity. Therefore, designers should ensure that at least one aspect of the eHMI aligns with cyclists' existing expectations to reduce cognitive load and prevent misinterpretation.

The versatility of eHMIs makes them suitable baseline interfaces for HACIs. They can facilitate interaction with all cyclists in all scenarios without changing the current cycling setup. This significantly advances the acceptability of upcoming HACI concepts in the thesis. This chapter showed that LightRing was the most successful eHMI. This communicates binary AV intention signals through colour changes and animations. This leaves room for more comprehensive messages when incorporating LightRing into HACIs. However, the range of devices, messages and modalities that can be connected to LightRing remains unclear. These potentially significant additions to LightRing maximise the cultural differences in how cyclists perceive HACIs. Therefore, it is critical to test any HACIs across cultures. The following chapter addresses RQ4 to investigate the design features HACIs should adopt and how these design features generalise between cultures.

Chapter 5

Cultural Inclusivity

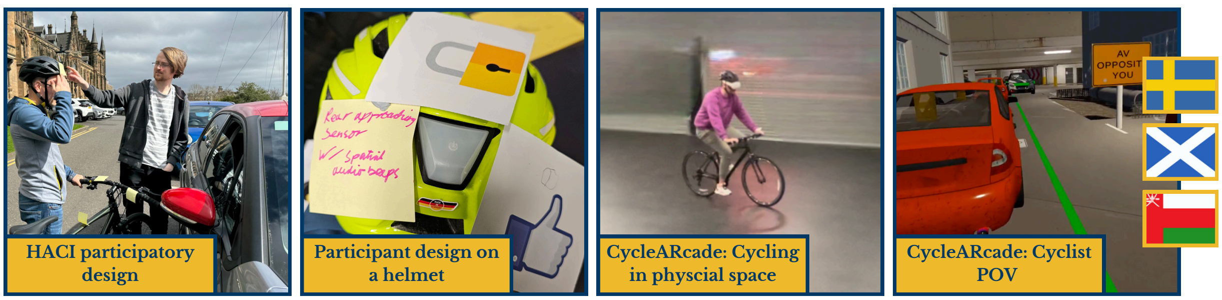

Figure 5.1: The two studies conducted in this chapter. The two images on the left are from the HACI design sessions conducted outdoors around real vehicles. The images on the right show the cross-cultural evaluation study conducted across three cities with cyclists using an AR cycling simulator to experience HACIs.

The previous chapter established LightRing as a versatile eHMI that communicates simple, binary AV intention signals. LightRing was not overloaded with messages, making it an ideal baseline interface for a HACI. Cyclists could incorporate additional devices for support, similar to how rearview radars or bike computers are used today [14]. This approach would allow AV-cyclist interfaces to improve upon today's interactions rather than only compensating for the social cues of human drivers [80].

Incorporating LightRing into a HACI would interconnect it with any other devices in the ecosystem, offering many advantages. For example, it would prevent contradictory AV signals between devices, minimising confusion and unsafe situations[9]. Moreover, the interconnectivity of devices would avoid overloading a single display, as comprehensive messages may be distributed and only communicated across the most effective modalities [80]. For example, spatial helmet audio could communicate the proximity of an AV behind the cyclist, while LightRing would indicate its yielding intentions. HACIs could also extend the reach of interfaces, such as eHMIs, onto wearables and make them multimodal. For example, a smartwatch could vibrate in sync with LightRing's animation patterns, reducing cyclists' need to check the eHMI constantly.

However, the optimal combination of devices, messages and modalities remains unknown. HACIs are a novel concept introduced in this thesis, so it was critical to investigate the design features HACIs should adopt to be effective. Moreover, HACIs bring a wider range of devices and messages than previous interfaces explored in this thesis. This maximises the cultural differences in how cyclists use and perceive HACIs [108]. Drivers and cyclists currently exchange different cues between cultures [26], and the degree of cyclist segregation from motorised traffic differs between countries and cities within these countries [62]. Therefore, the information needed from HACIs may depend on the local traffic culture. Testing HACIs in a single cultural setting is insufficient. It is critical to conduct a cross-cultural investigation to explore how HACIs may be adapted to be culturally inclusive and support the global deployment of AVs.

This chapter answers RQ3: *"What are the cultural differences in cyclist use and perceptions of AV-cyclist interfaces?"*. This involved the investigation of the design features HACIs should adopt to be successful, followed by a cross-cultural evaluation of these features to support the global adoption of HACIs. Two studies were conducted (see Figure 5.1):

1. **Study 7 - HACI Design Sessions:** This was an initial step in understanding the potential devices, modalities, and messages that HACIs can incorporate. The study followed a similar structure to the design sessions in Chapter 3. Researchers and cyclists collaborated around real parked vehicles to design HACIs. Vehicles were equipped with real prototypes of the LightRing eHMI, which was a baseline interface. Participants sketched and attached their designs on the environment, bicycle or themselves. Three novel HACIs were synthesised from the design session results. These incorporated wearable devices communicate different types of information in addition to the eHMI, such as AV location, AV intentions, or a combination of both.

2. **Study 8 - Cross-Cultural HACI Evaluation:** This was a cross-cultural user study conducted across Stockholm, Sweden (high cyclist segregation from vehicles), Glasgow, UK (some segregation) and Muscat, Oman (no segregation). The three HACIs from the design sessions were loaded onto CycleARcade, a novel AR cycling simulator developed for this study. Participants from all cities cycled in real, augmented space to test and compare the HACIs in different traffic scenarios. The studies captured the cultural differences in how cyclists use and perceive HACIs, including the type of information HACIs should communicate depending on local norms and traffic infrastructure.

This chapter informs how AV-cyclist interfaces can be culturally inclusive. It captures the cultural differences in the use of interfaces and contributes design guidelines that support overcoming the design challenge. The studies in this chapter are critical to ensure that AVs can be adopted globally as opposed to individual cities, as seen today [3].

5.1 Study 7: HACI Design Sessions

HACIs bring a wide range of devices, modalities, and messages to AV-cyclist communication. This study used a design session approach to understand the design features HACIs should adopt to be successful. HCI researchers and cyclists collaborated around real parked vehicles equipped with the LightRing eHMI to design HACIs by sketching and attaching their designs to relevant areas beyond the vehicle. This is the first exploration of how HACIs can be designed to facilitate AV-cyclist interaction.

5.1.1 Study Design

This study followed a similar approach to the eHMI design sessions from Chapter 4. HCI researchers and cyclists collaborated to design HACIs around real parked vehicles; see Figure 5.2. Transcripts of participant discussions during the design sessions and photographs of the final designs were collected for analysis.

Study scope

Participants designed a HACI that facilitates interaction at a specific traffic scenario category, as identified in Chapter 3: *controlled scenarios* (traffic lights), *uncontrolled infrastructure* (no traffic lights, but may have road markings or signs determining right-of-way, e.g. roundabout) and *dynamic manoeuvres* (could happen anywhere on the road, e.g. bottleneck or lane merging). As in the eHMI design sessions, each session focused on one traffic scenario category to ensure participants remained focused on the task without constraining them to a specific scenario. This approach also facilitated an exploration of HACI versatility, even if HACI devices may be interchangeable between scenarios. This provided an understanding of whether HACIs can operate consistently between traffic scenarios, which may be a desirable feature.

HACIs require a baseline interface to maintain acceptability and support cyclists who may not carry additional devices. The vehicles used in this study were equipped with the LightRing eHMI as implemented in the Ghost Driver study to fulfil this requirement. This helped avoid overlaps and redundant results between this study and the eHMI design sessions from the previous chapter, which already contributed and tested eHMIs. The inclusion of LightRing also provided participants with a clear scope to integrate devices beyond the vehicle. This was useful because HACIs can be challenging to design from scratch [28], and the Map-it participatory design approach [70] (which informed this method) recommended avoiding providing participants with large scopes during design sessions; therefore, LightRing provided a suitable starting point.

The LightRing eHMI was chosen because it was the best-performing eHMI in Chapter 4 and had the highest usability scores. Therefore, incorporating it into a HACI was a natural progression of the research. LightRing aligns with all the design guidelines from the previous chapter. This allowed participants to develop their HACIs without compromising the usability

Figure 5.2: Photographs from the design sessions. Left: Participants collaborating around a vehicle equipped with the LightRing eHMI. Middle (top and bottom): On-bicycle displays designed by participants. Right: AR lenses attached to the helmet.

or versatility of the baseline interface, which is critical for maintaining acceptability. For example, unlike Emoji-Car, which is placed on the roof, LightRing is placed on large surfaces around the vehicle. This was helpful for participants to contemplate the design of HACIs that utilise devices beyond the vehicle without overwhelming cyclists when a large eHMI is in their view. LightRing also communicated binary AV intentions through colour changes and animations. These messages are minimal, making it an ideal candidate for expanding these signals and communicating complementary messages through other devices. The animations used in LightRing are not present in Safe Zone or Emoji-Car; participants can use these signals and translate them to non-visual cues, for example, having a smartwatch vibrate at the same rhythm as LightRing. This leaves room for participants to make LightRing multimodal, not focusing exclusively on communicating complementary messages and ultimately expanding the potential design choices.

Study setup

The design sessions involved six teams, each comprising one HCI researcher and one cyclist. This study used HCI rather than AutomotiveUI researchers, as HACIs are not necessarily constrained to the vehicle. They may involve a wide range of wearable and on-environment displays, including AR glasses, smartwatch vibrations, and LED road markings. Therefore, it was important to involve researchers who have experience with these displays to explore the potential modalities or placements that may be used. The inclusion of cyclists was crucial for gaining an end-user perspective on the designs, which proved useful for maintaining acceptability in the eHMI design sessions.

The study was conducted in Glasgow, UK. It took place in an outdoor car park, and vehicles were parallel parked so participants could easily move around and contemplate all vehicle sides. Teams were given bike helmets, gloves, and bicycles to immerse themselves in the design sessions by simulating scenarios and AV positions to scale. These were also used to reference potential interface placements. Three design sessions were conducted, each featuring two teams working in parallel around two parked vehicles. Vehicles were parked 150 metres apart to prevent overlapping ideas during ideation. Each team was moderated by an experimenter who briefed participants and ensured they stayed focused on the task. Experimenters also video-recorded the sessions and photographed the final designs. They had at least one year of HCI research experience, allowing them to answer any questions on HACIs.

Study structure

The design sessions had the same structure as the eHMI ones. They were split into (1) 30 minutes of ideation with team members collaborating to design a HACI and (2) 15 minutes of feedback, where cyclists switched teams to provide feedback on the other team's design.

During ideation, participants discussed the traffic scenario category they were assigned. They sketched their designs and placed them on relevant areas, such as the helmet, bike or their own bodies. This helped them visualise the designs and discuss the features the displays should use. Participants were encouraged to think aloud as they worked to contextualise their design choices during analysis. They were given lock stickers to place on features they felt should remain unchanged, which helped them form strong opinions and justify their decisions.

After ideation, cyclists switched teams to evaluate and provide feedback on the other team's design. They were given like and bomb stickers to place on features they liked or disliked. This facilitated additional end-user perspectives to enhance the acceptability of the designs.

Measures

The study collected the following data to understand the design features that enhance the usability of HACIs:

- **Photographs of participant designs:** This identified the range of devices participants incorporated in their designs. It was useful for synthesising new HACIs based on participant designs to explore any cultural differences in the upcoming study;

- **Video footage of the design sessions:** These videos were useful for contextualising participant design decisions and gaining detailed end-user perspectives on the problem.

5.1.2 Apparatus

Two right-hand drive vehicles were used per session: a grey 2019 Citroen C3 and a 2022 red Volvo XC40. Vehicles were instrumented with the LightRing eHMI from the Ghost Driver study in the previous chapter. These were LED strips stuck to the vehicles using velcro and controlled by an experimenter using their smartphone via Bluetooth.

Teams had access to a Giant Escape or a Specialized Sirrus X hybrid bicycle for ideation; both bikes are popular for commuting. Cycling gear and stationery supplies were provided to support the creative process, including paper in sizes A5, A4, and A3, adhesives, sticky notes, markers, and laminate sheets. The experimenters recorded the sessions using their smartphones.

5.1.3 Participants

Six HCI researchers were recruited through personal contacts. They were PhD students, post-doctoral researchers, and lecturers from various HCI areas, including extended reality, audio interfaces, haptics, and automotive user interface design. Their demographics were: $M_{\text{age}} = 34.5$, $SD = 12.4$; $Male = 5$, $Female = 1$.

The sessions also included six cyclists recruited through social media. Cyclists must have been cycling in mixed UK traffic multiple days per week for at least one year. Their demographics were: $M_{\text{age}} = 28.8$, $SD = 6.2$; $Male = 3$, $Female = 3$.

5.1.4 Procedure

Participants registered for the study through an online survey, where they provided their demographic information and specified their cycling/HCI research experience. Cyclists ranked the three traffic scenario categories from most to least difficult so they could be assigned a category they considered challenging. They met their teammates and experimenters in the designated car park on the study day. Experimenters first briefed them about the task and reminded them of their assigned scenario category. They introduced the concept of a HACI: multiple individual interfaces designed to be part of a larger ecosystem while knowing the presence and state of other interfaces in that ecosystem. The experimenters also demonstrated the eHMI states by controlling LightRing through their smartphones. This gave participants a clear understanding of the eHMI signals.

Participants were then provided with the stationery, bicycle and cycling gear. They familiarised themselves with the parked vehicle. Experimenters then started the video recordings, and the ideation part of the study started. Participants were free to design the interfaces to their liking and were not pushed to accommodate any particular features or displays. After ideation and sketching, the cyclists switched teams. Researchers presented their designs, and cyclists shared feedback on the interfaces. The video recording concluded, and experimenters photographed the final designs. Participants were compensated for their time with £10 Amazon vouchers.

5.1.5 Analysis

The analysis was divided into two parts. First, participant designs were organised into a taxonomy of HACI components. Second, a thematic analysis was conducted on the design session footage. This extracted themes representing researcher and cyclist expectations of HACIs.

Design Analysis

One researcher used Canva to sketch each design over an AI-generated image of an AV-cyclist encounter to give the results a uniform presentation. A second researcher reviewed these against the design photographs and found no differences. One researcher then categorised them into a taxonomy, which was important to visualise the relationships between features, such as the placement, modality and communicated message of an interface, as demonstrated in the eHMI design sessions.

The taxonomy of eHMI features from Chapter 4 was adapted to suit HACIs. This was of six layers: (1) Traffic Scenario Category; (2) Placement (e.g., bicycle or cyclist); (3) Specific Placement (this layer was new. It included, e.g., bike handlebar or helmet as device placements were not only focused on the vehicle); (4) Message; (5) Modality; (6) Technology. Each HACI feature, e.g. visual modality or bicycle placement, was also populated with its frequency of appearance across the designs. A second researcher also categorised the designs according to the taxonomy and found no discrepancies.

Thematic Analysis

An inductive, data-driven thematic analysis [19] was conducted on the video transcripts. The transcripts were auto-transcribed by Otter.ai and subsequently corrected by a researcher. They were then imported into NVivo for coding. One researcher identified 33 unique codes from the data. Following this, two researchers collaboratively sorted these codes into three overarching themes based on their similarities. This process was iterative; disagreements were discussed and resolved, with codes being remapped as necessary. Themes containing two or more overlapping codes were reassessed and combined where appropriate.

5.1.6 Results

This section summarises each team's design based on design photographs and explanations from the video footage. Figure 5.3 includes sketches of each design. The section also presents the taxonomy of HACI components populated with features from participant designs; see Figure 5.4. Lastly, it reports the themes that reflect the perspectives and expectations of researchers and cyclists regarding HACIs.

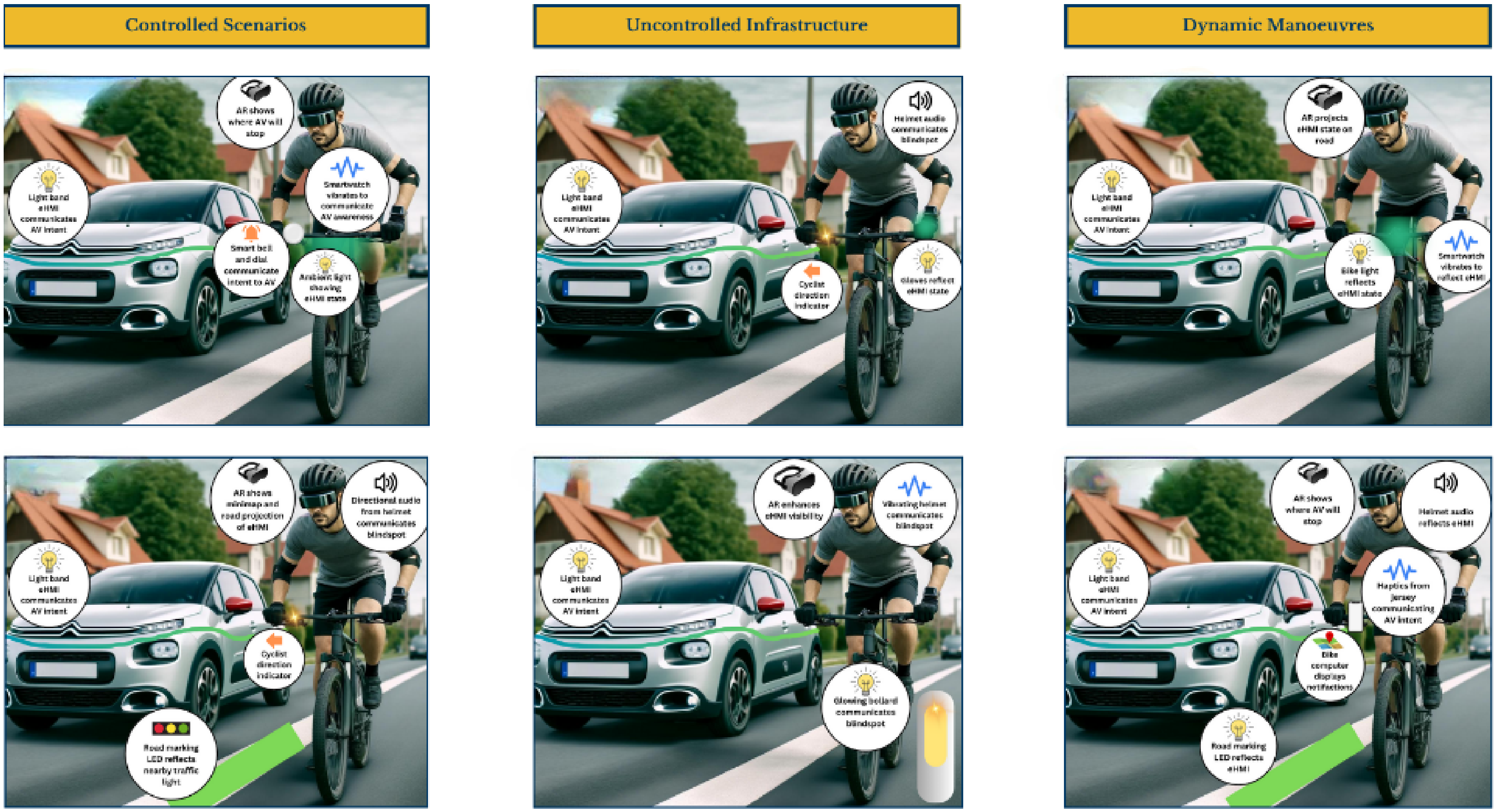

Figure 5.3: Participant designs sketched on an AI-generated image. Images on the top row show the designs of teams 1, 3 and 5. Images on the bottom row show the designs of teams 2, 4 and 6.

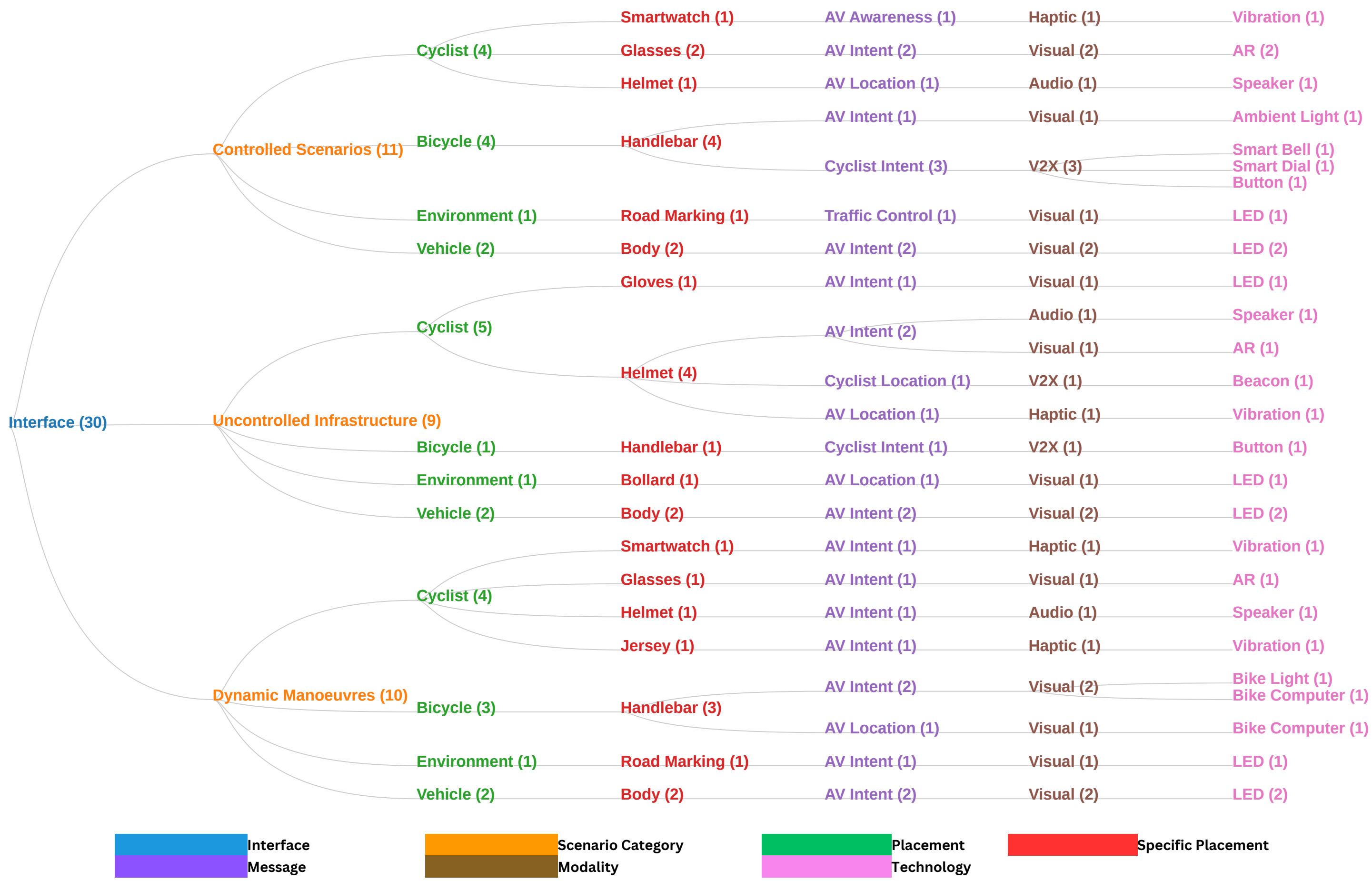

Figure 5.4: A tree diagram of the HACI taxonomy populated with HACI components from the study. Each branch is labelled with: *HACI feature (frequency of appearance)*

Designs and Taxonomy

The study produced six HACIs, two for each traffic scenario category. The taxonomy visualising the relationships between features in these designs is shown in Figure 5.4. This section reports how these features were used in context and summarises each design based on participant descriptions in the video footage. Participants mostly incorporated multimodal wearable or bike-mounted interfaces. They reused existing devices, such as smartwatches and cycling gear, such as helmets, to extend LightRing or warn cyclists of a potential blindspot. They also placed devices on the bicycle handlebar to facilitate two-way communication and send their intentions to AVs, such as directional indicators or smart bike bells.

Controlled Scenarios - Team 1 This design works in sequence. First, the cyclist's smartwatch or phone vibrates to alert them that an approaching AV detected them. Next, ambient lights on the handlebar glow in the same colour as the AV's eHMI; green when yielding and red when not. Then, AR glasses worn by the cyclist project a marker to indicate where the AV will stop if it is yielding. The design also facilitates two-way communication with a smart bike bell on the handlebar with V2X connectivity. This features a dial that cyclists can use to signal their urgency, such as *"not in a hurry"*, potentially influencing the AV's decision to yield.

Controlled Scenarios - Team 2 The cyclist's AR glasses display a minimap in the top right corner. This shows nearby AVs and their eHMI states; AV icons are green if yielding and red if not. The AR glasses also project red or green onto the road around the AV to enhance LightRing's visibility. Moreover, spatial audio from the cyclist's helmet provides blindspot warnings by beeping in the vehicle's direction.

Given that this design addressed controlled scenarios, participants added LEDs on road markings and bike boxes to mirror traffic lights at controlled intersections. This design also supports two-way communication through directional indicators mounted on the bike's handlebar. These send the cyclist's intentions directly to the AV via V2X. LED lights on the back of the saddle also reflect the cyclist's intended turn direction.

Uncontrolled Infrastructure - Team 3 Cyclists wear gloves equipped with LEDs that light up in red or green, corresponding to the LightRing's current state. Additionally, the cyclist's helmet emits a beeping sound if the AV does not yield. The helmet also features a beacon to signal the cyclist's location to the AV, ensuring the rider is detected. The bicycle's handlebar features directional indicators; the handlebar edges illuminate based on the cyclist's intended turn direction. These indicators are also connected to the AV via V2X technology, ensuring that the AV accurately receives the cyclist's turning intentions.

Uncontrolled Infrastructure - Team 4 The cyclist's helmet features built-in AR lenses; these overlay AVs with the colour and pulsing pattern of LightRing for increased visibility. The helmet is also equipped with spatial vibration motors that point in an AV's direction to warn cyclists of potential blindspots. The HACI also features on-environment displays in the form of bollards and traffic signs that light up when an AV approaches from a cyclist's blindspot.

Dynamic Manoeuvres - Team 5 The displays in this HACI operate sequentially. First, the cyclist's smartwatch vibrates in sync with LightRing's animation, alerting them to an approaching AV and its intentions. Next, the cyclist's AR glasses project LightRing's state onto the road around the AV to enhance visibility, pulsing green when yielding or flashing red when not. Finally, a smart bike light on the handlebar flashes red if the AV does not yield, providing an additional warning.

Dynamic Manoeuvres - Team 6 The helmet's audio is synchronised with LightRing, emitting a ringing sound when the AV is yielding and a beeping sound when it is not. This uses bone conduction technology to ensure that environmental sounds remain audible. Additionally, cyclists receive haptic feedback through their jersey, which applies pressure to their back if the AV is not yielding. The cyclist's bike computer is connected to AVs via V2X, displaying an accurate map of all nearby AVs. It also provides contextual notifications, such as *"This car has seen you, go ahead"* after the cyclist signals to merge lanes, or *"The car intends to overtake you"* when an AV approaches from behind. The HACI also incorporates smart road markings with embedded LEDs that synchronise with an approaching AV's eHMI. These LEDs pulse green when the AV intends to yield and flash red when it does not.

Themes

This section reports the themes resulting from participant discussions while developing their concepts. These captured the devices HACIs should use to be effective, the advantages they bring to AV-cyclist interaction and the challenges they must overcome before real-world use. Each theme is divided into subthemes for clarity and comprehensibility.

Theme 1: Devices in HACIs

This summarises participants' views on how individual interfaces may be used collectively and integrated into a HACI. Participants discussed how current devices, such as smartphones, may be repurposed for AV-cyclist interaction and the role future devices, including AR glasses, have in HACIs.

Repurposing personal devices Participants saw value in their current devices being repurposed for AV-cyclist interaction: *"You might as well augment everyday things. We're not re-*

quiring extra tech" - C3. However, devices such as smartphones may not always be in view, and displaying visual cues may not be practical in these cases: *"Smartphone - it stays in your pocket."* - C5; *"My sleeve covers my smartwatch"* - R5. This finding aligns with the online survey from Chapter 3, showing that smartphones are rarely in the cyclist's view. This prompted participants to use non-visual cues when repurposing personal devices: *"The smartwatch should vibrate when a car is near me"* - C3. Therefore, while personal devices are challenging to use in isolation [16], they can be integrated into HACIs to provide additional messages, such as alerting cyclists of an AV in a blindspot.

AR in HACIs Using AR glasses in isolation would hinder AV-cyclist interface acceptability: *"What happens if they don't have the AR headset?"* - C6. However, there is still value in using AR as part of a HACI. For example, participants in the previous eHMI design sessions explained that scalability is a challenge for eHMIs, especially when multiple cyclists are around an AV. AR displays could overcome this: *"You only see your information on the AR headset"* - R6. While this certainly generalises to personal devices, such as smartphones and smartwatches, AR provides a clear visual representation of these signals [67].

Participants mostly used AR to display an AV's intentions in addition to the eHMI: *"Glasses could overlay [AV] with the [eHMI] colour*" - C4. Therefore, AR could make eHMIs more visible while reassuring cyclists that the message is for them. Moreover, on-environment displays may be challenging to maintain on a large scale, and Chapter 4 showed that eHMIs road projections are not practical for real-world use. Participants used AR to overcome these challenges: *"It seems cheaper to have them in your glasses."* - R3. Therefore, AR has many advantages for AV-cyclist interaction. It is challenging to use in isolation, but it helps resolve scalability and acceptability challenges when incorporated into an HACI.

Adapting to cyclists and traffic scenarios HACIs can be modular, and not all devices must be active in a given ride. They may be included depending on availability: *"Different people will have access to different bits of equipment, you know? Like cheap minimum requirements or the more expensive alternative"* - C6. Similarly, different devices or modalities may be used depending on the traffic scenario: *"Maybe you have a sound with a recognised vibration when you have a movement [behind you]"* - C5. This allows cyclists to customise their setup, which would enhance AV-cyclist interface acceptability: *"I don't think I'll use all the devices in every trip"* - C3. Therefore, HACIs should be designed to accommodate interchangeable devices depending on the cyclist's circumstances, trip purpose or traffic scenario.

Interconnected devices Wearable or bike-mounted devices connected to the AV could reduce the workload of AV-cyclist interaction: *"You can just be on the bike, glance down and see the colour red - you don't need to go out of your way and look at the car moving"* - C1. However, these wearable devices would need to be connected to the AV to display accurate signals consistently: *"We need to ensure the devices are always connected to the car if we want to replicate the eHMI"* - R3. Therefore, it is useful for wearable or bike-mounted devices to display AV information. However, V2X or other means of connectivity are required to synchronise the interfaces.

Theme 2: Opportunities for HACIs

This section presents themes about the opportunities participants saw in HACIs to resolve key design challenges, including fostering two-way communication, working in diverse weather conditions, and reassuring riders of the AV's intentions to increase trust.

Two-way communication Chapter 3 showed that cyclists use hand gestures, facial expressions and other social cues to communicate with drivers. However, participants did not trust that AVs will always recognise these signals: *"How would you know that the cars pick [arm signals] up?"* - C5. They proposed new ways to signal AVs their intentions, such as on-bike directional indicators. They also needed AVs to respond appropriately: *"Cyclist indicates [through a button], the lights change colour, and the AV confirms message received"* - R1. This two-way communication was more preferred than instructions from the AV: *"Generally, cyclists prefer to be told what the car is doing, rather than have the car instruct the cyclist what to do"* - C4. This coincides with the *driver-cyclist communication is two-way* design guideline from Chapter 3. HACIs can foster two-way communication between AVs and cyclists. Input through buttons can utilise V2X to transmit messages, and displays can reassure cyclists that their messages were received.

Multimodal eHMIs LightRing used visual cues to communicate with cyclists. The eHMI design sessions from Chapter 4 showed that multimodal eHMIs can make messages more recognisable. However, the sessions also showed that auditory cues through speakers on an AV may be masked by the environment or make it difficult to target a specific cyclist. Participants utilised HACI's interconnected features to make LightRing multimodal: *"Key part is this synchronisation between the lights and the watch vibrations"* - R3. This reassures cyclists that LightRing's signal is for them and fosters trust: *"Continuous vibration on my hand and flashing lights help me know something changed for me"* - C3. Synchronising signals between HACI displays also minimises the workload of interaction, as HACIs will not be overloaded with different signals: *"I don't have to remember many things this way"* - C3. Therefore, HACIs can support the extension of eHMIs to overcome ambiguous signals and improve usability.

A failsafe for cyclists Cyclists must receive clear signals about AV intentions, and the previous chapters showed that AV-cyclist interfaces are an acceptable and effective way to address this. However, these interfaces might malfunction or be out of view, such as an eHMI behind the cyclist. HACIs can overcome these issues and provide cyclists with a failsafe: *"Good to have the vibration. Sometimes, super sunny conditions affect my view"* - R3; *"Ambient handlebar lights with the same colours as the eHMI. It confirms what the [AV you can't see] is doing"* - R5. Therefore, eHMI message redundancy can help cyclists notice an AV's intentions, even in demanding or imperfect conditions.

Exchanging new messages The previous chapter showed that AV intentions are critical messages for clear AV-cyclist interaction. HACIs can display intention signals but also allow the exchange of other messages that could enhance the interaction experience further: *"I feel like I want to be able to give [AVs] good or bad ratings. [...] It'd be nice if you could know where the car would stop"* - R5; *"I want to inform the car if I'm late, I want to go first"*- C5. These messages are not necessarily communicated in today's interactions. HACIs can facilitate the exchange of messages that may not be essential to navigating space-sharing conflicts but result in a more satisfying interaction experience.

Supporting the transition from human-driven to automated vehicles HACIs can help cyclists get accustomed to interaction with AVs. One participant described them as *"training wheels"* - E5. HACIs can display comprehensive information to cyclists until they are comfortable riding around AVs with just eHMIs: *"I think I will use them until I am used to the lights on the car"* - C3. Therefore, HACIs can help the initial deployment of AVs by ensuring riders are comfortable with the information they receive.

Theme 3: Challenges for HACIs

This section explains the challenges participants faced when designing HACIs. These include presenting information from multiple AVs or utilising wearable or bike-mounted devices without imposing an added responsibility on cyclists.

Displaying messages from multiple AVs AV-cyclist interfaces should be scalable, meaning they should handle interaction when multiple vehicles or cyclists are present. This study showed that wearable devices could help cyclists receive targeted messages from AVs, making one AV-many cyclist communication more manageable. However, presenting information from multiple AVs to a single cyclist remains challenging: *"There's two cars near to each other. How do you differentiate which one's buzzing at you?"* - C4; *"The [handlebar lights] are just telling me what a car will do. What if there were multiple cars?"* - C6. HACIs should scale to many-to-many interactions to be usable on real roads.

Maintaining interface acceptability AV-cyclist interfaces should impose minimal changes to the current cycling setup to be acceptable in traffic. Participants were concerned that wearable interfaces would make them responsible for avoiding AVs and have them give up their right-of-way: *"Responsibility for both sides because a car can't die"* - C5; *"Cyclists will know more, but the AV should still slow down"* - R6. This emphasises that AV-cyclist interaction must still be facilitated with no additional devices on the cyclist or bicycle and shows the importance of eHMIs as baseline interfaces. However, cyclists using these devices within a HACI should receive additional information about the AV without expecting to lose their right of way.

5.1.7 Discussion and Design Synthesis

Participants successfully designed HACIs that incorporate multimodal devices to work alongside the LightRing eHMI. The themes in this study showed many advantages of HACIs, which coincide with the design guidelines from Chapter 3. For example, participants appreciated the interconnected features of HACIs and saw value in using these to extend the reach of LightRing to wearables and make the eHMI multimodal. This illustrates a key benefit of interconnecting interfaces rather than grouping them without synchrony. Displaying AV intentions beyond the eHMI could be beneficial for cyclists as it could reduce the need for shoulder checks and added attention to the vehicle [140]. It could also help cyclists be more confident about an AV's intentions and make faster decisions [88]. A similar effect was observed with pedestrians at crossings [8, 80]. Many participants incorporated additional intention signals from wearables. However, they mostly opted to extend LightRing's design language (colour and animations) rather than develop new types of signals to communicate this information. For example, some participants used AR to project pulsing green onto the road around a yielding AV. The previous chapters recommended road projections as they cover a large surface, allowing riders to infer AV state through quick glances [67]. However, they were found to be difficult to implement across varying road textures or sunny environments, so HACIs offer a useful alternative.

Participants did not only use visual signals to extend and reiterate LightRing. For example, some teams synchronised smartwatch vibrations to LightRing's animation patterns. This shows that LightRing's signals were straightforward to communicate across modalities. It may be more complicated to implement with uni-colour eHMIs using directional animations, such as Dey et al.'s [39] light band design. Displaying AV intentions beyond LightRing would require V2X for the vehicle to transmit its intentions to the wearable or bike-mounted interfaces and synchronise them with the eHMI [110]. Participants discussed this, emphasising the importance of LightRing as a baseline interface, as it would act as a failsafe in case V2X was unavailable.

The general trend observed in participant designs was communicating an AV's location and intentions concurrently, and this is more comprehensive than successful eHMIs from the previous chapter. This leverages a key advantage of HACIs: their ability to communicate comprehensive information that can be divided across devices and modalities rather than overloading a single display. AV location information is particularly helpful during encounters with AVs behind the cyclist or occluded by obstacles. This could be implemented through V2X or even proximity sensors on the helmet or bike. Another way for HACIs to communicate comprehensive information is by presenting it in sequence so that not all devices are active simultaneously. Some participants utilised this to reduce the risk of information overload. This opens the door for interaction that caters to cyclists' natural behaviours. For example, interfaces could first communicate the AV's location, such as behind the cyclist. The cyclist would then indicate intentions to merge lanes with the AV to receive feedback on the eHMI or smartwatch.

However, the observations from Chapter 3 showed that right-of-way is not always up for negotiation, such as in controlled intersections. HACIs might not always be sequential and only communicate that *"there is a non-yielding AV on your left"*. The themes from this study showed that HACIs could be modular, with devices interchangeable between scenarios. This could also extend to the sequence of message presentation, meaning HACIs could be adaptable. For example, directional audio from the helmet can play a sonar-like sound that communicates the AV's location when right-of-way is negotiable. A ringing sound communicates AV-yielding intentions and beeps when it is not. This way, the audio will always be directional, but the specific clip will depend on the situation.

Findings and design guidelines from Chapter 3 showed that driver-cyclist communication is two-way, and AV-cyclist communication is not limited to the AV transmitting messages to cyclists. However, participants in this study did not trust that AVs always detect social cues, such as arm gestures. They preferred on-bike indicators and direct acknowledgement from the AV that these messages were received. This could be implemented by having the eHMI change its state to yield or not yield after receiving the cyclist's signal, rather than establishing a new signal to confirm message reception. This could reduce the workload as cyclists would not have to learn many signals.

Regarding HACI versatility, this study found that the exchanged messages and modalities were consistent between the traffic scenarios. However, participants utilised different placements and messages depending on their availability. For example, road markings in uncontrolled infrastructure, such as roundabouts, could reflect the eHMI signals, but bike boxes in controlled scenarios could reflect the traffic light states. This relates to the theme of HACIs being modular and adaptable between cyclists and scenarios. It is critical to consider the scenarios cyclists navigate to understand which traffic signs, road markings or other features may be used as HACI device placements. This could reduce the workload for cyclists navigating these scenarios.

Design Synthesis

This study showed that HACIs are more comprehensive than eHMIs. They use multimodal signals to communicate more detailed messages. This high detail and large combination of devices, messages and modalities maximises the potential for cyclists to have different perceptions and behaviours toward HACIs. This study only explored the design of HACIs with participants based in Glasgow, UK. However, it is critical to investigate HACIs across cultures to ensure

	Placement	Specific Placement	Message	Modality	Technology
FullIntel	Cyclist (Environment through AR)	Glasses	*AV Intent + Location*	Visual	AR
	Cyclist	Helmet	*AV Intent + Location*	Audio	Speakers
	Cyclist	Smartwatch	*AV Intent + Location*	Haptic	Vibration
	AV	Body (Around Vehicle)	AV Intent	Visual	Lights
Locator	Cyclist (Environment through AR)	Glasses	*AV Location*	Visual	AR
	Cyclist	Helmet	*AV Location*	Audio	Speakers
	Cyclist	Smartwatch	*AV Location*	Haptic	Vibration
	AV	Body (Around Vehicle)	AV Intent	Visual	Lights
Mirror	Cyclist (Environment through AR)	Glasses	*AV Intent*	Visual	AR
	Cyclist	Helmet	*AV Intent*	Audio	Speakers
	Cyclist	Smartwatch	*AV Intent*	Haptic	Vibration
	AV	Body (Around Vehicle)	AV Intent	Visual	Lights

Table 5.1: The three HACIs classified according to the HACI taxonomy

they generalise effectively and are culturally inclusive. This is especially important as this study showed that HACIs provide many advantages for AV-cyclist interaction, so ensuring cultural inclusivity would contribute positively to the global deployment of AVs. Therefore, three new HACIs were developed to be evaluated across cultural settings in the following study. These concepts are described below. Table 5.1 classifies the three HACIs according to the taxonomy.

Concept 1: FullIntel

Figure 5.5: FullIntel: Uses wearable devices to communicate AV locations and intentions in addition to LightRing.

Figure 5.5 visualises this concept. The taxonomy showed that most designs communicated a combination of AV locations and intentions. AV location information is useful to help cyclists locate an AV that may be out of their view and interpret its intentions through the eHMI and driving behaviour. AV intention cues add further support when conveyed through wearables without requiring cyclists to check the eHMI constantly. Moreover, the *"Failsafe for cyclists"* subtheme showed that intention signals from wearables complement the eHMI in case it is damaged. Therefore, FullIntel features the LightRing eHMI and communicates additional location and intention information through multimodal wearable devices.

The HACI uses AR glasses to display visual signals. This is because the taxonomy showed that AR was the most popular approach for visual cues, and the *"AR in HACIs"* subtheme discussed many advantages, including the ability of AR to augment the environment and avoid disrupting natural cycling behaviours. For location signals, the AR display incorporates a virtual traffic sign ahead of the cyclist; this traffic sign uses text to communicate an AV's location. For example, *"AV on your left"*. Previous studies in this thesis explored colour changes, icons, and animations; text was a compelling approach because it may overcome potential ambiguity [10]. Intention signals were presented as AR road projections onto nearby road markings. Road markings within a 15 metre radius from the cyclist would pulse green or flash red synchronised with the LightRing eHMI. This approach was popular in the taxonomy. It was used by teams designing for different scenario categories, including Teams 2 and 5. Road projections were effective in Chapter 4, but they were challenging to implement outdoors. AR provides a promising alternative, and AR road projections were positively evaluated in previous work with cyclists [140]. From a practical standpoint, AR displays are becoming more feasible. Recent technological advancements are making AR glasses lighter, allowing AR capabilities to be integrated into more traditional cycling glasses [138, 139]. More advanced depth-sensing sensors are also becoming standard; this makes AR road projections and traffic signs feasible solutions.

For auditory cues, FullIntel uses spatial helmet audio. This was a popular approach in the taxonomy. Participants (e.g., Teams 2 and 3) incorporated audio into helmets rather than headphones as this leaves the ears open, so they can still listen to environmental noise, such as sirens. Spatial audio in FullIntel points toward the AV to communicate its location. It loops a ringing noise if the AV is yielding and a beeping noise if not. This adheres to the *"Multimodal eHMIs"* subtheme, allowing cyclists also to receive LightRing's signals through audio cues. FullIntel also uses haptic cues to communicate AV locations and intentions. In contrast to previous work, participants in the study (e.g., Teams 1 and 5) used vibration from the smartwatch rather than bicycle handlebars. This aligns with the *"Reusing personal devices"* subtheme, as participants preferred to reuse their own devices rather than buying new ones to incorporate into a HACI. Therefore, FullIntel also features a smartwatch that pulses/vibrates in sync with the eHMI to communicate AV intentions: one pulse per second if the AV is yielding and two flashes per second if not. Vibrations are felt more strongly as the AV moves closer to communicate proximity.

Overall, FullIntel uses multimodal signals to communicate AV locations and intentions in addition to the eHMI. This may be overwhelming and may be received differently between cultures. Testing and evaluating FullIntel across cultures was critical as the next step. It is also critical to understand how cyclists use AV information between cultures. Therefore, two additional HACIs were synthesised to compare with FullIntel. These were variations of FullIntel that only focused on communicating either AV locations or intentions. They worked as follows.

Concept 2: Locator

Figure 5.6: Locator: Uses wearable devices to communicate AV locations in addition to LightRing.

Figure 5.6 visualises this concept. Locator is a variation of FullIntel that only communicates AV location so cyclists can check the eHMI for the AV's intentions. AR glasses display the traffic sign specifying the AV's location using text. The smartwatch vibrates with a continuous tone that gets stronger as the AV moves closer to communicate proximity. Spatial helmet audio loops a sonar-like sound pointing to the AV. The same sound is played independently of AV intentions.

Concept 3: Mirror

Figure 5.7: Mirror: Uses wearable devices to communicate AV intentions in addition to LightRing

Figure 5.7 visualises this concept. Mirror uses features from FullIntel to communicate AV intentions without location. AR glasses augment all road markings in a 15-metre radius from the cyclist to flash red or pulse green, synchronised with the eHMI. Smartwatch vibrations pulse in the same rhythm as the eHMI, but the pulse intensity remains consistent, independent of AV proximity. Helmet speakers also loop a ringing noise if the AV is yielding and a beeping noise if not. However, the audio is not spatial.

Overall, this section discussed three new HACIs based on the results. These were designed to highlight any cultural differences in how cyclists use multimodal interfaces and the information they require for them. FullIntel used multimodal signals to communicate AV locations and intentions; Locator focused only on AV locations; Mirror reiterated the LightRing eHMI only to communicate AV intentions through wearable devices. The following study tested these across three cities in different countries with different levels of cyclist segregation from vehicles.

5.2 Study 8: Cross-Cultural HACI Evaluation

FullIntel (AV location and intentions), Locator (AV location) and Mirror (AV intentions) communicated different information about AVs, and cyclists may use this information differently depending on their cultural norms and local traffic infrastructure. This study was a cross-cultural evaluation comparing the three HACIs and a baseline condition with just the LightRing eHMI. The study was conducted across three cities chosen for their varying levels of cyclist segregation from vehicles: Stockholm, Sweden (highly segregated cycle lanes); Glasgow, UK (partial segregation); and Muscat, Oman (no segregation). Participants in all cities used CycleARcade (a novel AR simulator developed for this study) to experience and compare the HACIs while riding in real physical space, across different traffic scenarios. This is the first study to reveal cultural differences in how cyclists use AV-cyclist interfaces following direct interaction. This is critical for ensuring the successful global deployment of AVs.

5.2.1 Study Design

The study used a mixed-design approach. It had *City* as a between-subjects independent variable and *HACI* and *Traffic Scenario* as within-subjects independent variables. The dependent variables were cyclist *perceptions* and *behaviours* toward using each HACI in each scenario. Participants in each *City* used CycleARcade to navigate an augmented environment and use each *HACI* to interact with an AV across the *Traffic Scenarios*. Participants indicated their *perceptions* through questionnaires, and CycleARcade logged their *behaviours*.

Study scope

The study was replicated across three *Cities* chosen for their varying levels of cyclist segregation from motorised vehicles. They were in different countries to maximise the differences between traffic cultures and allow for a cross-cultural comparison of the findings [26]. The Cities were:

Figure 5.8: The evaluated HACIs as implemented in CycleARcade. Top: Common components used in all of the HACIs. Bottom: Cyclist point-of-view in CycleARcade and the visual cues for each HACI. Virtual objects were overlaid on the real-world environment. No additional displays were used in the *Baseline eHMI* condition (light band around the vehicle; green means it is yielding, red means not yielding). Road marking projections were synchronised with the eHMI for the *Mirror* condition, and a traffic sign communicated the AV's location for *Locator*. *FullIntel* combined both of these into one interface.

Stockholm, Sweden, has highly segregated cycle lanes, providing minimal encounters with motorised traffic. *Glasgow*, UK, has some segregated lanes, and cyclists navigate mixed traffic for parts of their commutes. *Muscat*, Oman, has no dedicated cycle lanes, requiring cyclists to share the road with motorised vehicles at all times.

The *HACIs* were synthesised from the previous design sessions, each incorporating the LightRing eHMI alongside wearable interfaces for additional support: *Locator* used wearables to communicate the AV's location relative to the cyclist; *Mirror* reiterated LightRing's signals to display the AV's intentions beyond the eHMI; *FullIntel* combined both approaches, conveying the AV's location and intentions. The baseline condition featured only the LightRing *eHMI*; participants deduced AV intentions solely from the eHMI and AV driving behaviour without wearable support. Figure 5.8 shows these HACIs implemented in CycleARcade. This setup allowed for a cross-cultural investigation into how cyclists use different information about the AV. The HACIs were multimodal, so it also allowed a comparison of how cyclists from different cities perceive multimodality and which modalities they prioritise.

HACIs were tested across three *Traffic Scenarios* selected for their varying levels of traffic control and AV positions, consistent with previous evaluation studies. Although HACI devices may be interchangeable between scenarios, it was still important to explore versatility, as this could be a desirable feature that would not require cyclists to constantly switch between interfaces. It was also important to explore how cyclists from different cities perceive and navigate these scenarios. The selected scenarios were either standard between the cities or dynamic, meaning no formal traffic control influenced their presentation between locations. As in VirtuRide, the scenarios were modelled using video footage captured in the eye-tracking study from Chapter 3. *Roundabout* was excluded due to potential differences in layout and road rules between the cultural settings. The scenarios were mirrored in *Glasgow* for consistency with the city's right-hand drive traffic infrastructure. They were:

- **Uncontrolled Intersection:** This was a four-way intersection; it had four arms. There were give-way lines on each arm. The AV approached from the cyclist's right (left in Glasgow). It accelerated to 50 km/h when 50 metres from the cyclist and stopped 0.5 metres behind the give-way line if yielding. It maintained its speed and continued straight when not yielding.
- **Bottleneck:** This was a narrow lane with parked cars on both sides. The AV approached from opposite the cyclist. One road user had to steer away. The AV drove at 25 km/h, steered right (left in Glasgow), with the direction indicator active. The AV stopped between two parked cars when yielding. It continued straight and maintained speed when not yielding.
- **Lane Merging:** A parked vehicle obstructed the cyclist's path, forcing them to move to the other lane with an AV approaching from behind. Therefore, cyclists had to merge lanes with this AV. The AV drove at 40 km/h and decelerated to 15 km/h when yielding. It maintained its speed when not yielding.

Study setup

The experiment was conducted in a rented indoor hall in each city to maintain consistent environmental conditions across locations, such as weather. Each hall measured at least 25 metres in length and 12 metres in width. The flooring was dark grey to black to simulate tarmac and provide a contrasting background for white road markings.

CycleARcade's roads were designed to accommodate the traffic scenarios. The setup included a 15-metre cycle lane adjacent to a two-lane road that led to a three-way intersection. Standard traffic features were used for consistency between cities: the cycle lane featured bicycle symbol road markings with solid white borders, while the intersection had dashed give-way line markings on all ends to encourage negotiation between the cyclist and the AV.

Obstacles were placed on CycleARcade's roads to prompt dynamic manoeuvres. These included red parked cars (to differentiate from the white AVs) and road repairs positioned in the lane farther from the cyclists on the two-lane road. Participants navigated each *Traffic Scenario* twice per *HACI* condition: once with a yielding AV and once with a non-yielding AV. This approach minimised learning effects and ensured participants remained attentive throughout the

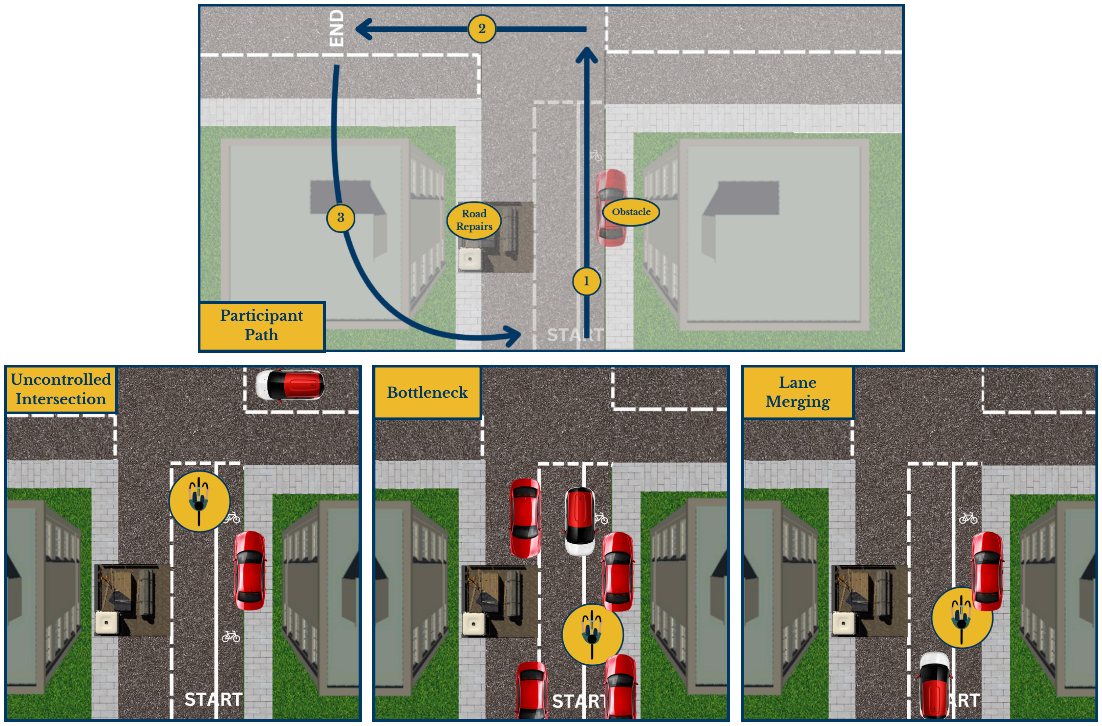

Figure 5.9: The top image shows the path participants took to loop from the start to the end point and navigate the traffic scenarios. The bottom images show the traffic scenario setups. Left for Uncontrolled Intersection, middle for Bottleneck and right for Lane Merging.

experiment. The results from both yielding conditions were aggregated in the final analysis for simplicity and clarity.

All *Scenarios* shared the same designated start and end points. These were marked in CycleARcade with white road markings labelled *Start* and *End*. The start point was located at the beginning of the cycle lane, while the end point was positioned 5 metres into the left turn at the intersection (right turn for Glasgow). Participants cycled in a loop, beginning at the start, reaching the endpoint, and then returning to the start (see Figure 5.9). Once participants crossed the *End* markings, any AR buildings disappeared, creating a clear path for them to loop back to the start for the next *Scenario*. This setup provided clear visual feedback indicating the completion of a *Scenario*, with the buildings reappearing as participants approached the start point again.

The study followed a similar structure to the previous eHMI evaluations from Chapter 4. *Scenarios* were grouped into four *tracks*, each representing a different *HACI* condition. Each *track* comprised six loops, covering every combination of scenario and AV-yielding state. The order of *Scenarios* within each *track* was randomised to minimise order effects. All AVs within a *track* utilised the same *HACI* condition, and the sequence of *HACI* conditions was counterbalanced using a Latin square design to reduce potential biases.

Measures

The following measures were collected:

- **Post Scenario Questionnaire:** This was answered after each *Traffic Scenario*. It featured the same questions as in the eHMI evaluations from Chapter 4;

- **Post Track Questionnaire:** This was answered after each group of *Traffic Scenarios* (track). It featured the same questions as in the eHMI evaluations from the previous chapter, and an additional five-point Likert scale question measuring *Trust* (strongly disagree-strongly agree): *"I trusted the interface"*. This was critical to measure across cultures, particularly for HACIs, which feature displays placed beyond the vehicle;

- **Perceived Usefulness of Displays:** As part of the *Post-Track Questionnaire*, participants ranked the *usefulness* of each display within each *HACI*. These were AR displays, eHMI, smartwatch vibrations, audio, and AV driving behaviour, into three categories: Not Useful, Somewhat Useful, and Very Useful;

- **Cycling Behaviour:** CycleARcade logged cycling behaviours when using each *HACI* in each *Traffic Scenario*. This included *cycling speed* (m/s) every 0.5 seconds, and the number of shoulder checks. A shoulder check occurred when the Unity camera (participant's head) Y-axis rotation > 90°, as determined through six pilot tests. CycleARcade also logged any collisions that occurred between the participant and an AV. Gaze behaviours were not recorded as the headset used in this study did not support eye-tracking;

- **Qualitative Data:** A short pre-study interview gathered participant comments on their experience riding in their *City*. Post-study semi-structured interviews provided additional context to the findings. Participants discussed and ranked each *HACI*.

5.2.2 CycleARcade Components and Apparatus

Figure 5.10 shows the hardware used in the study. CycleARcade was developed using Unity. It projected AR objects onto the real world. This allowed participants to cycle in a real physical space augmented with a virtual urban environment. The environment included AR buildings, road markings, and AVs. AVs were white Citroen C3s for consistency with the other studies in the thesis. All AR objects were to scale and aligned with the real world. CycleARcade was deployed on a Meta Quest 3[1] headset, which provided passthrough and depth-sensing features. This presented a wide field of view with a clear, coloured real-world background and opaque AR objects for enhanced immersion. The headset also supported spatial audio and controller haptics, suitable for multimodal HACIs. The left controller was attached to the participant's preferred wrist to simulate smartwatch vibrations and was visually represented as a smartwatch in AR. Participants were provided with a helmet and a city bike, which was a Van Moof S5 in *Stockholm*, Giant Escape 3 in *Glasgow*, and a Scott Metrix 20 in *Muscat*.

[1] Meta Quest 3: `meta.com/quest/quest-3/` ; Accessed 01/04/2025

Figure 5.10: The study hardware and setup. The left photograph shows a participant instrumented with a mixed-reality headset and a controller to simulate a smartwatch. The middle photo shows a participant riding in real physical space while wearing the headset. The right photo shows the participant's POV in the headset.

This study used a different approach from the previous chapter, which used a VR simulator study followed by a Ghost Driver evaluation of the eHMIs. This is partly due to technological advancements; pass-through technology had not yet matured to support riding while wearing a mixed-reality headset. AR headsets like the HoloLens offer a narrow field of view with translucent AR objects, reducing immersion [88]. The approach from the previous chapter was useful for complementing high-fidelity prototypes with outdoor riding around real obstacles. However, this study needed a *headset-only* setup to be highly replicable and centralise all the necessary props and apparatus, such as road markings, AVs, and HACI components. This facilitated easy transport between cities and ensured consistency between study locations. CycleARcade also helped maintain cohesion and synchrony between HACI displays. This would have been challenging to implement in an outdoor Ghost Driver setup, which was more suitable for eHMIs.

5.2.3 Participants

The experiment included 60 participants (20 from each city) recruited through social media advertising. Participants were either natives or long-term residents (e.g., international students) of their respective cities. Natives were required to have cycled in the city at least once a month over the past 18 months, while residents needed to have cycled multiple times a week during the same period. These criteria ensured all participants were familiar with the city's traffic culture. All participants were fluent in English, so no questionnaire translation was required. Participant demographics were:

- **Stockholm**: $Native = 17$, $Resident = 3$; $M_{\text{age}} = 29.5$, $SD = 6.6$; $Male = 10$, $Female = 10$;
- **Glasgow**: $Native = 18$, $Resident = 2$; $M_{\text{age}} = 30.2$, $SD = 5.5$; $Male = 12$, $Female = 8$;
- **Muscat**: $Native = 18$, $Resident = 2$; $M_{\text{age}} = 30.1$, $SD = 6.0$; $Male = 14$, $Female = 6$.

5.2.4 Procedure

The same procedure was followed in each *City*. The participant arrived at the designated hall; they were briefed on the study and completed a demographics survey. They also participated in a short pre-study interview about their experiences cycling in the *City*. Next, the participant tested their comfort with the bike gear and saddle height by riding for 3 minutes without the headset; adjustments were made if needed. The experimenter calibrated the AR headset and secured the left controller around the participant's wrist to simulate the smartwatch. The participant practised riding loops in the AR environment for 7 to 15 minutes without any AVs to become familiar with the setup and equipment.

After practice, they removed the headset, and the experimenter selected the *HACI* and *Track* according to the Latin square. The experimenter explained that the participant would start encountering AVs, clarified the scenario setups, and described how the selected *HACI* worked. The participant then wore the headset and began riding. After completing each *Scenario*, they stopped at the endpoint, where the experimenter read the *Post Scenario Questionnaire* for the participant to answer verbally. After each *Track*, the participant removed the headset and answered the *Post Track Questionnaire* using a tablet, providing a break from the AR environment. This was repeated four times, allowing the participant to experience all the interfaces. Following the experiment, a semi-structured interview was conducted to gather additional insights. The entire study lasted approximately 80 minutes. The same experimenter conducted the study across the three cities, ensuring consistency. Participants were compensated for their time with £10 vouchers for online stores in their respective currencies.

5.2.5 Results

This section reports the cultural differences in cyclist perceptions and behaviours toward each HACI.

Pre-Study Interview Results

This section presents a summary of the pre-study interviews conducted with participants regarding their cycling experiences in their respective cities. A deductive thematic analysis was carried out to address the research question: "What is participants' experience riding in each city?"

Interview transcripts were transcribed by Otter.ai and corrected by a researcher. They were then uploaded to NVivo for coding. One researcher identified 12 unique codes from the data. Two researchers then collaboratively sorted these codes into themes for each city based on their relevance to the research question. This process involved discussing and resolving any disagreements through code remapping. Themes containing two or more overlapping codes were reassessed and combined when necessary.

Stockholm Cyclists ride on segregated lanes and rarely encounter vehicles: *"I have been biking to work for ten years. I rarely see cars"* - P5. *"I only see cars in the suburbs. They move at very low speeds"* - P10. Interactions mostly happen at stationary infrastructure, e.g., intersections, so they could also interpret intentions from expressive social cues and driving behaviour: *"Most of my encounters are at intersections or something, we negotiate through gestures. I expect the car to completely stop before doing anything"* - P11; *"I ensure the driver saw me through eye contact, and wait for them to stop"* - P13. Therefore, cyclists in *Stockholm* have slower-paced interactions with drivers, allowing the exchange of diverse social cues while interpreting intention from driving behaviour before deciding on the next manoeuvre.

Glasgow Cyclists switch between segregated lanes and mixed traffic. This increases attentiveness and anxiety: *"It's great when you're segregated, then poof! There are many scary cars"* - P35; *"It makes me nervous. You must plan and know where the bike lane will end"* - P38. Cyclists encounter vehicles in a mix of slower-paced and dynamic scenarios: *"You see them at roundabouts, but I hate it when they overtake me"* - P22; *"You see cars throughout. Sometimes, they slow down, but they mostly speed past you"* - P30. These diverse encounters require cyclists to adapt their interaction behaviour: *"I wait for the car to stop and drivers to gesture, but when I'm in moving traffic, I don't have that luxury"* - P36. In summary, *Glasgow* cyclists encounter vehicles in scenarios with different traffic control levels but can expect drivers to give them right of way at intersections or roundabouts. The exchanged cues depend on the interaction scenario.

Muscat Has higher-speed roads without cycle lanes: *"It feels like swimming with sharks"* - P51. Constantly riding in mixed traffic means interactions happen in more dynamic scenarios: *"Cars move quickly with little patience"* - P48; *"Cars can be behind you, in front of you; you must be assertive; there's no infrastructure to do this daily"* - P51. Interactions are fast-paced, leaving little room for expressive cues such as driver hand gestures: *"It happens so fast; cars don't really stop at intersections. You have to make decisions based on little information"* - P59. To summarise, *Muscat's* cyclists share the road with motorised vehicles at higher speeds. Vehicles rarely come to a complete stop, and cyclists must have fast-paced interaction to negotiate the right of way quickly.

Post Scenario Questionnaire

The data were not normally distributed; a three-way ART ANOVA was conducted to explore the fixed effects of *City*, *HACI*, *Scenario*, and their interactions on each *Post Scenario Questionnaire* subscale. The model included a random intercept for *Participant* to account for individual variability. *Post hoc* comparisons were performed using the ART-C method. Mean values are in Table 5.2. These are visualised as bar charts in Figure 5.11.

	City			HACI				Scenario		
	Stockholm	*Glasgow*	*Muscat*	*FullIntel*	*Locator*	*Mirror*	*eHMI*	*Intersection*	*Bottleneck*	*Lane Merging*
Workload	8.95 ± 2.93	7.67 ± 2.55	8.24 ± 4.09	8.04 ± 3.32	8.18 ± 3.15	8.36 ± 3.29	8.58 ± 3.41	7.59 ± 2.95	9.02 ± 3.48	8.25 ± 3.39
Awareness Confidence	3.29 ± 1.05	3.97 ± 0.96	3.92 ± 1.26	3.91 ± 1.13	3.73 ± 1.17	3.76 ± 1.12	3.51 ± 1.12	3.82 ± 1.06	3.82 ± 1.11	3.54 ± 1.23
Intention Confidence	3.85 ± 1.01	4.10 ± 1.10	4.24 ± 1.15	4.31 ± 0.88	4.02 ± 1.13	4.13 ± 1.05	3.78 ± 1.23	4.34 ± 0.88	4.10 ± 1.04	3.75 ± 1.26

Table 5.2: Mean ± SD of each Post-Scenario subscale per City, HACI and Traffic Scenario.

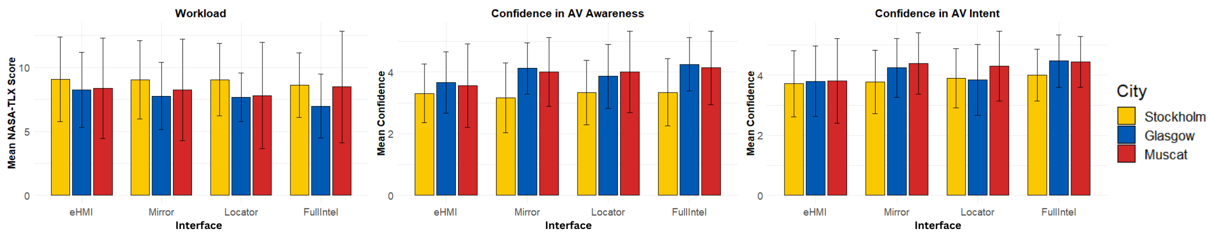

Figure 5.11: Bar charts showing mean ± SD of the Post-Scenario Questionnaire subscales for each HACI in each City. Left for workload, middle for confidence in AV awareness and right for confidence in AV intentions. Stockholm participants reported a higher workload and lower confidence. FullIntel performed well in all cities.

Results showed that *Stockholm* cyclists did not trust interfaces enough to be confident in AV awareness or intentions compared to those from other cities. *HACI* did not meaningfully influence the workload. However, confidence in AV awareness was increased when receiving cues through wearable devices, e.g. a smartwatch. This reassured cyclists that the AV had seen and communicated with them directly [47]. Confidence in AV intentions was increased when communicated outside the eHMI in *Mirror* and *FullIntel*. Regarding the *Scenarios*, participants consistently found *Uncontrolled Intersection* less demanding. This effect was more pronounced in *Muscat*, where pre-study interviews revealed that vehicles do not usually stop at intersections.

Workload There were no significant effects of *City* (F(2, 57) = 1.26, $P = .3$) or *HACI* (F(3, 627) = 2.1, $P = .1$). Therefore, the interaction workload remained consistent across the three cities and was not influenced by the HACI used. However, a significant effect of *Traffic Scenario* was found (F(2, 627) = 30.98, $P < .001$; $\eta^2 = 0.09$). The workload varied depending on the traffic scenario, with some scenarios being more challenging than others.

Post hoc comparisons between *Traffic Scenario* pairs showed that *Uncontrolled Intersection* required a significantly lower workload than the other scenarios ($P < .0001$ for all). This indicates that road markings (traffic control) substantially reduced the interaction workload. *Lane Merging* also required a significantly lower workload than *Bottleneck* ($P = .0001$), likely due to the constrained space and the AV approaching directly toward the cyclist in the bottleneck, which required quick decision-making in a narrow lane.

Workload - Interactions There was no significant interaction between *City* and *HACI* (F(6, 627) = 1.78, $P = .1$). Therefore, HACIs imposed similar interaction workloads across cities, and the interfaces were culturally inclusive regarding workload. However, there was a significant interaction between *City* and *Traffic Scenario* (F(4, 627) = 2.38, $P = .05$; $\eta^2 = .01$), meaning participants perceived the workload of navigating each scenario differently depending on their city. No significant interaction was found between *HACI* and *Traffic Scenario* (F(6, 627) = 1.6, $P = .2$), suggesting that the HACIs were versatile across scenarios in terms of workload. Finally, there was no significant interaction between all three variables (F(12, 627) = 0.84, $P = .6$).

Post hoc comparisons of *Traffic Scenario* workloads within each *City* revealed that *Uncontrolled Intersection* consistently required a significantly lower workload than *Bottleneck* across all *Cities* ($P < .01$ for all). However, in *Muscat*, *Uncontrolled Intersection* also resulted in a significantly lower workload than *Lane Merging* ($P = .0004$). This may be attributed to cyclists in Muscat being less accustomed to vehicles stopping at intersections, as explained in the pre-study interviews. This made the uncontrolled intersection scenario more predictable and easier to navigate.

Confidence in AV Awareness There were significant effects of *City* (F(2, 57) = 4.72, $P = .01$; $\eta^2 = 0.14$), *HACI* (F(3, 627) = 8.68, $P < .001$; $\eta^2 = 0.04$), and *Traffic Scenario* (F(2, 627) = 9.49, $P < .001$; $\eta^2 = 0.03$). This means that participants' confidence that the AV had detected them was influenced by the city they were from, the type of HACI they used, and the traffic scenario they were navigating. All three factors played a role in shaping how confident participants felt about the AV's awareness of them.

Post hoc comparisons between *Cities* showed that cyclists in *Stockholm* were significantly less confident in the AV's awareness than those from the other cities ($P = .02$ for all). This could be attributed to Stockholm's cyclists being more accustomed to slower-paced interactions that involve direct eye contact. Regarding *HACIs*, the *eHMI* was significantly less effective at promoting confidence than the others ($P < .005$ for all). This suggests that receiving cues through wearables, such as smartwatches, reassured cyclists that the AV had detected them and was actively communicating with them. For *Traffic Scenarios*, participants felt significantly less confident during *Lane Merging* than the other scenarios ($P = .0005$ for all). This is likely because they preferred having the AV within their view to be sure it was aware of their presence.

Confidence in AV Awareness - Interactions There was a significant interaction between *City* and *HACI* (F(6, 627) = 3.00, $P = .007$; $\eta^2 = 0.03$), meaning that the HACIs affected participant confidence differently depending on the city. However, there were no significant interactions between *City* and *Traffic Scenario* (F(4, 627) = 1.52, $P = .2$), *HACI* and *Traffic Scenario* (F(6, 627) = 1.12, $P = .4$), or between all three factors (F(12, 627) = 1.17, $P = .3$).

Post hoc comparisons of confidence when using each *HACI* within each *City* revealed that in *Glasgow* and *Muscat*, *eHMI* resulted in significantly lower confidence than *FullIntel* and *Locator* ($P < .005$ for all). Additionally, *FullIntel* in *Glasgow* was significantly more effective in promoting confidence than *Mirror* and *eHMI* in *Stockholm* ($P = .003$ for both). These findings suggest that providing AV location cues significantly enhanced cyclist confidence in AV awareness, particularly in Glasgow and Muscat. Interfaces that communicated AV intentions without location information were not as effective in Stockholm.

Confidence in AV Intentions There was no effect of *City* (F(2, 57) = 2.83, $P = .07$). Participant confidence in AV intentions did not depend on their local traffic culture. There were still significant effects of *HACI* (F(3, 627) = 17.14, $P < .001$; $\eta^2 = 0.08$) and *Traffic Scenario* (F(2, 627) = 38.66, $P < .001$; $\eta^2 = 0.11$).

Post hoc comparisons between *HACI* pairs showed that *eHMI* was significantly less effective than all other conditions ($P < .001$ for all). Additionally, *Locator* resulted in significantly lower confidence than *FullIntel* ($P = .005$). Therefore, providing redundant AV intention cues beyond the eHMI enhanced confidence in the AV's intentions. For *Traffic Scenarios*, participants were significantly more confident in AV intentions when navigating *Uncontrolled Intersection* than the other scenarios ($P < .0001$ for all). This suggests that the presence of traffic control made AV behaviour more predictable. Additionally, participants were significantly more confident in *Bottleneck* than *Lane Merging* ($P = .003$), likely because participants had the eHMI directly in their view when navigating the bottleneck scenario.

Confidence in AV Intentions - Interactions There was a significant interaction between *City* and *HACI* (F(6, 627) = 3.10, $P = .005$; $\eta^2 = 0.09$). Therefore, the effectiveness of a HACI in promoting confidence depends on the cultural setting. There was no significant interaction between *City* and *Traffic Scenario* (F(4, 627) = 0.28, $P = .9$). However, there was a significant interaction between *HACI* and *Traffic Scenario* (F(6, 627) = 8.12, $P < .001$; $\eta^2 = 0.07$). This suggests that HACIs performed differently between scenarios. There was no significant interaction between the three variables (F(12, 627) = 1.16, $P = .3$).

Post hoc comparisons of participant confidence when using each *HACI* in each *City* revealed that *eHMI* in *Stockholm* resulted in significantly lower confidence than *FullIntel* in *Glasgow* and both *FullIntel* and *Mirror* in *Muscat* ($P < .005$ for all). In Glasgow, *FullIntel* was significantly more effective than *Locator* and *eHMI* ($P < .0001$ for both). These findings show that participants found the combination of AV location and intention cues most effective. In *Muscat*, *eHMI* was significantly less effective than all other conditions ($P < .0001$ for all), suggesting that any additional information beyond basic eHMI cues enhanced participant confidence in Muscat.

Post hoc comparisons of participant confidence in AV intentions when using each *HACI* within each *Traffic Scenario* showed that *eHMI* during *Lane Merging* was significantly less effective than all other conditions ($P < .001$ for all). This was likely because the eHMI was out of view, and no additional signals alerted participants to the AV's presence, location, or intentions. Similarly, *Locator* during *Lane Merging* was significantly less effective than *Locator*

	City			HACI			
	Stockholm	*Glasgow*	*Muscat*	*FullIntel*	*Locator*	*Mirror*	*eHMI*
Cycling Performance	3.68 ± 0.68	3.78 ±0.83	4.01 ± 1.03	4.17 ± 0.84	3.95 ± 0.69	3.86 ± 0.83	3.31 ± 0.86
Anxiety	2.52 ± 0.54	2.51 ± 0.64	2.50 ± 0.61	2.35 ± 0.55	2.48 ± 0.52	2.51 ± 0.60	2.69 ± 0.67
Trust	3.73 ± 0.80	3.83 ± 1.00	4.23 ± 0.89	4.08 ± 0.87	3.92 ± 0.85	3.93 ± 0.92	3.77 ± 1.00
Perceived Safety	3.48 ± 0.69	3.75 ± 0.89	3.91 ± 0.87	3.94 ± 0.82	3.7 ± 0.86	3.77 ± 0.82	3.44 ± 0.79
Usability	0.65 ± 0.55	0.79 ± 0.61	1.2 ± 0.69	0.99 ± 0.65	0.90 ± 0.62	0.93 ± 0.64	0.69 ± 0.7
Cycling Speed	1.56 ± 0.38	1.29 ± 0.30	1.64 ± 0.43	1.49 ± 0.43	1.46 ± 0.38	1.50 ± 0.39	1.53 ± 0.41

Table 5.3: Mean ± SD values for each Post-Track Questionnaire subscale for each City and HACI.

at *Uncontrolled Intersection* ($P = .004$) and *FullIntel* at both *Uncontrolled Intersection* ($P <$ .0001) and *Bottleneck* ($P = .007$). This indicates that providing location cues without intention signals was insufficient when the AV was out of view. Additionally, *Mirror* at *Bottleneck* was significantly less effective than *FullIntel* at *Uncontrolled Intersection* ($P = .01$), suggesting that reiterating AV intentions was ineffective when the eHMI was already clearly visible.

Post Track Questionnaire

The data were not normally distributed; a two-way ART ANOVA was conducted to explore the fixed effects of *City*, *HACI*, and their interactions on each *Post Track Questionnaire* subscale. The model included a random intercept for *Participant* to account for individual variability. *Post hoc* comparisons were performed using the ART-C method. Mean values are in Table 5.3. These are visualised as bar charts in Figure 5.12.

Participants from *Muscat* were the most receptive to AV-cyclist interfaces. They trusted displays more and found the interaction more usable than cyclists from other cities, regardless of the *HACI* used. This is likely due to their experience with fast-paced, dynamic interactions. Cyclists from all cities consistently rated *FullIntel* as the best-performing *HACI*; the *eHMI* was perceived as the most cumbersome. *FullIntel* significantly reduced anxiety in *Glasgow*, addressing a key concern raised in pre-study interviews.

Perceived Cycling Performance There were significant effects of *City* ($F(2, 57) = 3.67$, $P = .03$; $\eta^2 = 0.11$) and *HACI* ($F(3, 171) = 22.13$, $P < .001$; $\eta^2 = 0.28$). They had no interaction ($F(6, 171) = 1.22$, $P = .3$). *Post hoc* comparisons between *Cities* showed that participants from *Muscat* rated their performance significantly higher than those from *Stockholm* ($P = .01$). This may be because Stockholm cyclists encounter vehicles less frequently due to more dedicated cycling infrastructure.

Among *HACIs*, *eHMI* caused significantly poorer cycling performance than all other interfaces ($P < .0001$ for all). In contrast, *FullIntel* led to significantly better performance than *Locator* ($P = .02$) and *Mirror* ($P = .003$). This suggests that providing comprehensive information on both AV location and intentions improved cycling performance without overwhelming cyclists or hindering their ability to navigate effectively.

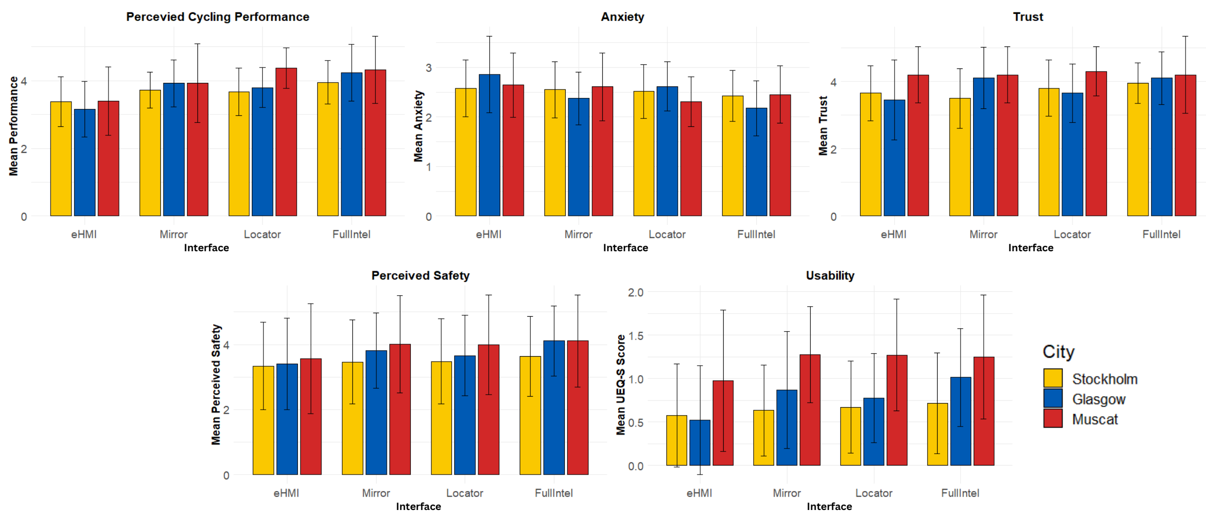

Figure 5.12: Bar charts showing the mean ± SD values of the Post-Track Questionnaire subscales for each HACI in each City. HACIs had particularly high performance in Muscat. FullIntel outperformed the other HACIs in all cities.

Anxiety There was no significant effect of *City* (F(2, 57) = 0.0004, $P = .996$). However, there was a significant effect of *HACI* (F(3, 171) = 4.29, $P = .006$; $\eta^2 = 0.07$) and a significant interaction between *City* and *HACI* (F(6, 171) = 2.83, $P = .01$; $\eta^2 = 0.09$). *Post hoc* comparisons between *HACIs* showed that *FullIntel* caused significantly lower anxiety than *eHMI* ($P = .0005$). Comparing anxiety scores between *HACIs* within each *City* showed that *FullIntel* caused significantly lower anxiety than *eHMI* in *Glasgow* ($P < .0001$). Therefore, communicating AV location and intentions in addition to the eHMI was most effective in *Glasgow*.

Trust There were significant effects of *City* (F(2, 57) = 3.48, $P = .04$; $\eta^2 = 0.11$) and *HACI* (F(3, 171) = 3.89, $P = .01$; $\eta^2 = 0.06$). However, there was no interaction (F(6, 171) = 1.85, $P = .09$). *Post hoc* comparisons between *Cities* showed that participants in *Muscat* exhibited significantly higher trust in the HACIs compared to those in *Stockholm* ($P = .02$). This may stem from Muscat cyclists' greater appreciation for clear, explicit signals on AV intentions, which contrast with the brief, fast-paced interactions they currently experience in their current traffic environment. Among the *HACIs*, participants trusted *FullIntel* significantly more than *eHMI* ($P = .0009$). This suggests that providing redundant cues about AV intentions increased trust. However, cyclists also needed information about the AV's location to validate and rely on these cues fully.

Perceived Safety There was no significant effect of *City* (F(2, 57) = 2.44, $P = .1$). There was still a significant effect of *HACI* (F(3, 171) = 10.97, $P < .001$; $\eta^2 = 0.01$), but no interaction (F(6, 171) = 1.05, $P = .4$). *Post hoc* comparisons between *HACIs* revealed that participants felt significantly less safe using *eHMI* compared to *FullIntel* ($P < .0001$), *Locator* ($P = .005$),

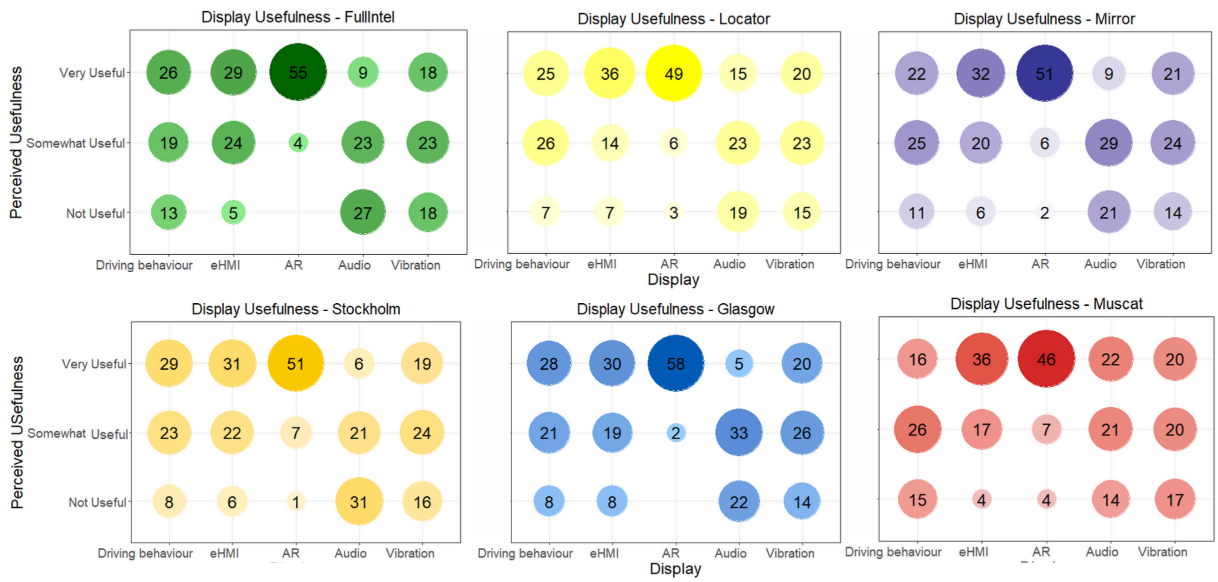

Figure 5.13: Dot plots showing the number of times each display was in each usefulness category for each City and HACI.

and *Mirror* ($P = .0003$). This suggests that relying solely on cues placed on the AV reduced perceived safety, highlighting the potential of additional signals provided through wearables.

Usability There were significant effects of *City* (F(2, 57) = 7.15, $P = .002$; $\eta^2 = 0.2$) and *HACI* (F(3, 171) = 7.08, $P < .001$; $\eta^2 = 0.11$), but no significant interaction between them (F(6, 171) = 1.48, $P = .2$). Between *Cities*, participants in *Muscat* rated usability significantly higher than those in *Glasgow* ($P = .03$) and *Stockholm* ($P = .001$). This may be because Muscat cyclists are more accustomed to interpreting complex social cues while navigating mixed traffic. Between *HACIs*, *eHMI* was rated significantly less usable than *FullIntel* ($P < .0001$), *Locator* ($P = .02$), and *Mirror* ($P = .004$). This suggests that the inclusion of additional displays beyond the eHMI enhances usability and the overall interaction experience.

Perceived usefulness of displays

The frequency of each display within each usefulness category is in Figure 5.13. Data from the baseline *eHMI* condition were excluded as there were no additional displays. To explore the relationship between *Display* and *Perceived Usefulness*, a Chi-square test of independence was performed for each *City* and *HACI*. *Post hoc* tests were conducted using Chi-square tests of independence with Bonferroni correction. Results are in Table 5.4.

Between *Cities*, participants from *Muscat* primarily relied on explicit visual cues, such as *AR* displays and *eHMI*, to make decisions. In contrast, participants from *Glasgow* and *Stockholm* also placed importance on AV *Driving Behaviour*. Between *HACIs*, participants consistently found *AR* displays to be the most useful. They also rated *Vibration* as more useful than *Audio* cues throughout. *eHMI* and *Driving Behaviour* were important for inferring AV intentions in *Locator*. However, these were less valuable when AV intentions were beyond the eHMI in *FullIntel* and *Mirror*.

	Chi-Square (χ^2)	P-Value	Significant Post Hocs	Post Hoc P
City				
Stockholm	$\chi^2(8,295) = 95.621$	$P < .001$	AR > All Displays	$P < .001$
			Audio < All Displays	$P < .05$
Glasgow	$\chi^2(8,294) = 102.83$	$P < .001$	AR > All Displays	$P < .0001$
			Audio < All Displays	$P < .0001$
Muscat	$\chi^2(8,285) = 48.198$	$P < .001$	AR > Driving Behaviour, Audio, Vibration	$P < .0005$
			eHMI > Driving Behaviour, Vibration	$P < .01$
HACI				
FullIntel	$\chi^2(8,295) = 94.08$	$P < .001$	AR > All Displays	$P < .0001$
			Audio < Driving Behaviour, eHMI	$P < .01$
Locator	$\chi^2(8,288) = 57.294$	$P < .001$	AR > Driving Behaviour, Audio, Vibration	$P < .0005$
			Audio < eHMI	$P < .005$
Mirror	$\chi^2(8,293) = 71.12$	$P < .001$	AR > All Displays	$P < .001$
			Audio < eHMI	$P = .0001$

Table 5.4: Chi-Square test of independence results on the Perceived Display Usefulness for each City and HACI. The Significant *Post Hocs* column shows which displays were useful compared to others; > means more useful, and < means less useful.

Cycling Behaviour

To summarise cycling behaviour, *Glasgow* participants were notably slower and conducted more shoulder checks, which aligns with the findings on their higher anxiety. This cautious cycling resulted in the fewest collisions among cities. Participants from all cities were slower in *Locator*. They reduced their speed and took less frequent but longer shoulder checks to infer AV intentions through its eHMI or driving behaviour. Collisions predominantly occurred in dynamic scenarios with no traffic control, especially during *Lane Merging*. They were more frequent when AV locations were not communicated, i.e. in the *Mirror* and *eHMI* conditions.

Cycling Speed Figure 5.14 shows the mean cycling speed for each *City* per *HACI* condition. The same analysis approach as the Post Track Questionnaire was conducted on speed. There were significant effects of *City* (F(2, 59) = 10.97, $P < .001$; η^2 = 0.27) and *HACI* (F(3, 658) = 3.77, $P = .01$; η^2 = 0.02). However, there was no interaction between them (F(6, 658) = 0.48,$P = .8$). Therefore, while cycling speeds varied based on participants' cities and the HACIs used, the effect of HACIs on speed was consistent across all cities.

Post hoc comparisons between *Cities* showed that cyclists from *Glasgow* were significantly slower than those from the other cities ($P < .001$ for all). Comparisons between *HACI*s showed that participants cycled significantly faster when using *eHMI* than *Locator* ($P = .001$). This

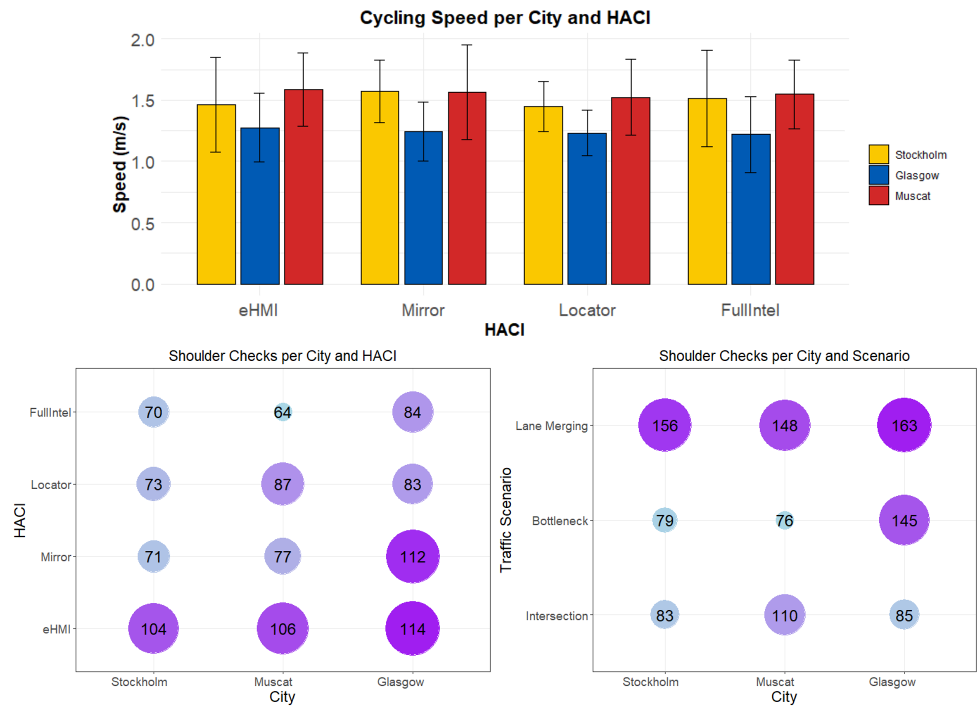

Figure 5.14: Cycling behaviours between cultures. The top bar chart shows the mean ± SD of cycling speed for each HACI in each City. The bottom dot plots show the frequency of shoulder checks in each City per HACI and Traffic Scenario conditions.

may be attributed to the need for participants to slow down when using *Locator*, as they had to interpret the AV's location cues and then check the eHMI to determine their next manoeuvre.

Shoulder Checking Figure 5.14 shows the number of shoulder checks cyclists in each *City* conducted when using each *HACI* in each *Traffic Scenario*. A Chi-Square test of Independence was conducted to deduce the relationship between *City* and *HACI*. No significant association was found (χ^2(6, 1045)= 6.83, $P = .3$). Therefore, the HACI used did not influence shoulder checking behaviours between cities.

There was a significant association between *City* and *Traffic Scenario* (χ^2(4, 1045) = 25.95, $P < .001$). *Post hoc* tests using the Chi-Square test of Independence with a Bonferroni correction showed that shoulder checks were significantly more likely in *Glasgow* than all other cities ($P < .001$ for all). They were also significantly less likely when navigating *Bottleneck* than all other scenarios ($P < .005$ for all). This is because the AV was opposite the cyclist in Bottleneck.

Collisions Figure 5.15 shows that CycleARcade logged 38 collisions. Most collisions (55%) happened in *Muscat*. This could be due to cyclists being accustomed to faster-paced interactions, which may result in more reckless riding. The lowest amount of collisions occurred in *Glasgow* (13%); this could be because cyclists in Glasgow are more anxious and careful when riding in mixed traffic. Results also showed that most collisions occurred during *Lane Merging* (66%);

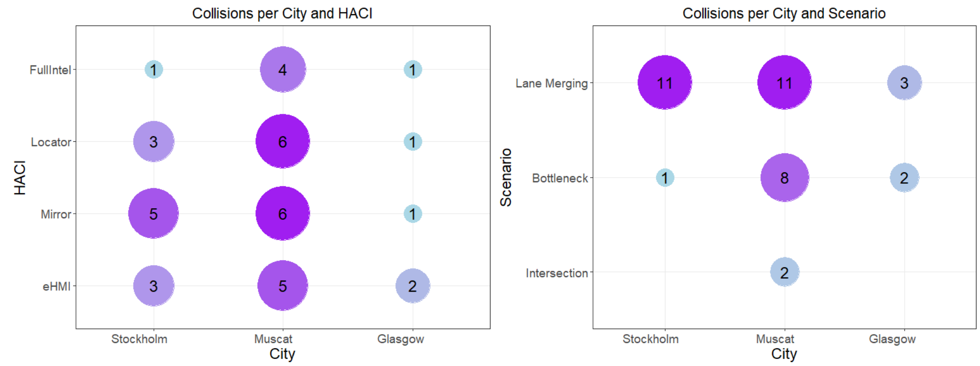

Figure 5.15: Dot plots showing the number of collisions that occurred in each City. The left graph shows the frequency of collisions per HACI conditions; the right graph shows the collision frequency per Traffic Scenario.

this was most prominent when cyclists did not receive any AV location cues in the *Locator* and *eHMI* conditions. This suggests that AV location information is key for enhancing cyclist safety.

Post-Study Qualitative Results

This section presents themes derived from post-study interviews with participants. Interviews were auto-transcribed using Otter.ai and subsequently corrected by a researcher. An inductive thematic analysis was applied to the transcripts, which were imported into NVivo for coding. One researcher identified 15 unique codes from the data, which were then collaboratively sorted into themes by two researchers based on their similarities. This was an iterative process, with disagreements discussed and codes remapped until consensus was achieved. Themes with overlapping codes were reassessed and merged where appropriate. This analysis identified the following three themes.

Participant rankings of the *HACIs* in each *City* are in Figure 5.16. *FullIntel* was favoured in all cities, with the *eHMI* condition being the least favoured throughout. Participants in *Stockholm* favoured *Locator* over *Mirror*, while those in *Muscat* favoured *Mirror*. This suggests that AV location information was more valuable in *Stockholm*.

Theme 1: Immersion of CycleARcade Participants across all cities praised the immersive experience provided by CycleARcade: *"It just felt so real!"* - P18; *"I totally forgot the car was virtual; I didn't expect myself to steer away from that car, but it felt too real"* - P31; *"Wow! I totally forgot these cars aren't real"* - P45. These responses indicate that CycleARcade was an effective tool for simulating cycling around AVs in various scenarios, highlighting the potential of AR simulators in HCI cycling research. Additionally, cyclists reported that their riding felt natural: *"It just felt like as normal!"* - P29; *"The threat felt completely real. I felt like I needed to avoid crashing, just as normal"* - P55. This suggests that CycleARcade successfully captured authentic cycling behaviours.

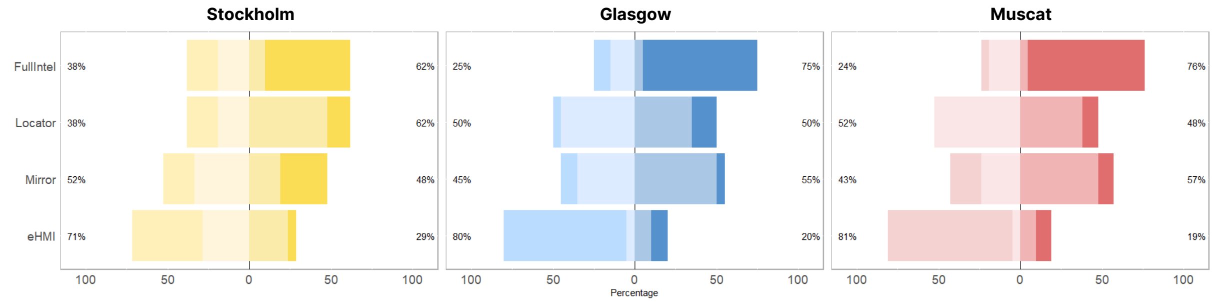

Figure 5.16: Participant rankings of the HACIs. The left chart shows rankings for Stockholm participants, the middle shows rankings for Glasgow, and the right shows rankings for Muscat. Bars on the left are lower rankings, and the bars on the right are higher rankings in all three graphs.

Theme 2: Non-visual HACI cues Participants generally appreciated non-visual cues: *"It's good that not everything is visual; it helps if I miss anything, I can always rely on other signals"* - P19. Audio required careful interpretation to understand and differentiate: *"Spatial audio needs more focus, you need to carefully deduce where it's pointing"* - P30; *"I think with all the visual displays, I don't really have the head-space to process different sounds for vehicle intentions"* - P40. Vibration cues effectively communicated AV proximity and enhanced confidence in AV awareness: *"Vibration messages felt more personal to me, like the car was talking to me directly"* - P55.

Theme 3: AR cues for AV location Participants across cultures had varying preferences regarding the design of AR location cues. Text was universally appreciated: *"Text is great. It's unambiguous; if an arrow was used, I wouldn't be so sure if I should turn or the car"* - P10. However, opinions diverged on whether the text should appear as a HUD or a traffic sign. Some preferred a HUD for quicker recognition: *"I had to look for the sign, this would be confusing when there are many traffic signs on the road, a HUD would be faster to find"* - P35. Others favoured the traffic sign format: *"I like the traffic sign. It reminds me of signs for traffic lights or speed bumps. You can see them, like how I can sometimes see the car, but you get extra warning that there is a car approaching"* - P48. It could be beneficial to take an adaptive approach, displaying a HUD when the AV is out of the cyclist's field of view and a traffic sign otherwise.

5.2.6 Discussion

Cyclists from all cities preferred FullIntel, which communicates AV location and intentions. This provided a culturally inclusive solution; it communicated comprehensive information, and cyclists used different design aspects according to their traffic culture norms. Regarding the scenarios, this study's findings coincide with those from the previous chapter: stationary infrastructure, e.g. uncontrolled intersections, is less demanding than dynamic scenarios, e.g. lane merging. In line with the design guidelines from Chapter 3, incorporating LightRing into a HACI improved confidence, safety and usability.

Stockholm: HACI Signals Must Be Validated With Driving Behaviour

Stockholm's participants were the most conservative toward interfaces. Pre-study interviews showed they were used to slower-paced interactions at stationary infrastructure by exchanging social cues with drivers before making decisions. They also typically wait until a vehicle completely stops before proceeding. This was mirrored in the study. Participants expected expressive signals compared to binary AV intentions, and for the AV to always prioritise them. This aligns with previous work where cyclists accustomed to highly segregated cycle lanes anticipated right-of-way [26], and led to lower interaction usability scores than participants from other cities. Stockholm cyclists also reported lower perceived cycling performance, likely due to the study featuring bottleneck and lane merging scenarios, which are more challenging than the stationary infrastructure they typically navigate [12]. The previous chapters showed that understanding AV intentions is key to navigating traffic scenarios. However, Stockholm cyclists did not trust these when communicated on wearable devices. They also required AV location cues to locate the vehicle and verify any intention signals with the eHMI and driving behaviour.

Similarly, Stockholm participants remained sceptical about AV awareness, regardless of the HACI, perhaps because they were used to regular eye contact with drivers. In contrast, the previous chapter, which featured UK cyclists, reported that changing eHMI states, i.e., shifting between yielding and not yielding, implicitly conveyed AV awareness. These insights highlight compelling directions for future research. Stockholm cyclists placed great value on AV driving behaviour to derive its intentions. Therefore, AVs could use exaggerated braking and driving behaviours in Stockholm to facilitate quicker validation of HACI signals, especially in dynamic scenarios where the AV does not completely stop. Moreover, the binary nature of AV intention signals is minimal compared to the more expressive negotiations that Stockholm cyclists typically have. More detailed messages could improve their confidence in AV intentions and awareness. HACIs can support more detailed messages with minimal adjustments to the current setup. For example, AR glasses could display a HUD showing a pair of eyes when the AV detects the cyclist and uses animated hand gestures as intention cues, complementing the eHMI rather than redundantly displaying its signals. This could improve global adoption because AR displays may be customised by their owner [123], whereas changing physical eHMIs on vehicles would be more challenging, especially given the success of binary signals in other cities.

Glasgow: Location and Intention Signals Valuable at Different Points

Glasgow's participants regularly navigate stationary infrastructure and dynamic scenarios, leading to more cautious cycling. They performed more shoulder checks and cycled slower, giving them time to process and validate signals. This resulted in the fewest collisions among the cities.

More cautious riding may be attributed to higher anxiety reported in pre-study interviews and post-track questionnaire scores. This aligns with the online survey and observations from Chapter 3, which showed that transitioning from segregated cycle lanes to mixed traffic is one of the most challenging scenarios for cyclists.

FullIntel proved particularly effective for Glasgow cyclists, significantly lowering their anxiety. Participants equally valued AV location and intention cues to adapt their interaction behaviours based on the scenario. This shows that the previous design sessions were effective, as they were conducted in Glasgow, and participants designed HACIs communicating AV locations and intentions. The success of FullIntel aligns with the observations from Chapter 3, which showed that cyclists in Glasgow interacted differently with drivers depending on the information they needed. For example, awareness was enough at bottlenecks, but intentions were necessary in uncontrolled intersections. Similar to Stockholm's participants, Glasgow cyclists relied heavily on observing driving behaviour. Location cues were beneficial for identifying AVs and validating signals at stationary infrastructure like intersections, where clear changes in AV driving behaviour are expected. This aligns with the eye-tracking study from Chapter 3, which also showed that cyclists interpreted social cues from drivers at intersections and then looked at the vehicle's bumper to verify the driver's message through braking behaviours. Therefore, FullIntel aligned with the more reflexive behaviours of Glasgow's cyclists.

Cyclists trusted interfaces more than their Stockholm counterparts, leading to greater confidence in AV intentions when these signals reiterated the eHMI through wearables. This contributed to a more pleasant experience during *Lane Merging*, which previous studies in the thesis and prior work [67] showed to be demanding due to the need to frequently shoulder check. Unlike in Stockholm, providing personalised location cues, such as changing vibration intensity based on AV proximity, increased Glasgow and Muscat cyclists' confidence in AV awareness. This gave the sensation that the AV had detected and communicated with them directly. This aligns with the previous HACI design sessions, which found that communication through wearable devices reduces ambiguity about with whom the AV is communicating. Ultimately, FullIntel was suitable for Glasgow's cyclists, but future work may consider adjusting AR location cues to address anxiety. The qualitative results suggested that traffic signs may be more difficult to find, so these could be used for bottlenecks or uncontrolled intersections where the AV is in view. Additional visual location cues may be needed for lane merging; AR glasses could display a HUD that is easy to spot so cyclists can quickly process FullIntel's signals.

Muscat: Fast Paced Interaction with AV Intention Signals

Muscat's participants were the most receptive to interfaces, likely due to their experience navigating fast-paced interactions without the benefit of cycle lanes. In pre-study interviews, they noted that vehicles rarely stop, even at intersections. The findings confirmed this: Muscat cyclists found the uncontrolled intersection significantly easier than those from other cities, as vehicles in the study came to a complete stop. This may have contributed to Muscat cyclists' higher perceived cycling performance scores. Participants mentioned they are rarely prioritised on the road and often negotiate right-of-way assertively rather than relying on expressive social cues. This contrasts with Stockholm participants' experiences and emphasises the impact of segregated cycle lanes on cycling behaviours [108]. Muscat cyclists' assertive riding style was reflected in their cycling behaviour during the study, where they displayed more aggressive and sometimes reckless cycling, leading to the highest collision rate among all cities. This aligns with previous research showing that countries with emerging cycling infrastructure, especially in Asia, tend to exhibit more reckless riding patterns [130].

Unlike other participants, Muscat cyclists did not heavily rely on AV driving behaviour, likely due to vehicle braking being harder to differentiate on faster roads. They focused on quickly interpreting AV intentions. They placed significantly more trust in interfaces, and minimal eHMI cues were sufficient for them to make decisions. This prompted higher interface usability scores than Glasgow and Stockholm participants. Perhaps because the eHMI already provides more affirming information than their real-world interactions, this led them to prioritise AV intention signals over location cues. Interestingly, location cues also improved Muscat cyclists' confidence in AV intentions because they were used differently than in other cities; cyclists located the AV faster to understand its eHMI rather than validating intention signals with driving behaviour. This raises important questions about how AVs should behave in Muscat. If AVs consistently yield while cyclists continue encountering assertive human drivers, AVs may be seen as out of place and confusing. Cyclists may take advantage of their predictable yielding behaviour, particularly in dynamic situations with ambiguous right-of-way. This could result in negative experiences for AV passengers, reducing adoption. Conversely, making AVs more assertive could create unsafe conditions for cyclists, who already display more reckless riding.

Muscat remains unexplored in AutomotiveUI; research must understand behavioural changes in AV deployment in the city. This should be longitudinal to see whether cyclists adapt to less assertive AVs over time or if AVs should employ more assertive driving instead. This is critical for safe global AV adoption. Muscat cyclists may be safer if AV intentions were only displayed after cyclists indicate their intentions. This may be a departure from requirements in other cities, but it would promote clear two-way communication between road users. For example, cyclists may gesture or use on-bike direction indicators to send AVs their intentions, as designed in the previous study. Only then will the eHMI show its state, and Mirror or FullIntel will display this. This would make Muscat's interactions more expressive and may reduce collisions.

5.3 Overall Discussion and Design Guidelines

This chapter answered RQ3: *"What are the cultural differences in cyclist use and perceptions of AV-cyclist interfaces?"*. Overall, the studies in this chapter showed that HACIs are effective solutions. Participants from the design sessions expressed many advantages of HACIs, and the cross-cultural evaluation showed them to outperform the baseline condition consistently. HACIs can be multimodal, and participants leveraged their interconnected features to extend the reach of the LightRing eHMI and communicate the AV's location in case the AV is in a blindspot. This resulted in more comprehensive interfaces than LightRing.

Comprehensive HACIs using multimodal cues to communicate AV locations and intentions were found to be culturally inclusive. Cyclists from all tested cities preferred FullIntel and expressed no concerns over information overload. However, they still used this information differently; for example, cyclists in Stockholm preferred AV location cues, while those in Muscat preferred AV intention cues. This shows that traffic infrastructure affects the information required from HACIs. However, it also shows that communicating comprehensive information improved cultural inclusivity by allowing cyclists to adapt this information to their local needs. The results from the cross-cultural study showed that it is critical to understand the cultural differences in how cyclists use interfaces to ensure that they display sufficient information for cyclists to resolve space-sharing conflicts. The study had a complex setup. This section describes lessons learned from cross-cultural research and design guidelines for culturally inclusive AV-cyclist interfaces. This is critical to motivate researchers and designers to explore concepts between cultures.

5.3.1 Lessons Learned from Cross-Cultural Research

The cross-cultural evaluation study was novel as it was the first cycling HCI user study where cyclists directly interacted with interfaces in a fully replicated setup across multiple cities in different countries. This required a complex study design that facilitated cross-cultural replication and enabled the identification of key trends in the data. Given its novelty, the following lessons were derived from conducting the study and interpreting its findings. These insights are valuable for informing future cross-cultural studies, which this chapter demonstrated as essential for ensuring the cultural inclusivity of displays and meeting the expectations of end users from diverse cultural backgrounds.

LL1: Classify any potential influencing factors between cities

The cross-cultural evaluation highlighted physical infrastructure and vehicle driving behaviours as key factors influencing cyclist perceptions and behaviours toward interfaces. Cities were classified by their level of cyclist segregation, which helped reveal key patterns. For instance, greater segregation and slower vehicle speeds led cyclists to prioritise AV location cues over intention signals. Future research should identify additional influencing factors. This could be achieved through pre-study interviews, which proved useful in the study presented in this chapter. Cross-cultural studies can then use these insights to classify study locations based on relevant characteristics, such as high versus low cyclist segregation from motorised vehicles. This would help contextualise findings, identify overarching trends, and refine interface design recommendations.

LL2: Surveys are not always sufficient for cross-cultural evaluation studies

Cross-cultural studies are often conducted using online surveys [26, 108], which are valuable for reaching large, diverse participant pools across multiple cities and countries [62]. However, this chapter showed that replicable user studies provide critical insights into physical interactions, particularly for evaluating multimodal interfaces in greater depth [67]. For example, the HACIs incorporated haptic cues, which are difficult to assess through surveys alone. This chapter also showed that user studies enable a more detailed examination of cyclist behaviours when interacting with interfaces [14, 37]. For example, cycling speed and shoulder-checking patterns were logged [49]. This offered insights into behavioural differences across cultures, such as Glasgow cyclists being more anxious and cycling slower with more frequent shoulder checks.

LL3: Utilise platforms enabling study replication

Cross-cultural research should seek identical setups across cities to isolate cultural factors clearly. In this research, CycleARcade enabled a *headset-only* approach. This was easy to transport and made replication highly convenient. It projected a complete urban environment, including road markings, AVs, and interfaces, eliminating the need for additional research equipment. Participants in all cities experienced identical AV behaviours and interface implementations, ensuring consistency across locations. Strict requirements for indoor halls, such as floor colours and dimensions, were also established to minimise variability. Future cross-cultural studies should prioritise centralised hardware and adopt similar standardised approaches wherever feasible to enhance study replication.

5.3.2 Design Guidelines for Culturally Inclusive AV-Cyclist Interfaces

The studies in this chapter provided key insights into developing acceptable and culturally inclusive HACIs. This section synthesises the findings from both studies to present design guidelines for culturally inclusive AV-cyclist interfaces. These guidelines are valuable to minimise ambiguity and ensure clear communication as AVs are deployed globally.

DG1: Cross-cultural interfaces should be built around a common baseline

The vehicles in the design sessions were equipped with the LightRing eHMI to establish a baseline of safety for cyclists who may not carry additional devices. Participant designs demonstrated that LightRing's signals were easily extendable onto wearable devices. For example, smartwatch vibrations could mimic LightRing's animation patterns to reinforce AV intentions. This approach was applied in developing FullIntel and Mirror, which displayed AV intentions beyond the eHMI. The cross-cultural study confirmed that LightRing's simple binary signals on AV intentions were universally understood across cities, demonstrating its cultural inclusivity. This suggests that LightRing is a reliable failsafe for cyclists without additional devices, even when navigating unfamiliar cities. A consistent eHMI can facilitate seamless transitions between cities, reducing the need for cyclists to adapt to new signals [37]. This approach also enhanced the acceptability of HACIs. FullIntel was well-received across cultural contexts due to its minimal learning curve, which was achieved by maintaining a consistent design language with LightRing. Including AV location cues further improved trust and enabled easy verification of redundant signals. Designers could adopt a similar ground-up approach to this chapter's design sessions by anchoring HACIs around a culturally inclusive baseline. This baseline could be a standardised eHMI or a broader display feature, such as an extendable animation pattern.

DG2: Comprehensive 'middle-ground' interfaces were effective for cultural inclusivity

The design sessions resulted in three multimodal HACIs that communicated different levels of information beyond LightRing: AV location (Locator), AV intentions (Mirror) and a combination of both (FullIntel). While there was a risk that FullIntel might be too comprehensive or overwhelming to generalise across cities, it was ultimately ranked as the most effective HACI after evaluation. FullIntel's cultural inclusivity is attributed to allowing cyclists from different cities to use the same HACI but adapt the information to their local needs. For example, cyclists in Stockholm preferred AV location cues, but those in Muscat used AV intention cues, and they can get this information from the same HACI without being overwhelmed with signals. FullIntel also supported versatility, as Glasgow cyclists showed that this information can be adjusted across traffic scenarios, not just cities. Therefore, designers could consider comprehensive solutions that give different features and information equal footing. Users could then adapt these to their local requirements.

DG3: Alterations to suit local norms should be on wearable devices

One particular advantage of HACIs identified in the design sessions was that they may be modular. This means cyclists could customise HACIs by incorporating different devices based on their needs and device availability. This modularity could support the cultural inclusivity of HACIs. The evaluation showed that some cyclists may need additional information that could overload middle-ground solutions. For example, cyclists in Stockholm could benefit from explicit cues confirming AV awareness. However, such cues might overwhelm Muscat and Glasgow cyclists if integrated into FullIntel. Awareness cues could be tailored for Stockholm cyclists without imposing them on users in other cities by altering wearable or bike-mounted devices rather than modifying baseline displays. This ensures that there is still a common baseline between cities. Tailoring wearable or bike-mounted devices allows personalised signals to reach only those cyclists who opt for them [123, 124], ensuring adaptability without disrupting global standards. Moreover, these alterations should not alter the design language of universally understood signals. For example, changing flashing animations to mean yielding and pulsing to mean not yielding would compromise cultural inclusivity and hinder communication across regions [37]. Notably, vibration cues effectively reassured cyclists of AV awareness, especially when indicating proximity. Designers should explore non-visual cues further, as these can communicate specific information without being redundant to eHMIs. This approach allows tailored support without compromising the baseline's cultural inclusivity.

Overall, this chapter showed that HACIs are effective solutions for AV-cyclist interaction across different cultures. However, they have only been tested for one-to-one AV-cyclist interaction; this was important to understand how cyclists between cultures perceive scenarios with distinct AV positions. The HACI design sessions showed that these interfaces overcome ambiguity in multi-cyclist encounters by incorporating wearable devices that assure cyclists that the message is for them. However, it remains unknown how HACIs can present information from multiple AVs. This is critical for using HACIs on real roads. This is investigated in the following chapter to answer RQ4.

Chapter 6

Scalability

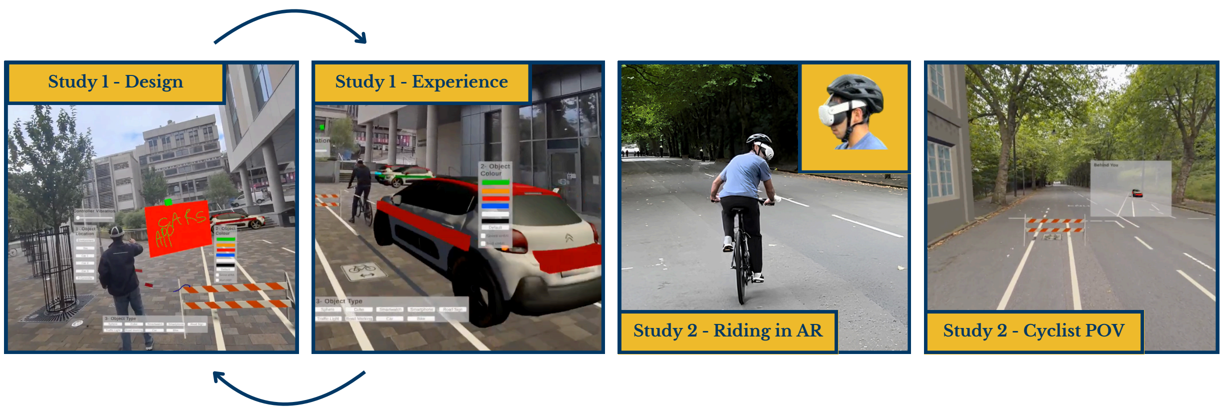

Figure 6.1: The two outdoor studies using CycleARcade. First, a novel participatory design method with participants iteratively designing, experiencing (through real cycling) and refining multimodal HACIs. Second, an empirical evaluation with riders testing three distinct HACIs.

The previous studies in this thesis focused on one-to-one AV-cyclist interaction. In real-world scenarios, multiple cyclists may simultaneously be in a space-sharing conflict with multiple AVs [37]. AV-cyclist interfaces must scale accordingly, ensuring each cyclist is confident that an AV's message is for them and can correctly associate the signal with the respective AV [123]. The previous chapter showed that HACIs address the scalability problem by allowing cyclists to receive messages through their personal devices, reassuring cyclists that an AV's message is directed to them. This finding is supported by previous research on pedestrians [47].

However, displaying information from multiple AVs to a cyclist remains unresolved. This is especially complex as AVs in the space-sharing conflict may be in different relative positions and subject to varying traffic control [12]. Some AVs may yield to allow cyclists to pass, while others may not. Monitoring and processing this information while cycling is challenging [123], and the potential for signal ambiguity or misinterpretation increases the risk of collisions [82].

HACIs present an opportunity for centralising this information to minimise the workload [124]. However, they must be able to display contrasting intentions and allow cyclists to correctly associate this information with the respective AV to avoid miscommunication.

It remains unknown how HACIs can be designed to display multi-AV information, which is critical to prepare them for real-world use. This is not possible with the designs from the previous chapter. For example, it is challenging to use spatial audio to point to multiple AVs or synchronise smartwatch vibrations with multiple eHMIs. Therefore, this chapter closes the loop on the scalability problem by understanding how HACIs can display multi-AV information. This way, multiple cyclists can receive AV signals through wearable devices, being confident they are meant for them, while checking information from multiple AVs in a central location.

The chapter answers RQ4: *"How can AV-cyclist interfaces be scalable to facilitate interaction with an increasing number of AVs and cyclists?"*. A complex scenario with three AVs approaching a cyclist from different directions was deduced and investigated through two studies (see Figure 6.1):

1. **Study 9 - Scalable HACI Design Sessions:** This study involved researchers and cyclists collaborating to design HACIs for scalability. However, participants needed to experience the complex three-AV scenario to gain a shared understanding and design fitting solutions. Therefore, this study employed a novel participatory design method. Design sessions were conducted within CycleARcade. New multi-user features were added to CycleARcade; researchers and cyclists had a common view of the AR scene. They could also experience the scenario and spawn multimodal designs directly into the scene. This allowed rapid iterative design, with participants experiencing and refining their concepts. The study resulted in six HACIs from participants. However, there were some diverging participant opinions on the types of information these HACIs should communicate and the placements any visual displays should use. Therefore, three new HACIs were developed to capture these differences for evaluation in the second study.

2. **Study 10 - Scalable HACI Evaluation:** Participants used CycleARcade to experience each HACI in the three-AV scenario. They provided feedback on HACI acceptability and usability. This revealed each design's strengths and weaknesses, informing the design of successful scalable HACIs.

This chapter demonstrates how HACIs can be used to facilitate scalable AV-cyclist interaction. The first study revealed the potential design features that may be adopted, and the second revealed each feature's strengths and weaknesses. These findings were combined to form novel design guidelines for scalable HACIs.

6.1 Prerequisites

Investigating scalability required some foundational work before conducting the studies. First, multi-AV scenarios are more complex and more challenging to capture from real traffic than one-to-one scenarios [37, 123, 135]. Therefore, a novel approach was used to develop a three-AV scenario for investigation in this chapter. Second, the design sessions in this chapter were conducted in AR within CycleARcade to give participants a clear understanding of multi-AV scenarios. This required incorporating new participatory design features into CycleARcade to support this novel methodology. This section details this initial work.

6.1.1 Developing a Scenario for Scalability

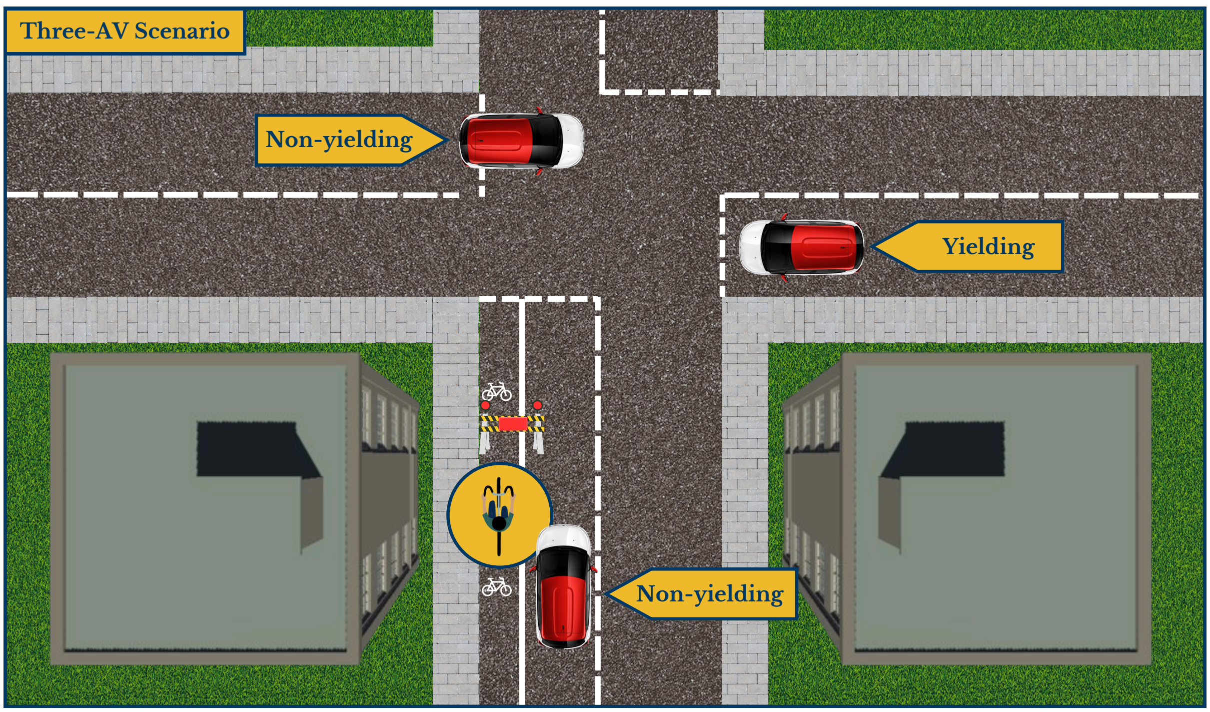

Figure 6.2: The three-AV scenario: Three AVs approaching a cyclist from different locations. One yielding AV approached from the right at the intersection, while another non-yielding one approached from the left. A third non-yielding AV approached from behind the cyclist, while a road repair barrier obstructed the cyclist's path, forcing them to merge lanes.

Scalable AV-cyclist scenarios are complex, especially when AVs are in different positions around a cyclist. These are challenging to contemplate and capture in real traffic. The previous design sessions in this thesis gave participants greater autonomy to contemplate scenarios within their assigned category, which was useful to promote versatility. However, this would have given participants in this chapter too big a scope, as multi-AV scenarios may have greater variations of AV intentions and positions. Relying on participant brainstorming would result in a lack of common ground between team members. Therefore, a novel "scenario-grouping" approach was developed to derive a single multi-AV scenario for use in this chapter. Participants would then clearly understand the use case to design for, and team members would have a shared understanding of the situation, meaning they could have more in-depth discussions of their solutions.

Scenario-grouping involved combining traffic scenarios from real traffic, as captured in Chapter 3, into a larger multi-AV scenario. This featured vehicles in different locations relative to the cyclist and governed by different traffic control features. This brought new use cases for versatility, as interfaces must facilitate interaction across traffic scenarios that cyclists navigate simultaneously rather than sequentially.

This chapter investigated a three-AV scenario that brought together two AVs at a four-way intersection and a lane merging scenario. Therefore, it grouped uncontrolled infrastructure with a dynamic manoeuvre. Two AVs were in the cyclist's view, and one approached from behind. This can be seen in Figure 6.2. AVs drove as follows.

Uncontrolled Intersection

AVs followed identical driving behaviours as in the previous chapters. At the intersection, one AV approached from the cyclist's right and yielded, while another approached from the left without yielding. Both drove at 50 km/h. The yielding AV stopped 0.5 metres behind the give-way line, and the non-yielding AV maintained its speed. Give-way lines were present on all four intersection corners to make right of way more ambiguous, as interaction is more likely in these settings [82]. This made it more realistic to have a non-yielding AV, especially as it was farther from the cyclist.

AVs approached from the intersection sides rather than directly ahead, as this was the focus of the previous studies exploring uncontrolled intersections in Chapter 4 and Chapter 5. This also enhanced the scenario's generalisability to other intersection forms, such as two or three-way ones [12]. From a participatory design perspective, the intersection setup encouraged participants to design HACIs capable of displaying contrasting AV intentions.

Studies from Chapter 3 showed that the uncontrolled intersection is a common scenario that frequently triggers interaction. Chapter 3 also showed that interactions at uncontrolled intersections trigger similar interaction behaviours to other scenarios in the uncontrolled infrastructure category, such as roundabouts and crossings. Uncontrolled intersections were also the focus of previous work exploring AV-cyclist interaction. However, they were only explored in isolation, with a single AV. Including multiple AVs in the intersection also aligned the multi-AV scenario to pedestrian-based setups, featuring two AVs approaching a crossing. These factors helped the three-AV scenario in this chapter to generalise to other potential scenario groups.

Lane Merging

Both AVs at the intersection were initially within the cyclist's view and subject to similar traffic control. The cyclist's focus would shift to the non-yielding AV once intentions became clear, reducing the scalability impact. Therefore, a third non-yielding AV was added. This travelled at 40 km/h and approached from behind the cyclist. A road repair barrier 10 metres into the cycle lane forced the cyclist to merge into the lane with this AV.

Including an AV behind the cyclist prompted design session participants to account for distinct AV positions, including those out of the cyclist's view. Unlike the intersection, there was no traffic control regulating right of way, prompting HACI designs to adapt to traffic control levels. This also made it realistic to make the AV non-yielding, which was crucial to divide cyclist attention among all vehicles rather than solely on the intersection.

Studies from Chapter 3 showed that lane merging is common. Chapter 4 and Chapter 5 showed the scenario as cognitively demanding, as cyclists must frequently shoulder check before manoeuvring. Studies from the previous chapters and prior work have only explored lane merging in isolation. However, exploring it in the presence of other AVs is critical to preparing AV-cyclist interfaces for real-world use.

Scenario generalisability

While this chapter only explores one multi-AV scenario to investigate scalable interfaces, combining an intersection with lane merging is representative of real-world settings. All studies in Chapter 3 showed that cycle lanes often lead to intersections and may be obstructed by road repairs, parked cars or other obstacles. This three-AV scenario's novelty lies in its grouping of common and complex vehicle-cyclist encounters. It advances the field of AV-cyclist interaction by allowing the exploration of interfaces beyond isolated situations with a single AV. This brings their generalisability closer to real-world setups. It encouraged participants to design HACIs that capture the core requirements of (1) displaying contrasting AV intentions, (2) mapping them to the correct AV, (3) regardless of the AV's location, and (4) traffic control. HACIs meeting these criteria would generalise effectively across multi-AV scenarios.

6.1.2 CycleARcade for Participatory Design

The previous design sessions in this thesis were more exploratory, serving as the initial step in creating the interfaces. For example, the eHMI design sessions were the first dedicated to AV-cyclist eHMIs, while the HACI sessions were the first to introduce HACIs into the field. This required extensive brainstorming as there was no understanding of the design features the interfaces should adopt. Moreover, participants were free to contemplate different scenarios within their assigned category to promote the versatility of their designs, so they did not need to experience any specific scenario.

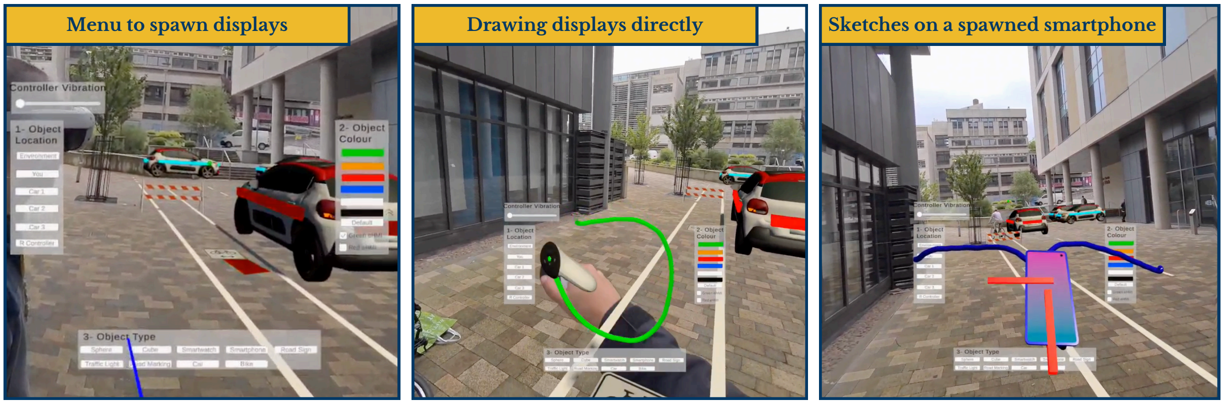

Figure 6.3: CycleARcade's participatory design features. The left image shows the menu participants used to spawn multimodal design objects. The middle image shows a participant drawing a design object into the AR scene. The right image shows a smartphone spawned by a participant with some sketches on the smartphone.

The design sessions in this chapter had a specific objective: developing scalable HACIs for interaction in the three-AV scenario. The scenario was highly complex and challenging to comprehend without experience. Participants needed to navigate the scenario firsthand to develop a shared understanding and design fitting solutions. Therefore, these design sessions were conducted in AR using CycleARcade to allow participants to experience the scenario, incorporate their solutions into the AR environment, and iteratively test and revise their concepts. New features were added to CycleARcade to support this study (see Figure 6.3):

Multi-user features

This allowed multiple participants to have a shared view of the AR scene, with any design changes made by one participant reflected in real-time for all others. This was critical to maintain collaboration between researchers and end users, as in the previous design sessions.

Design Mode

AVs were stationary and positioned closer together so participants could move around and ideate. Participants used a menu to spawn and set up new design objects, using the right controller for selection (see Table 6.1). They could choose from abstract shapes like cubes or spheres and a palette of specific items such as a smartphone or a traffic sign. Once selected, objects were spawned one metre opposite the participant. If the menu lacked a suitable option, participants could draw a 3D object directly into the scene by holding the right trigger. Additionally, they could customise the object's colour and animation, e.g. flashing or pulsing, as recommended by previous HACI research. Objects could be attached to the environment, a vehicle, the participant, or the right controller and would move with their *parent* during *Experience Mode*.

Abstract Visual Object	High-Fidelity Visual Object	Auditory Cue	Haptic Cue
Sphere	City car	Audio recorded by participant	1 pulse per second
Cube	Bicycle		2 pulses per second
2D Square	Traffic cone		3 pulses per second
	Empty yellow traffic sign		4 pulses per second
	Smartphone		Continious pulse
	Smartwatch		

Table 6.1: Multimodal objects participants could add into the AR scene. Auditory cues played in a loop, and haptic cues were headset controller vibrations. Participants could change the colours of visual objects. They could also draw objects directly into the scene. Any visual objects can be resized and rotated.

The left controller projected a ray for manipulating spawned objects; participants could grab, move, rotate, resize, or delete objects as needed. *CycleARcade* supported multimodal interfaces. Participants could set controller vibrations via a menu slider, ranging from none to 3 pulses per second to continuous, reflecting various haptic patterns for handlebars or wearables like smartwatches. They could attach audio to objects by recording sound, which would play on a loop and be spatially relative to the object's position.

Experience Mode

This served two key purposes. First, it allowed participants to navigate the scenario and gain a shared understanding before starting their designs. Second, it enabled participants to experience their designs in action. In this mode, AVs and attached design objects moved to start positions aligned with the traffic scenario. One participant rode a bike from the start of the cycle lane to the intersection's end while AVs followed pre-recorded driving animations triggered by the cyclist's position. All objects created in *Design Mode* were active, providing fully functional visual, haptic, and auditory cues. Any other participants sharing the AR view could observe the encounter, allowing for post-experience discussions.

6.2 Study 9: Scalable HACI Design Sessions

HACIs must scale to display information from multiple AVs to be effective in real-world scenarios [123]. Similar to the previous chapters, this study used a design session approach to gain researcher and cyclist insights into the design features that scalable HACIs should adopt to present information from multiple AVs. However, multi-AV scenarios may be more challenging to contemplate than previous ones explored in this thesis [12]. Therefore, HCI researchers and cyclists collaborated within CycleARcade to experience the multi-AV scenario and design HACIs that facilitate interaction with the three AVs. The design process was iterative, with participants testing and refining each design iteration. This study was critical for understanding the potential features that contribute to successful, scalable HACIs.

6.2.1 Study Design

This study was a set of participatory design sessions in which HCI experts and cyclists collaborated to design a HACI for the three-AV scenario. Participants used *CycleARcade's* new multi-user features to share a common view of the AR scene. They iteratively designed and experienced their HACI. Transcripts of participant discussions during the design sessions and photographs of the final designs were collected for analysis.

Study setup

Six design sessions were conducted, each involving a team of one HCI researcher and one cyclist. As in the previous design sessions, recruiting researchers and cyclists facilitated a comprehensive exploration of HACIs for scalability. Researchers contributed expertise on emerging technologies and their pragmatic qualities, while cyclists reflected on the real-world usefulness of any proposed interfaces, which enhanced their acceptability. Teams alternated between *CycleARcade*'s *Design* and *Experience modes* to develop their concepts; see Figure 6.4. Similar to the previous design sessions, teams were moderated by an experimenter with at least one year of HCI research experience. The experimenter also used CycleARcade and was present in the shared AR scene with the participants.

The experimenter explained the concept of HACIs and provided technical support for CycleARcade. They also ensured that each iteration (which participants perceived as their complete design) was experienced. The experimenter also captured video footage and design photographs using their headset's built-in camera. The sessions were conducted outdoors in a quiet, pedestrianised area. This ensured a safe environment free from real traffic. The area offered full WiFi connectivity to support CycleARcade's multiplayer features. It measured 20 metres long and 15 metres wide, giving participants ample space to move around the AVs, ideate, and cycle in AR to experience their designs and the scenario.

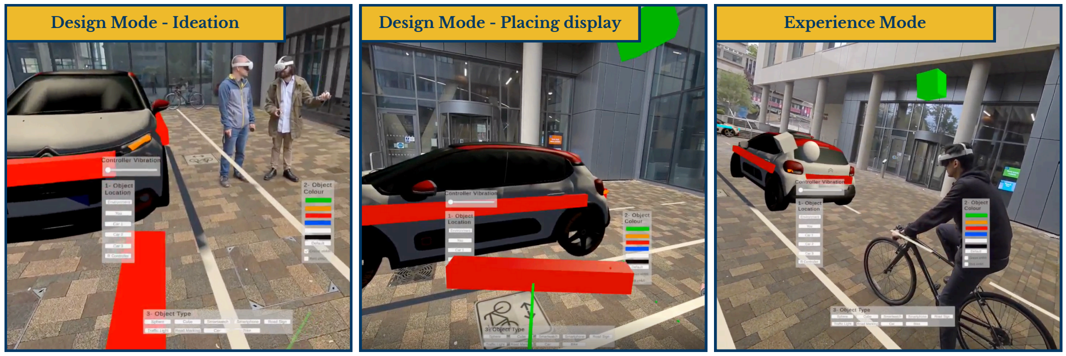

Figure 6.4: Design and Experience Modes in CycleARcade. The left image shows participants ideating in Design Mode. The middle image shows a participant placing a design object onto the road. The right image shows a participant experiencing their design in Experience Mode.

Study scope

Teams had complete creative freedom without restriction on display placements, cues, or modalities. The only requirement was that the displays had to be interconnected and aware of each other's presence, leaving it to the participants to determine how best to achieve this. Similar to the previous HACI design sessions, AVs were instrumented with the LightRing eHMI. This was to ensure that cyclists without additional wearable or bike-mounted devices would still have a baseline of safety. However, unlike in previous sessions, participants could modify LightRing. They could use it as a foundation to expand upon or start from scratch after considering its limitations. This was because this research explored scalability, and participants only experienced LightRing in one-to-one scenarios in the previous chapters. If LightRing was removed, they were instructed to provide a *baseline interface* by placing a display on the environment or AV. CycleARcade's Experience Mode was particularly helpful here, as participants will be better informed of any alterations to LightRing since they would have had first-hand experience in a multi-AV scenario.

Measures

The study collected the following data to understand the design features that allow HACIs to scale and display information from multiple AVs:

- **Photographs of participant designs:** These showed the AR environment and participant designs integrated into the real world. The photographs identified the range of devices participants incorporated into their designs. It was useful for synthesising new HACIs based on participant designs for evaluation in the upcoming study;

- **Video footage of the design sessions:** The videos showed participants working in the AR scene. These videos were useful for contextualising participant design decisions and gaining detailed end-user perspectives on the problem.

6.2.2 Apparatus

CycleARcade's new multi-user features were developed using Photon Fusion[1], a multiplayer framework for Unity applications. The cross-cultural study from the previous chapter showed that the Meta Quest 3 provided suitable passthrough and depth-sensing to support riding in AR. Therefore, CycleARcade was installed on Quest 3 headsets, one each for the experimenter, HCI researcher and cyclist. Teams were provided with a helmet and Giant Escape 3 bicycle to use when CycleARcade was in Experience Mode.

6.2.3 Participants

Six HCI researchers were recruited through personal contacts. Similar to the previous HACI design sessions, their experience ranged from PhD students to lecturers from diverse HCI areas, such as haptics, audio interfaces and AutomotiveUI. Their demographics were: $M_{\text{age}} = 34.3$, $SD = 6.9$; $Male = 4$, $Female = 2$. Six cyclists were recruited through social media advertising. They must have been cycling in mixed UK traffic multiple days per week for at least one year. Their demographics were: $M_{\text{age}} = 28.5$, $SD = 6.4$; $Male = 4$, $Female = 2$.

6.2.4 Procedure

Participants met the experimenter and their teammate at the designated outdoor area. They began by completing a survey about their demographics and cycling/HCI experience. The experimenter briefed the participants about the study and explained the concept of HACIs. Each participant then rode the bike for three minutes without wearing the headset to ensure the bike gear and saddle height were suitable, with adjustments between participants made easily using a quick-release clamp on the bike's saddle. The experimenter set up *CycleARcade* on each headset, calibrating AR with real-world floor levels. Participants were given their headsets and each practised riding the bike in the AR environment for 5 minutes without approaching AVs to get accustomed to the equipment and minimise novelty effects. The experimenter then started the headset video recording and set up an online room, instructing participants to click the *Join Room* button. The session began with *Experience Mode*, so each participant could navigate the scenario with moving AVs and gain a shared understanding. The experimenter then switched to *Design Mode* and spent five minutes guiding participants on how to spawn and manipulate objects. Participants discussed the scenario and began designing the HACI. They had 45 minutes to alternate between *Experience Mode* and *Design Mode*, experiencing and refining their concepts until they were satisfied with their designs. Each session lasted one hour. Participants were compensated for their time with £10 Amazon vouchers.

[1]Photon Fusion Multiplayer: `photonengine.com`

6.2.5 Analysis

This study used the same analysis approach as Chapter 4 and Chapter 5. Participant designs were organised into a taxonomy to visualise the relationships between HACI features, following the same structure as the HACI taxonomy from Chapter 5. Additionally, a thematic analysis of the design session videos was conducted to extract themes that represent the expectations of HCI researchers and cyclists regarding scalable HACIs.

Taxonomy Development

One researcher sketched each design on the same AI-generated image from the previous HACI design sessions, ensuring a uniform presentation. A second researcher reviewed the sketches against the original designs captured in the videos and found no discrepancies. One researcher then categorised each individual display within a HACI (e.g., AR glasses or vibrating handlebars) into the taxonomy. The taxonomy maintained the same structure as that from Chapter 5, consisting of five layers: (1) Placement (e.g., environment or cyclist), (2) Specific Placement (e.g., road or helmet), (3) Message, (4) Modality, and (5) Technology. Each feature was recorded along with its frequency of appearance across the designs to determine its popularity. A second researcher independently categorised the designs using the taxonomy and confirmed there were no inaccuracies.

Thematic Analysis

An inductive, data-driven thematic analysis [19] was conducted on the video transcripts. The transcripts were auto-transcribed by Otter.ai and subsequently corrected by a researcher. They were then imported into NVivo for coding. One researcher identified 19 unique codes from the data. Following this, two researchers collaboratively sorted these codes into four overarching themes based on their similarities. This process was iterative; disagreements were discussed and resolved, with codes being remapped as necessary. Themes containing two or more overlapping codes were reassessed and combined where appropriate.

6.2.6 Results

This section summarises each team's design based on design photographs and explanations from the video footage. Figure 6.5 includes sketches of each design. The section also presents the taxonomy of scalable HACI components populated with features from participant designs; this is shown in Figure 6.6. Lastly, it reports the themes that reflect researcher and cyclist perspectives and expectations of scalable HACIs.

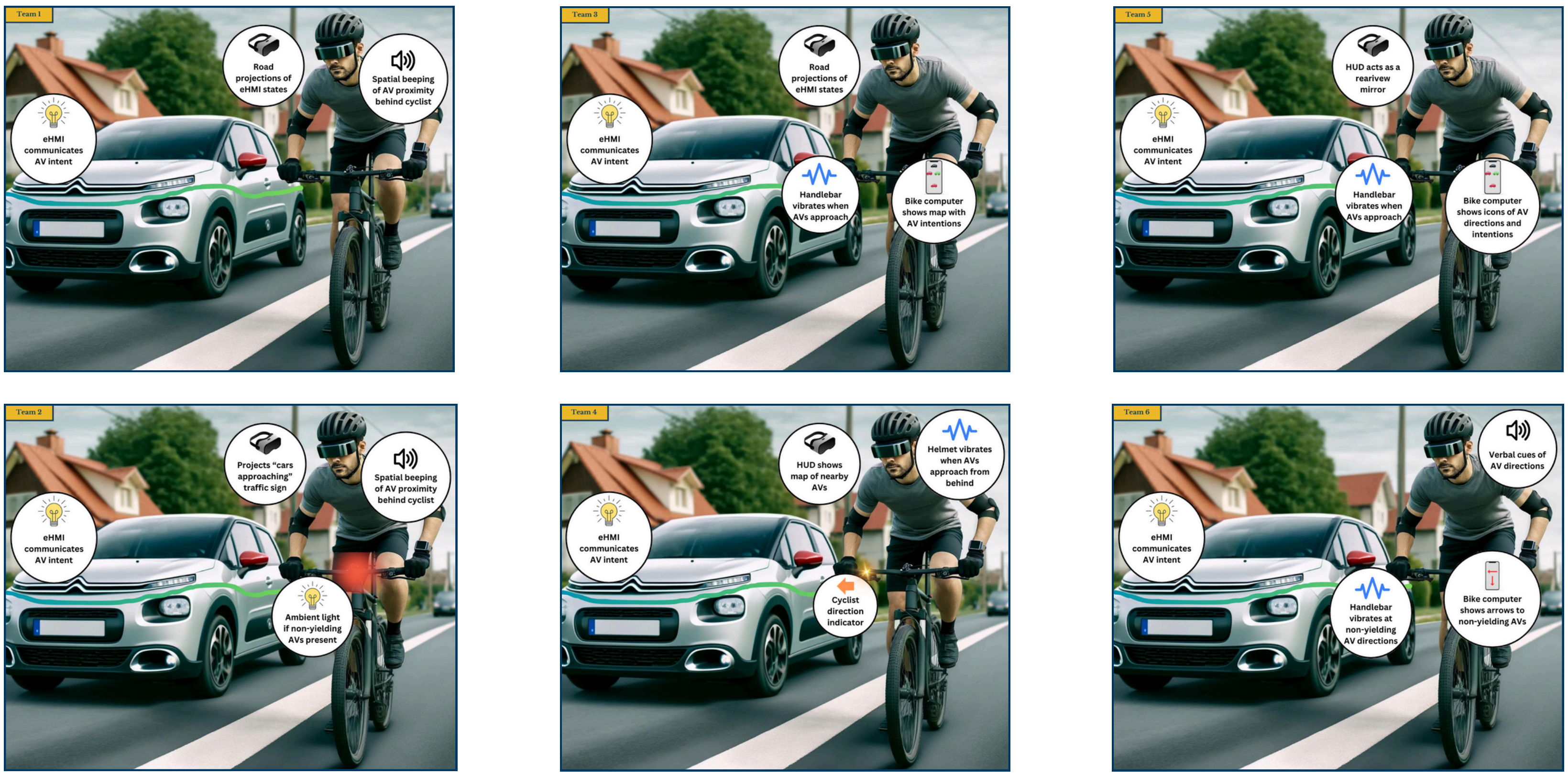

Figure 6.5: Participant designs from the study. The top row shows designs of teams 1, 3 and 5. The bottom shows designs of teams 2, 4 and 6.

Figure 6.6: Tree diagram showing the taxonomy of scalable HACI components populated with participant designs. Branches are labelled with: *HACI feature (appearance frequency).*

Designs and Taxonomy

The sessions produced six multimodal HACI designs that facilitated interaction in the three-AV scenario. All teams retained the *LightRing* eHMI on vehicle exteriors. They supplemented this with interconnected displays on the bike, cyclist, or environment. The taxonomy shows that participants placed visual cues either on the handlebar using devices such as bike computers or onto the environment using AR displays. These visual displays often communicated AV intentions. Participants also added auditory cues from the helmet to communicate AV locations and haptic cues through handlebar vibrations to alert them of oncoming AVs. This section reports how these features were used in context and summarises each design based on participant descriptions in the video footage.

Team 1 Cyclist AR glasses project the eHMI state onto road markings; the cycle lane and the intersection's left give-way line flash red to indicate that oncoming AVs (behind and to the cyclist's left) will not yield. The intersection's right give-way line pulses green to show that an approaching AV from that direction will yield. Additionally, spatial audio from the helmet beeps to alert cyclists of the AV approaching behind them. This also communicates the vehicle's proximity, with the volume getting louder as the vehicle moves closer.

Team 2 AR glasses project a *"Cars Approaching"* traffic sign onto a nearby pavement to prepare cyclists for potential space-sharing conflicts. Red ambient handlebar lights glow if any AVs will not yield. Similar to Team 1's design, spatial audio from the helmet beeps to warn cyclists that a vehicle is approaching from behind.

Team 3 Displays operate in sequence. First, the handlebar vibrates to alert cyclists of approaching AVs. This prompts them to look down towards their bike computer, which displays a map showing AV positions with vehicle icons flashing red or pulsing green in sync with their eHMI to communicate each AV's intentions. Simultaneously, AR road markings flash red or pulse green according to the approaching AV's eHMI, similar to Team 1's design.

Team 4 AR glasses project a Head-Up Display (HUD) with a map of non-yielding AVs. The back of the helmet vibrates to alert cyclists of an approaching vehicle behind them. This HACI also facilitates two-way communication, with directional indicator buttons on the handlebar for cyclists to communicate their own intentions to the AVs.

Team 5 Displays operate in sequence. First, the handlebar vibrates to alert cyclists of approaching vehicles. Then, AR glasses project a HUD functioning like a rearview mirror, showing cyclists the AV behind them. A bike computer displays each AV's position using static icons on the screen's top, bottom, and sides. If an AV is present in that direction, the icons flash red or pulse green based on their eHMI.

Team 6 The bike's handlebar vibrates to indicate non-yielding AV directions, with both sides vibrating for AVs approaching from the front or back. Audio from the helmet provides explicit verbal cues on the AV positions, such as "cars on your left, right and behind". A bike computer displays red arrows pointing to non-yielding AVs.

Themes

This section reports four themes resulting from the thematic analysis of the video transcripts. These themes are supplemented with participant quotes from the transcripts.

Theme 1: Ensuring situational awareness. Participants explained that receiving information about the number and location of surrounding AVs is crucial: *"You need to know how many AVs are around you, where they are, and what they will do"* - C5. This would allow more informed decision-making: *"You need to be fully aware of the situation to know how to proceed"* - R4. In contrast, relying solely on eHMIs is insufficient when AVs approach from different directions, as in the three-AV scenario: *"[eHMIs] may not be enough. I still need some indication of where all the vehicles are"* - C3. Therefore, additional displays help supplement eHMIs to offer a broader view of nearby vehicles and aid cyclists in planning their manoeuvres.

Theme 2: Communicating the optimal level of information Participants expressed different opinions on the type of information HACIs should display so cyclists have full situational awareness. Some teams preferred detailed displays communicating each AV's location and intentions: *"A map on my bike computer showing vehicles as they move, with icons blinking the same way as [eHMIs]"* - C3. Other teams favoured more indirect signals that require cyclists to validate HACI signals with eHMIs and AV driving behaviours: *"It's enough to have a camera showing what's behind me. I will check the [eHMI] anyway. I cannot fully trust displays outside the car"* - C5. Therefore, cyclist preferences may depend on how much they trust displays beyond the vehicles to convey vehicle intentions accurately.

Theme 3: Prioritising challenging encounters The three-AV scenario is already overwhelming, and HACIs must be carefully designed to avoid overloading cyclists with signals: *"There's a lot going on. We should avoid putting too many things into these displays"* - R1. This prompted participants to design HACIs that alert cyclists only to the most challenging encounters. They identified two key factors that categorise an encounter as challenging:

- *Traffic control level and AV position:* The AV behind the cyclist was seen as challenging to communicate with as it was out of view, and no formal traffic control dictated its intentions: *"The one behind me is the most important because I can see the others"* - C1. Participants suggested adding cues that would alert them of the AV without requiring them to shoulder check, such as spatial audio: *"Spatial audio from the helmet pointing you to the AV behind you would prepare you for that"* - R2.

- *AV yielding intentions:* Non-yielding AVs were viewed as more critical, with participants wanting alerts for these situations: *"The yielding AV will wait, and I can see its eHMI. Additional interfaces should highlight the location of non-yielding vehicles"* - R4. Focusing on non-yielding AVs may improve usability and avoid unnecessary signals from HACIs: *"This would make the interface clearer and focus on what's important"* - C4.

In short, HACIs that focus on out-of-view or non-yielding AVs can enhance awareness without overwhelming cyclists with too much information.

Theme 4: Placing visual displays There was a spread of views on visual display placements within a HACI. Some participants favoured more traditional handlebar displays, such as bike computers: *"Putting stuff on the road would overwhelm me; there are already many signs there"* - C6. Others preferred augmenting the environment: *"Projecting the eHMI onto the road; I can still focus ahead"* - C1; *"Something on the handlebar will be distracting; I'll have to constantly look at it"* - C2. Therefore, there was no clear consensus about where to place visual displays.

6.2.7 Discussion and Design Synthesis

This study presented the expectations of HCI researchers and cyclists regarding scalable HACIs. It identified key design features HACIs should adopt to centralise information from multiple AVs. Designs showed notable overlaps, such as handlebar displays and spatial audio. This contrasts with the earlier participatory design sessions in the thesis, where participants created more diverse displays involving various cues and modalities for one-to-one interaction. This may be due to all teams designing for a single scenario rather than a broader category of scenarios. Participants in this study favoured simpler, less demanding interfaces to avoid being overwhelmed by signals in such a complex scenario. They also experienced the scenario and tested each design iteration so their designs were closer to the final versions. Previous design sessions were exploratory and encouraged more brainstorming. The designs were refined only after evaluation, as seen in the VirtuRide study. Traditional participatory design methods were beneficial for early design sessions in the thesis, including those that first introduced HACIs in the previous chapter. These initial stages encouraged participants to provide more creative input. However, this study had a distinct requirement: enabling interaction with multiple AVs across different positions, yielding conditions, and traffic control levels. This would have been difficult without first-hand experience.

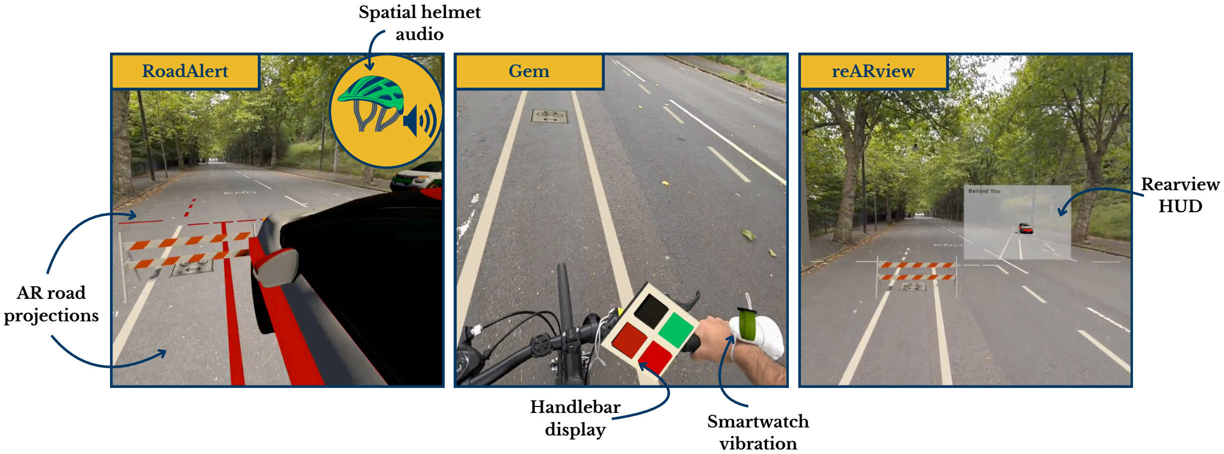

Figure 6.7: The three new HACI concepts implemented in CycleARcade. RoadAlert features AR road projections and spatial audio; Gem includes a central handlebar display and smartwatch vibrations, and reARview displays an AR HUD showing the AV behind the cyclist.

	Addressed Themes	Placement	Placement (Specific)	Message	Modality	Technology
RoadAlert	*Prioritising Challenging Encounters* *Ensuring Situational Awareness* *Placing Visual Displays*	Environment Cyclist Vehicle	Road Helmet Body	AV Intent AV Location AV Intent	Visual Audio Visual	Cyclist AR Glasses Spatial Audio Lights
reARview	*Communicating the Optimal Level of Information*	Cyclist Vehicle	Glasses Body	AV Location + AV Intent (Indirectly) AV Intent	Visual Visual	Cyclist AR Glasses Lights
Gem	*Placing Visual Displays*	Bicycle Cyclist Vehicle	Handlebar Watch Body	AV Location + AV Intent Warning AV Intent	Visual Haptic Visual	Bike Computer Smartwatch Vibration Lights

Table 6.2: The three HACIs classified according to the scalable HACI taxonomy and the themes that motivated their development.

Design Synthesis

This study identified promising directions for scalable HACIs but lacked a platform for comparing designs, which is crucial for understanding how contrasting features between participant designs compare relative to one another [14, 28]. Rather than directly comparing participant designs, which shared overlapping ideas, three new HACIs were developed. Each new HACI focused on distinct aspects of this study's findings. All new designs included the *LightRing* eHMI, as participants consistently chose not to alter it, suggesting it was well-suited for scalability. This stems from the eHMI broadcasting simple, binary AV intent signals. Adding more complex information, such as AV awareness of specific cyclists, could hinder scalability. Such messages may overload the display and make it hard to process, especially when multiple vehicles are around, as shown with the first iteration of LightRing in the VirtuRide study. The three new HACIs are shown in Figure 6.7. Table 6.2 classifies them according to the taxonomy.

Concept 1: RoadAlert

The *"Placing visual displays"* theme required a comparison of bike-mounted and on-environment displays. This would show whether environmental augmentations overwhelm cyclists or help them make quick decisions without diverting attention from the road. RoadAlert conceptualises on-environment displays. The taxonomy showed that cyclist AR glasses are a popular approach for presenting cues on the environment. Therefore, similar to Teams 1 and 3, RoadAlert uses AR to project the eHMI state onto road markings. However, the *"Prioritising challenging encounters"* theme suggested that HACIs should focus on non-yielding AVs when visual displays may cause clutter. Consequently, RoadAlert's AR display only projects non-yielding AV states due to the large areas that road projections cover. The intersection's left give-way line and cycle lane road markings would flash red. Flashing cycle lane road markings do not explicitly communicate that they correspond to the AV behind the cyclist. The *"Ensuring situational awareness"* theme showed that cyclists should know AV locations to map intentions correctly. Therefore, drawing from Teams 1, 2 and 3, RoadAlert also features spatial audio beeps from the helmet to indicate the AV behind the cyclist. Similar to Team 1's approach, the beeps get louder as the AV moves closer to communicate proximity, which would potentially minimise shoulder checks [67]. This allowed the following evaluation study to explore multimodality with non-visual cues complementing visual ones rather than redundantly presenting AV intentions.

RoadAlert shares similarities with FullIntel from the previous chapter but offers a more scalable variation. FullIntel featured cues that are difficult to generalise for scalability, such as smartwatch vibrations synchronised with a single AV's eHMI. RoadAlert addresses these scalability challenges. For example, it does not reiterate the intentions of yielding AVs to avoid overwhelming cyclists. Unlike FullIntel, where spatial audio redundantly reiterated LightRing, RoadAlert uses spatial audio that only points to the AV behind the cyclist and does not redundantly communicate the AV's intentions. This distinction enhanced scalability, as using spatial audio to point to all AVs in the scenario is challenging. It also allowed an investigation into whether cyclists can effectively process cues that convey different types of messages rather than reinforcing the same information. Since FullIntel was the best-performing HACI across cultures, and its AR road projections were valued in all cities, it was crucial to understand how these projections adapt to encounters with multiple AVs. RoadAlert presented an opportunity to explore the generalisability of AR road projections in multi-AV interactions. From a practical standpoint, RoadAlert's implementation remains largely similar to FullIntel. It relies on V2X connectivity to ensure accurate AV intention displays [110]. The LightRing eHMI remains essential as a baseline display for cyclists without AR glasses and serves as a failsafe in cases where V2X connectivity is unavailable. Additionally, spatial audio offers a significant advantage over AV-based audio, as it is less likely to be masked by environmental noise.

Concept 2: Gem

This design further explored the *"Placing visual displays"* theme. It contrasts RoadAlert's AR projections by displaying AV intentions using a visual display on the handlebar, a popular approach in the taxonomy. Building on Teams 3, 5 and 6's bike computer designs, Gem uses a diamond-shaped display mounted on the handlebar. It has black cubes at each corner: each cube pulses or flashes in sync with the AV's eHMI based on its direction. Flashing red cubes at the bottom and left corners indicate non-yielding AVs behind and to the left, while a pulsing green cube on the right points to the yielding AV. Therefore, Gem uses a consistent visual language between the handlebar display and LightRing so cyclists can validate signals and maintain a minimal learning curve when the LightRing is a failsafe; the previous cross-cultural study showed that this is key to fostering trust and enhancing HACI usability. This is especially key for Gem as the cues are not viewable alongside the LightRing eHMI, which is possible in RoadAlert.

Unlike RoadAlert, cyclists must shift attention between Gem's visual display and the road. Gem's visual cues communicate AV directions more clearly than RoadAlert's. There was a lesser need to incorporate non-visual signals. However, cyclists may need prompts to look at the handlebar. Participant designs showed that interconnected HACI displays could work sequentially. Therefore, drawing from Teams 3, 5 and 6, Gem also featured haptic cues from the cyclist's smartwatch. The smartwatch would vibrate for 3 seconds to warn of approaching AVs and prompt cyclists to look at the handlebar. Even though participant designs used handlebar vibrations, Gem places these cues on a smartwatch as the HACI design sessions from the previous chapter showed that smartwatch vibrations are easier to distinguish across varying road textures or potholes. Vibrations do not communicate AV directions or proximities, contrasting them with RoadAlert's spatial audio. This allowed the follow-up evaluation to explore the level of detail required from non-visual signals. The online survey from Chapter 3 showed that some cyclists already mount bike computers on the handlebar [14]. Therefore, cyclists may find Gem more acceptable as it uses a familiar setup. Gem can also leverage existing technology, such as a smartphone or bike computer app, connected to the cyclist's smartwatch. Like RoadAlert, it requires V2X to receive information to display AV intentions accurately [110].

Concept 3: reARview

The *"Communicating the optimal level of information"* theme warranted comparing direct communication of AV locations and intentions, as seen in RoadAlert and Gem, versus indirect signals widening a cyclist's view, leaving them to track AVs and deduce intentions. This gives cyclists more autonomy in their decisions, affecting their manoeuvre choices and decision-making speed. Cyclist preferences on the level of information they receive from HACIs may depend on how much they trust the displays, as seen in the cross-cultural study.

reARview conceptualises indirect signals, contrasting it to the other designs. Drawing from Team 5, reARview is a HUD in the top right corner of cyclist AR glasses, aligned with the UK traffic overtaking side [128]. The HUD functions as a rearview mirror and presents live footage of the AV behind the cyclist. It appears when there is a 15-metre or less distance between the cyclist and an AV behind them. reARview still requires cyclists to interpret AV intentions from eHMIs and driving behaviour. It is unimodal, contrasting it with the other multimodal designs.

The previous studies in the thesis exploring lane merging showed that out-of-view AVs present significant challenges for cyclists [67]. These challenges are heightened with other vehicles present, so cyclists may appreciate the emphasis of rearview warnings in this design. The online survey from Chapter 3 also showed that some cyclists already use rearview alerts on bike computers and may be accustomed to car rearview mirrors. However, reARview goes beyond alerts; it provides detailed information, such as the AV's distance and speed, making it critical to explore in the follow-up study.

From a scalability perspective, reARview facilitated an investigation of whether visual rearview information helps cyclists manage attention across multiple AVs or diverts focus from those ahead [124]. Regarding its practical implementation, reARview does not require V2X because it does not explicitly display AV intentions. It also does not need depth sensing for precise display placement; the HUD overlays the environment. Therefore, reARview could use currently available technology, using an AR or mixed reality headset connected to a proximity sensor and camera that streams live footage to the HUD when an AV approaches. Many cyclists already mount cameras on their bikes in case of collision [14], so reARview could leverage this setup without much disruption, enhancing acceptability. The eye-tracking study from Chapter 3 showed a range of scenarios where the vehicle is initially behind the cyclist, such as being overtaken. reARview may also generalise to these situations effectively.

To summarise, three scalable HACIs were developed based on this study's findings. RoadAlert facilitated the exploration of whether projecting the eHMI state onto the road generalises to scenarios with multiple AVs or overwhelms cyclists. It also allowed an investigation of whether communicating the directions and intentions of only non-yielding or out-of-view AVs is sufficient. Gem presented cyclists with the directions and yielding intentions of the three AVs on a central handlebar display, contrasting it with RoadAlert's projections. reARview expanded the cyclist's field of view, allowing the follow-up study to investigate whether cyclists need HACIs to state AV directions or yielding intentions explicitly or if projecting rearview information is enough in the three-AV scenario. The designs take different approaches to multimodality. RoadAlert used concurrent multimodal signals, Gem employed sequential multimodality, and reARview was unimodal. In the follow-up study, the three designs were loaded onto CycleARcade so cyclists could experience and compare them, allowing identification of the most effective features of scalable HACIs.

6.3 Study 10: Scalable HACI Evaluation

The previous study showed new ways for HACIs to display information from multiple AVs. However, participants had some diverging opinions on device placements and the type of information HACIs should communicate. Consequently, RoadAlert, Gem and reARview were designed to capture these differences. The next step was to evaluate and compare them to identify the most successful features. This was an outdoor evaluation study in which Cyclists used CycleARcade to experience and compare the three HACIs and a baseline condition with just the LightRing eHMI. This provided insights into each HACI's strengths, weaknesses and usability, preparing them for real-world use.

6.3.1 Study Design

This was a within-subjects study with *HACI* as an independent variable and cyclist *perceptions* and *behaviours* as dependent variables. Participants used CycleARcade to navigate the three-AV scenario using each *HACI*. They indicated their *perceptions* through questionnaires, and CycleARcade logged their *behaviours*.

Study Scope

The HACIs tested in this study were synthesised from the previous design sessions. All HACIs featured the *LightRing eHMI* on each AV and supplementary wearable devices for added support. The three HACIs were *RoadAlert*, which featured AR road projections and spatial helmet audio; *Gem*, which included a handlebar-mounted display and smartwatch vibrations; and *reARview*, a HUD providing live footage of the AV behind the cyclist. The baseline condition featured only the *LightRing eHMI* mounted on each AV, so there were no wearable devices. Participants used each HACI in the same three-AV scenario as the previous study. CycleARcade was beneficial here, as it maintained identical AV driving behaviours and traffic features between the two studies in this chapter.

Study Setup

The study was conducted outdoors on an 8-metre-wide pedestrianised tarmac road, simulating real-world cycling conditions. This was narrower than the 15-metre-wide space used in the design sessions, as this study focused on evaluating HACIs rather than requiring additional space for ideation. CycleARcade was set up similarly to the cross-cultural HACI evaluation in Chapter 5; displays started responding when an AV was 15 metres from the cyclist, and the AR environment included marked start and end points. The start point was at the beginning of the cycle lane, and the end point was two meters after the intersection. Participants cycled in a loop from the start to the end and then back to the start. Figure 6.8 illustrates the designated path. Each participant completed four loops, one for each HACI condition. The order of HACI conditions was counterbalanced using a Latin square to minimise order effects. Participants were informed that the scenario might differ before each loop to prevent learning effects.

Measures

The following data were measured to compare HACI performance:

- **Post Scenario Questionnaire**: This combined the *Post-Scenario* and *Post-Track Questionnaires* from the previous evaluation studies, as the HACIs were only tested in one scenario. It included the Perceived Performance and Anxiety dimensions from the Car Technology Acceptance Model (CTAM) [94]. The NASA-TLX [61] assessed the workload imposed by each HACI, and the User Experience Questionnaire - Short Version (UEQ-S) [114] indicated usability. Participants also responded to five-point Likert scale questions (strongly disagree-strongly agree): *"I trusted the interface"*, *"I felt safe using the interface while riding"*, *"The AV was aware of my presence"*, and *"I was confident in the AV's next manoeuvre"*;

- **Cycling Behaviour**: This was logged by CycleARcade using the same approach as the previous studies. It included *cycling speed* in m/s logged every 0.5 seconds, the number of shoulder checks, and any collisions with the cyclist and an AV. The log specified which AV the cyclist collided with.

- **Qualitative Measures**: Participants could provide feedback on the HACI's performance using a textbox in the *Post-Scenario Questionnaire*. After the study, they ranked the HACI conditions and justified their choices.

6.3.2 Apparatus

This study used CycleARcade to test the scalable HACIs. Similar to the previous studies, CycleARcade was installed on a Meta Quest 3 headset. The HACIs were selectable via a start menu in CycleARcade. Only *Experience Mode* was used, and the multi-user feature was turned off because each session involved a single participant. Participants were provided with a helmet and a Giant Escape 3 bicycle.

6.3.3 Participants

The study involved 20 cyclists recruited through social media. Their demographics were: $M_{\text{age}} = 29.6$, $SD = 5.8$; $Male = 15$, $Female = 5$. All participants had experience riding in the UK. Ten cycled at least once a week, five at least once a month and five multiple times a year.

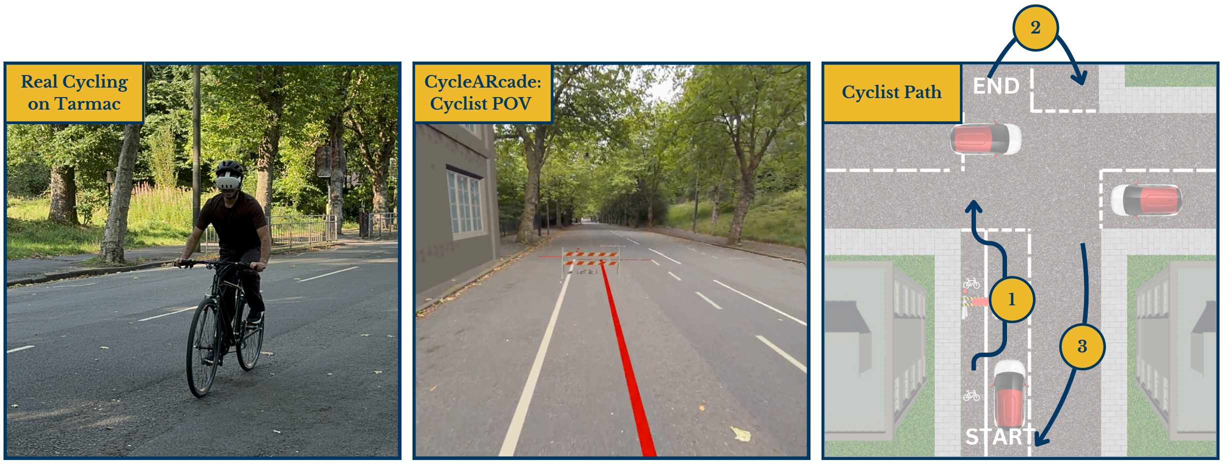

Figure 6.8: The study setup: Participants used CycleARcade to cycle outdoors and experience each HACI. They cycled in a loop from the start to the end point and back.

6.3.4 Procedure

The participant met the experimenter in the designated outdoor area. They were briefed about the study and completed a demographics survey. The participant then checked their comfort with the bike gear and saddle height by riding without the headset for 3 minutes. Adjustments were made if anything was uncomfortable. Next, the experimenter calibrated the headset and aligned the AR with the real-world floor level. The participant wore the headset to practise 5 to 10 minutes of riding in a loop in the AR environment without AVs. They cycled from the start to the end point, then back to the start. This was to reduce novelty effects and help them get used to the setup. After practice, the participant removed the headset, and the experimenter selected the HACI based on a Latin square design and explained how the selected interface worked.

The participant wore the headset again. If Gem was selected, the right controller was attached to their non-dominant wrist; this was displayed as a smartwatch in AR and vibrated accordingly. The left controller was taped to the bicycle handlebar to place the visual Gem display. The participant rode from the start to the endpoint, with the three AVs approaching them, then back to the start. They removed the headset to answer the Post Scenario Questionnaire using a tablet. This process was repeated four times so the participant could experience all HACI conditions. After the experiment, the participant used an online form to rank the HACIs and explain their choices. The study took about 45 minutes. Participants were compensated for their time with £10 Amazon vouchers.

	HACI			
	RoadAlert	*Gem*	*reARview*	*eHMI*
Workload	4.50 ± 3.21	9.50 ± 7.13	5.17 ± 5.50	7.92 ± 4.29
Awareness Confidence	4.00 ± 0.00	4.00 ± 1.25	3.00 ± 2.00	2.00 ± 1.50
Intention Confidence	4.00 ± 1.00	4.00 ± 2.00	4.00 ± 0.25	3.00 ± 2.00
Cycling Performance	4.13 ± 0.56	3.34 ± 1.31	3.88 ± 0.75	2.63 ± 1.25
Anxiety	2.33 ± 0.38	3.00 ± 0.58	2.50 ± 0.42	3.33 ± 1.21
Perceived Safety	4.00 ± 0.25	3.00 ± 2.00	4.00 ± 1.00	2.00 ± 1.00
Trust	4.00 ± 0.25	3.50 ± 2.00	4.00 ± 1.00	3.00 ± 2.00
Usability	1.63 ± 0.59	0.50 ± 1.34	1.44 ± 0.81	0.19 ± 1.10

Table 6.3: Median ± IQR for each Post-Scenario Questionnaire subscale per HACI.

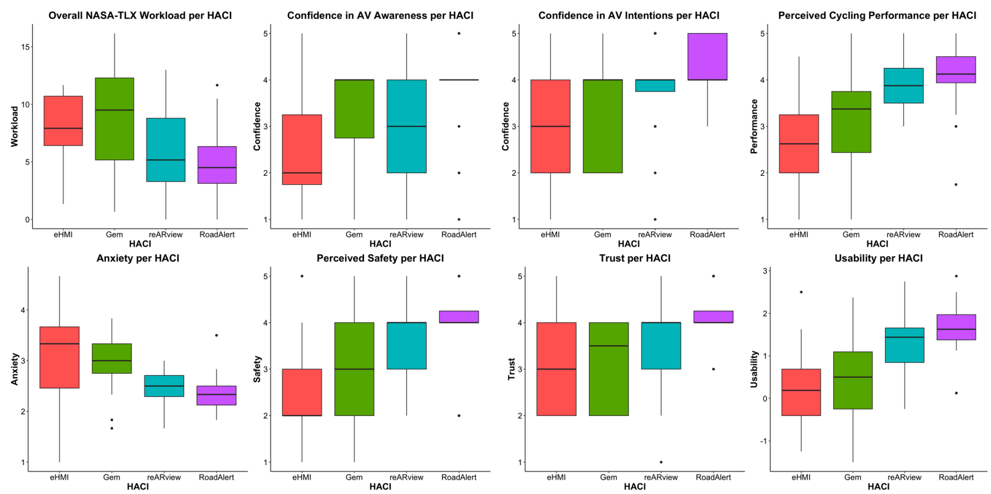

Figure 6.9: Box plots showing the median ± IQR for each Post-Scenario Questionnaire subscale. RoadAlert consistently outperformed the other HACIs, while No eHMI underperformed.

6.3.5 Results

This section reports the study outcomes through cyclist perceptions and behaviours toward each HACI. These findings are contextualised with qualitative feedback from participants.

Post Scenario Questionnaire

Data were not normally distributed; a Friedman's test was conducted to examine the effect of *HACI* on each questionnaire subscale. *Participant* was a blocking factor to account for individual variability. *Post hoc* comparisons between *HACI*s were performed using the Nemenyi test. Results are in Table 6.4. Median values are in Table 6.3. Figure 6.9 visualises these as box plots.

The overall results show that *RoadAlert* consistently outperformed the other conditions. This means that incorporating AR road projections helped participants deduce AV intentions through quick glances without diverting their attention from the road. Including spatial audio further helped maintain participants' focus on the path ahead. The baseline *eHMI* condition significantly underperformed, suggesting that incorporating wearable devices was beneficial for centralising multi-AV information and supporting the scalability of AV-cyclist interaction.

Measure	Friedman's Test	Significant *Post Hoc*s	Takeaway
Workload	$\chi^2 = 20.62$, df = 3, $P = .0001$; $\eta^2 = 0.26$	*RoadAlert* < *eHMI* ($P = .006$) *RoadAlert* < *Gem* ($P = .0001$)	Handlebar displays divided attention between the road and display, increasing the workload.
Awareness Confidence	$\chi^2 = 11.86$, df = 3, $P < .01$; $\eta^2 = 0.17$	*RoadAlert* > *eHMI* ($P = .02$)	Receiving cues on wearables increased confidence.
Intentions Confidence	$\chi^2 = 9.36$, df = 3, $P < .05$; $\eta^2 = 0.14$	No significant *post hocs*	Binary *eHMI* signals about AV intentions were still effective.
Cycling Performance	$\chi^2 = 24.67$, df = 3, $P < .001$; $\eta^2 = 0.29$	*RoadAlert* > *eHMI* ($P < .0001$) *reARview* > *eHMI* ($P = .004$)	Performance was improved when riders could maintain their attention on the road ahead.
Anxiety	$\chi^2 = 17.67$, df = 3, $P < .001$; $\eta^2 = 0.23$	*RoadAlert* < *eHMI* ($P = .002$) *RoadAlert* < *Gem* ($P = .02$) *reARview* < *eHMI* ($P = .03$)	Dividing attention between the three AVs and display increased anxiety.
Perceived Safety	$\chi^2 = 15.18$, df = 3, $P < .01$; $\eta^2 = 0.2$	*RoadAlert* > *eHMI* ($P = .006$) *reARview* > *eHMI* ($P = .05$)	Prioritising challenging encounters improved perceived safety.
Trust	$\chi^2 = 14.05$, df = 3, $P < .01$; $\eta^2 = 0.19$	*RoadAlert* > *eHMI* ($P = .03$) *RoadAlert* > *Gem* ($P = .04$)	AR signals in view alongside *eHMI*s for quick validation increased trust.
Usability	$\chi^2 = 21.36$, df = 3, $P < .001$; $\eta^2 = 0.26$	*RoadAlert* > *eHMI* ($P = .0003$) *RoadAlert* > *Gem* ($P = .002$) *reARview* > *eHMI* ($P = .05$)	Informing cyclists about challenging encounters without taking attention from the road was most usable.

Table 6.4: Friedman's Test results for Post-Scenario Questionnaire subscales. RoadAlert consistently outperformed the other HACIs, while Gem and eHMI underperformed.

Cycling Behaviour

This section reports participants' cycling behaviours toward the HACIs. This includes their speed, shoulder checking behaviour and collisions with AVs. The findings align with those of cyclist perceptions. *RoadAlert* outperformed the other HACIs; it significantly reduced the need for shoulder checks, showing that spatial audio was an effective component of the HACI. It also resulted in fewer collisions than the baseline *eHMI* condition. *reARview* did not perform well in these metrics. It triggered more shoulder checks and collisions than *RoadAlert* and *Gem*.

Cycling Speed Mean cycling speed values per *HACI* condition are in Figure 6.10. Data were non-parametric; a one-way ART ANOVA was conducted to explore the effects of *HACI* on *Speed*. There was no significant effect (F(3, 57) = 0.68, $P = .6$). The HACI used did not influence the cycling speed of participants.

Shoulder Checking Figure 6.10 shows that participants were most likely to shoulder check during the *eHMI* and *reARview* conditions; this was particularly interesting as reARview displayed the most detail about the AV behind the cyclist.

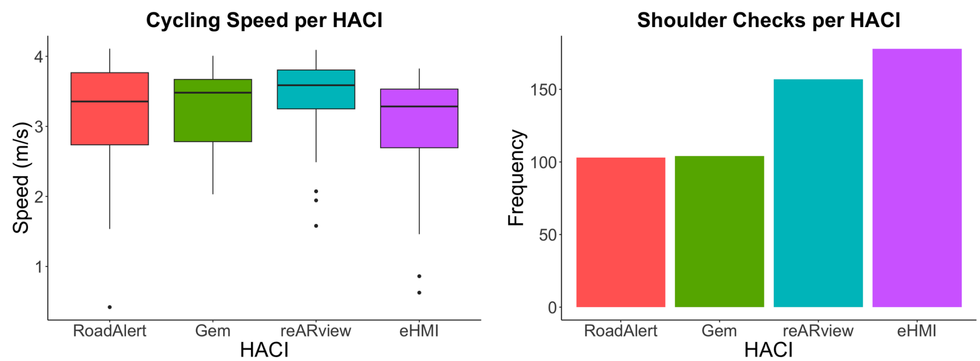

Figure 6.10: Cycling behaviours logged by CycleARcade. The left box plot shows the mean ± SD cycling speed when using each HACI; the right bar chart shows the frequency of shoulder checks when using each HACI.

Collisions There were five collisions in total. All were with the AV behind the cyclist. There were no collisions when *Gem* was used. One collision occurred when *RoadAlert* was used, two when *reARview* was used, and two during the baseline *eHMI* condition. This pattern suggests that collisions were reduced when participants received additional information from HACIs, but only when the information was about all non-yielding AVs, not just the one behind the cyclist.

Qualitative Findings

The same inductive thematic analysis was conducted on participant feedback on the HACIs as the one from the previous design sessions. One researcher uploaded the text output from the feedback form onto NVivo for coding. They identified 9 unique codes from the data. Following this, two researchers collaboratively sorted these codes into three overarching themes based on their similarities. This process was iterative; disagreements were discussed and resolved, with codes being remapped as necessary. Themes containing two or more overlapping codes were reassessed and combined where appropriate. Figure 6.11 shows participant rankings of the HACIs.

Theme 1: RoadAlert presented important information with minimal distraction On-environment displays maintained cyclist focus on the road: *"Road markings required no deviation from my normal view"* - P4; *"Road markings and audio let me pay visual attention to the road and other vehicles"* - P7. Signals were easy to understand as they were similar to the eHMI's: *"I enjoyed the road markings being synchronised with the eHMI"* - P11. This was supported by informative spatial audio that avoided overloading the projections: *"The beep of a car behind me was very useful"* - P9; *"I liked having multimodal feedback."* - P10.

Theme 2: reARview enhanced situational awareness but was too detailed Indirect guidance gave cyclists more freedom in decision-making: *"This system teaches you to be more*

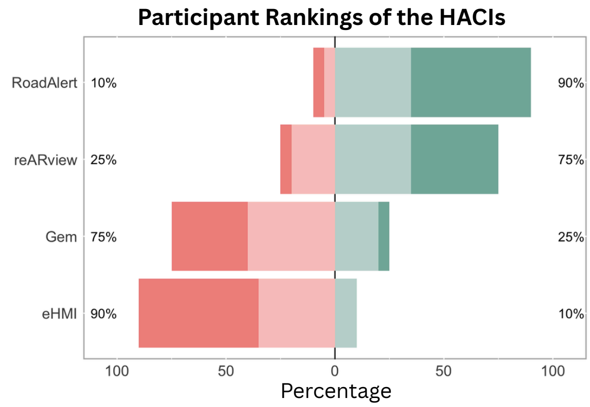

Figure 6.11: Participant rankings for the HACIs. Left in red are lower ranks, and right in green are higher ranks. Participants ranked RoadAlert as the best HACI, and eHMI as the worst.

self-dependent than the other systems" - P19. It successfully enhanced situational awareness: *"Rearview camera allows the best level of understanding of the situation around me"* - P14; *"I felt like I had the most information about my surroundings"* - P18. However, it used detailed visual signals that are difficult to process on the move: *"Camera was quite distracting with too much overload while cycling"* - P13; *"It could be improved by simplifying the interface"* - P14.

Theme 3: Gem imposed a higher workload On-handlebar displays required constant checking, which detracted cyclist attention from the road: *"I had to look down and away from the road to engage with the system"* - P6. Participants preferred on-environment displays: *"This took a dangerous amount of my attention away from my environment. An AR headset would make more sense to me"* - P6; *"Very useful information; too bad it was a bit out of my peripheral view"* - P14. The vibration alerts were not informative enough: *"Vibration of the watch wasn't that useful or even noticeable"* - P3.

6.3.6 Discussion

The baseline eHMI condition consistently underperformed across all metrics and was ranked as the least effective interface. Without additional support, cyclists had limited situational awareness and had to manually locate each AV and interpret its eHMI and driving behaviour. This increased cognitive load, as cyclists performed frequent shoulder checks and had to divide their attention among all AVs, including the yielding one until they could confirm each vehicle's intentions. Unlike in simpler, one-to-one interactions, cyclists had insufficient time to interpret the eHMIs and compare them with AV driving behaviours. Previous studies in the thesis showed that trust is closely tied to the ability to cross-validate explicit signals with driving behaviour. As a result, trust in the eHMI condition was reduced, despite being placed directly on the AVs. In contrast, HACI displays on the handlebar or environment centralised AV intentions. This increased trust because less physical effort was required to interpret AV intentions. It allowed cyclists to cross-reference these messages with eHMIs and driving behaviours, meaning they had two sources for validating the information, not just driving behaviours as in the eHMI condition.

All HACIs enhanced situational awareness, helping cyclists associate AV positions and intentions more clearly. Centralised information allowed cyclists to navigate the scenario with a lower workload and increased interface usability. Therefore, HACIs are key to resolving scalable AV-cyclist interactions. This aligns with scalable AV-pedestrian interaction research recommending wearable displays to centralise eHMI cues [123, 124]. This study shows that centralising information from multiple AVs is also effective for cyclists, even when AVs are in different positions. Most collisions occurred with the eHMI and reARview conditions, indicating that cyclists benefit from more direct guidance to navigate multi-AV situations. Similar to the previous chapter, it is important to emphasise that eHMIs are critical to ensure HACI acceptability as they require no changes to existing cycling setups. HACIs improved usability and reduced anxiety, even in complex multi-AV situations. However, they need to include a baseline of safety to support cyclists who may not have access to such devices, even if the baseline underperforms compared to the added support.

RoadAlert maintained focus on the road

RoadAlert was ranked as the best HACI. This aligns with the results for FullIntel, which had similar design features for one-to-one interaction. RoadAlert effectively managed cyclist attention, which is key, considering the cognitive demand imposed in multi-AV scenarios, as seen with the eHMI condition. Projections were placed on the environment; the eye-tracking study in Chapter 3 showed this aligns with cyclists' reflexive behaviours. Participants did not need to take their attention off the road to process AV intentions, and this helped them incorporate AV proximities and driving behaviours into decisions, resulting in greater confidence.

As observed with FullIntel in Chapter 5, projections lowered the workload using a unified visual language with LightRing. Cyclists could process intentions faster, on a larger surface, and validate them with eHMIs and driving behaviour, which increased trust. Projections were well received in prior work [67, 140] and Chapter 4 and Chapter 5. This study confirms their effectiveness in multi-AV situations if managed correctly to only display important information with minimal visual clutter. RoadAlert coincides with the previous study's themes and shows that HACIs do not need to direct cyclists to all AVs around them. It is sufficient to focus on challenging encounters to enhance situational awareness. RoadAlert was multimodal to avoid overloading visual cues. Cyclists successfully processed comprehensive spatial audio signals communicating out-of-view AV proximity alongside the projections. They conducted fewer shoulder checks, suggesting they trusted non-visual cues and had a lesser need to confirm them visually. This motivates further exploration of other potential multimodal signal combinations.

Gem required too much attention

Gem's vibrations were simple alerts that AVs were approaching; however, they were not informative enough. Cyclists relied solely on visual cues after being alerted. Visual displays on the handlebar required cyclists to divide attention between the AVs and the display, increasing cognitive load and hindering the interaction experience. In contrast, RoadAlert's spatial audio was more informative than vibration, and its visual displays were integrated into the environment, so attention was not as divided. Even though Gem used a unified design language with the eHMI, its detachment from the road led to lower trust. At the same time, the absence of on-display proximity indicators required participants to deduce this information entirely from the road. Although Chapter 3 showed that cyclists are familiar with handlebar-mounted devices like bike computers, these typically communicate less urgent information [14, 16].

Additionally, Gem presented information on all three AVs, potentially creating unnecessary redundancy since the yielding AV was already visible. A similar finding was observed in the cross-cultural study when Mirror was used during Bottleneck; the eHMI was clearly visible, so there was less of a need for redundant signals. Gem caused higher anxiety as it required participants to switch attention between the visual display and each AV constantly. This may have been reduced if cues focused only on non-yielding AVs. Gem might perform better in single-AV situations where attention is not as divided. For multi-AV scenarios, HACIs should incorporate AV proximity and driving behaviours into displays or position displays where driving behaviours remain visible.

reARview enhanced situational awareness but was overloaded

Interestingly, participants felt that reARview's indirect guidance gave them greater autonomy in decision-making. Participants reported high situational awareness, even though reARview did not explicitly display AV intentions beyond the eHMI. This lowered anxiety and heightened perceived safety and cycling performance. This coincides with the previous study's *"Ensuring Situational Awareness"* theme and highlights the significant challenges that out-of-view AVs impose on cyclists [67], reinforcing the argument that AV-cyclist interfaces must work across AV positions. However, these positive perceptions of reARview did not translate to scores in cycling behaviours. reARview did not meaningfully reduce shoulder checks or collision rates, showing that while greater autonomy in decisions improves cyclist perceptions, cyclists may need more guidance for improved behaviours.

Similar to RoadAlert, reARview received high usability scores as it was placed in the cyclist's field of view, with no need to divert attention from the road to interpret signals. However, cyclists did not trust it as much as RoadAlert; they performed frequent shoulder checks to verify an AV behind them. Trust was particularly important, as the previous study showed that the effectiveness of less direct guidance depends heavily on how much cyclists trust it. This likely stems from the HUD's lack of a unified visual language with the eHMI, which created a sense of detachment in visual cues. As reported in this study's qualitative findings, reARview communicated complex visual cues, increasing the workload and imposing greater effort to process visual signals. In contrast, RoadAlert showed that spatial audio performed well in communicating similar messages. Therefore, unimodal displays do not necessarily lower cognitive load compared to multimodal ones, especially when overloaded with detailed information. This aligns with the findings from the VirtuRide study, where the first iteration of LightRing was too detailed, and participants did not respond well to the eHMI. Visual cues may not always be ideal. Another approach could rely solely on spatial audio, synchronising different sounds with the eHMI, as seen in FullIntel.

Generalisability to other scenarios

The HACIs were only tested in the three-AV scenario, as it explored each design's ability to display contrasting intentions and operate across traffic control features and AV positions. This allowed the HACIs to generalise across more complex situations. For example, RoadAlert was shown to operate successfully in busy traffic with multiple AVs. Therefore, it could generalise to more complex scenarios in mixed traffic where unexpected manoeuvres can lead to ripple effects. For instance, if a vehicle unexpectedly does not yield, a cyclist may brake abruptly, prompting risky reactions from nearby road users, such as steering into lanes with oncoming vehicles [97]. RoadAlert is well suited to address this; it communicates AV intentions in advance through road projections, even when obstacles or buildings obscure the AV and its eHMI. It also keeps cyclists' attention on the road, making them aware of surrounding road users and allowing more informed decisions.

In more complex scenarios, AVs might not follow fixed yielding or not-yielding behaviours and could change their intentions. Here, RoadAlert and Gem may outperform reARview because they provide updates using a consistent visual language with the eHMI; cyclists can recognise and verify changes quickly. Non-visual cues could enhance awareness; Gem can use a smartwatch vibration to alert cyclists of a change. In contrast, reARview, unimodal and focused on AVs behind the cyclist, requires continuous HUD monitoring for updates while tracking other AVs in view. Its lack of alignment with the eHMI's visual language and reduced trust may lead to more shoulder checks to confirm changes via the physical eHMI. Despite its shortcomings, reARview may be the most generalisable HACI. It would work across a wider range of eHMI designs, and its high detail could prepare cyclists for a wider range of challenges. For example, Gem and RoadAlert do not communicate the type of approaching vehicle (e.g., bus or truck), which may influence cyclist behaviour, as reported in the online survey from Chapter 3. reARview would show cyclists the vehicle type, allowing them to react accordingly. Given its positive usability scores, reARview's generalisability and ease of implementation suggest that it could be used in today's traffic instead of more basic rearview radars.

Overall, although participants iteratively designed and experienced their concepts in the previous design sessions, evaluation was still necessary. It provided a platform for comparing HACI strengths and weaknesses relative to each other. The HACIs did not necessarily underperform; they all improved the baseline eHMI condition and were closer to their final versions, as participant feedback was not on basic features such as colour or animations but more advanced ones, such as the level of detail in the information presented by displays.

6.4 Overall Discussion and Design Guidelines

Overall, this chapter addressed RQ4: *"How can AV-cyclist interfaces facilitate interaction between an increasing number of AVs and cyclists to support scalable communication?"*. The findings demonstrated that HACIs play a key role in addressing the scalability challenge. The previous chapter established that incorporating wearable or bike-mounted devices helps cyclists distinguish whether an AV's message is directed at them in situations involving multiple cyclists. This aligns with prior research in AV-pedestrian interaction [47, 123].

This chapter specifically investigated multi-AV interactions, where cyclists must simultaneously process signals from multiple AVs. The design sessions revealed that while eHMIs are crucial for communicating each AV's intentions, cyclists also wanted a centralised display to provide information about AV locations and their intentions in a single view. This would enhance situational awareness and allow cyclists to safely navigate complex and overwhelming environments. This finding also aligns with previous research on pedestrians, which recommended centralising multi-AV information into AR displays [124]. The evaluation study reinforced the value of HACIs for scalable interaction. It showed that HACIs significantly reduced workload, decreased shoulder checks, and lowered collision rates compared to using the eHMI alone. However, HACIs must maintain cyclists' attention on the road to be effective. This could be achieved by integrating AR displays into the environment. AR displays were particularly preferred over handlebar-mounted displays, as they allow information to be placed into a cyclist's field of view without requiring significant head movements or distractions.

Avoiding excessive detail in HACIs is also critical, as scalable scenarios are already overwhelming. Therefore, overly detailed interfaces can be divided into multimodal displays, each modality communicating one aspect of the information. For example, spatial audio could provide information about AV proximity, reducing reliance on visual information. HACIs can also avoid being overloaded with information by only alerting cyclists to AVs that are non-yielding or out of view. Yielding AVs can still communicate their state through eHMIs. This ensures that cyclists receive only the most relevant information, preventing cognitive overload.

6.4.1 Design Guidelines for Scalable AV-Cyclist Interfaces

These findings from the two studies in this chapter form the basis for design guidelines (DGs) for scalable HACIs, which are presented below and provide a foundation for further discussion.

DG1: CycleARcade enabled a novel 'design, experience, and evaluate' approach

CycleARcade centralised the three-AV scenario into an AR scene that was used in the design sessions and evaluation study. This facilitated a novel 'design, experience and evaluate' approach. The design and experience components of the approach were in the design sessions, where participants experienced their concepts immediately after spawning them in the scene. This facilitated the creation of more complete designs with more substantial overlaps in the taxonomy compared to the taxonomies from Chapter 4 and Chapter 5. Any differing opinions were clearly highlighted in the themes, and this facilitated the synthesis of distinct and fully functional concepts for comparison. The evaluation portion of the approach was in the follow-up evaluation study to compare these concepts. The evaluation study in this chapter provided deeper insights beyond basic refinements, such as the type of information HACIs should communicate, because participants had already experienced and refined basic features, such as colour. In comparison, participants of the eHMI design sessions from Chapter 4 did not experience their concepts. This required a two-study evaluation of the concepts, first using VirtuRide for basic refinement and then an outdoor one with the revised concepts.

It is important to emphasise that participant designs in this chapter did not necessarily underperform, as they all outperformed the baseline eHMI condition. This shows the benefits of incorporating experience features into design sessions to ensure that the resulting solutions effectively address the problem. However, the design sessions did not offer a platform to compare the designs. Both prior work [14, 67] and the previous chapters showed that evaluation is a key part of the process. It enables the extraction of design strengths and weaknesses relative to one another and identifies their most effective features [85]. This was evident in this chapter's evaluation study. Future work should adopt this 'design, experience and evaluate' approach. CycleARcade is customisable and can be used for displays inside or, as in this case, outside vehicles. The approach also has potential applications beyond the AutomotiveUI domain.

DG2: Multimodal cues can communicate distinct rather than redundant messages

HACIs from the previous chapter primarily used non-visual cues to provide redundant signals synchronised with LightRing. These were effective in one-to-one interaction but can cause confusion in multi-AV scenarios. For example, cyclists may struggle to match vibrations to the corresponding eHMI, or spatial audio may be difficult to distinguish if pointing to multiple AVs.

The design sessions in this chapter showed that non-visual cues do not need to replicate visual signals but can provide different, complementary information. The evaluation study confirmed this. Cyclists preferred spatial audio cues indicating AV proximity over simple vibration alerts. This shows that non-visual cues can provide detailed information distinct from visual ones. This approach leverages HACI features by breaking complex information into manageable parts delivered through the most appropriate modalities.

DG3: HACI signals should be easy to validate between displays

Even though multimodal cues can communicate distinct messages, redundancy can still improve cyclist trust and confidence in HACIs. However, designers must ensure that any redundant interfaces within a HACI are straightforward to validate with each other. Design sessions from this chapter and the previous one showed that LightRing's visual language was straightforward to extend across displays. For example, some designs used red ambient lights on the handlebar for non-yielding AVs. The evaluation study showed that this was useful. RoadAlert's flashing red road projections were in view alongside eHMIs, making them straightforward to validate, which increased trust and improved usability. However, redundant signals should use a placement that allows quick validation. Gem used the same visual language as LightRing but was ineffective as it required participants to divert their attention from the road. This guideline may extend to non-visual cues. For example, rather than pointing to all AVs, spatial audio pointing to an out-of-view AV, as seen in RoadAlert, could play different sounds depending on the AV's eHMI state. Designers should leverage the interconnected features of HACIs to minimise the learning curve and promote synchronised, easy-to-validate messages between displays.

DG4: HACIs must effectively manage cyclist attention

Multi-AV encounters impose a higher cognitive load [123], with cyclists locating each AV, interpreting its driving behaviours and associating its intentions. The design sessions showed approaches for HACIs to lower cognitive load by centralising information about AV locations and intentions. This would reduce the need for cyclists to track each AV's state manually. Interestingly, all designs used a multimodal approach, combining visual and non-visual cues. The synthesised designs used different approaches to multimodality: reARview was unimodal, Gem employed sequential multimodality, and RoadAlert used concurrent multimodal signals, with the latter proving most effective at reducing cognitive load. Comparing these designs showed that multimodal signals must not hinder cyclists' focus and view of the road. Any visual displays should be integrated into the environment but not overloaded with information, as cyclists may not have time to process complex visual signals. They could be broken down and complemented with non-visual cues. These should be informative enough to communicate useful messages, such as proximity or AV awareness, so cyclists do not deem them unnecessary. Ultimately, HACIs can leverage multimodality to decrease cognitive load if they prioritise managing cyclist attention between AVs and the road.

In conclusion, this chapter answered the final research question and overcame the scalability design challenge. This is critical for ensuring that cyclists can receive information from multiple AVs and associate any signals with the correct AV to avoid miscommunication. The findings in this chapter bring AV-cyclist interfaces closer to real-world use and large-scale deployment. The following chapter is the main discussion chapter of the thesis. It provides a perspective into how studies investigating each design challenge relate to each other and contribute to the overall successful deployment of AVs without compromising the benefits and accessibility of cycling.

Chapter 7

Discussion

This thesis investigated how AV-cyclist interfaces can be designed to facilitate clear communication between the road users to resolve space-sharing conflicts safely and without ambiguity. The following thesis statement was presented in Chapter 1.

> Introducing AVs into traffic will diminish the social interactions cyclists rely on with drivers to resolve space-sharing conflicts and safely navigate the road. This thesis explores the design of new interfaces to facilitate AV-cyclist interaction by ensuring **acceptability** among cyclists, **versatility** across traffic scenarios, **cultural inclusivity** for clear communication across cities and countries, and **scalability** to support interaction with multiple AVs and cyclists. **Acceptability** was achieved by placing interfaces on vehicles to accommodate cyclists who may not use wearable devices; **versatility** required interfaces to convey binary signals (AV-yielding/not yielding) that generalise across scenarios; **cultural inclusivity** was ensured by communicating comprehensive messages adaptable to different cultural norms, and **scalability** was achieved by incorporating wearable devices to assure cyclists the messages were for them when other cyclists were nearby and centralising messages from multiple AVs into multimodal displays that maintain cyclist attention on the road.

This chapter presents a discussion of the research outcomes reported in this thesis. It begins with a thesis summary, including answers to each research question. This is followed by a discussion of the research limitations and an outline of the thesis's primary contributions. The chapter concludes with a reflection on the overall findings and final remarks.

7.1 Thesis Summary and Research Question Answers

The literature review in Chapter 2 showed that, while some research has investigated how AVs can interact with human road users, little has considered cyclists [37]. Even then, prior work investigating AV-cyclist interaction was limited in scope [67, 88]. It only explored one-to-one

AV-cyclist interactions [67] for specific traffic scenarios, such as intersections [140], in specific cultural settings, with the research skewed towards Western cultures [14, 67, 140]. However, the literature review highlighted how interfaces must be acceptable [41, 49], versatile [1], scalable [123] and culturally inclusive [108] to be used on real roads and support the successful global deployment of AVs. The research in this thesis answered the following research questions to overcome these design challenges.

7.1.1 RQ1: How can insights from current driver-cyclist interaction inform the design of acceptable AV-cyclist interfaces?

This was answered in Chapter 3. The AV-pedestrian interaction domain has advanced significantly due to a strong foundation of studies investigating human driver-pedestrian interaction in real crossings [104]. These informed the cues and messages AVs should recognise and use in response [41] and the areas where interfaces should be placed [49], such as on-vehicle eHMIs in this case [37]. The AV-cyclist interaction domain would benefit from similar foundational knowledge; understanding how drivers and cyclists interact would allow AV-cyclist interfaces to maintain familiarity and minimise the learning curve without significantly changing the current cycling setup [16].

Approach

Three studies were conducted to address RQ1. Study 1 was an online survey to provide an overview of the AV-cyclist interaction problem from cyclist perspectives. Results showed that participants could not form clear expectations of AVs as they had no experience interacting with them. This prompted user studies in the thesis to take a more practical approach, e.g. using simulators. Participants also saw value in interfaces but preferred placing them on vehicles or the surrounding environment to avoid being compelled to carry devices on every trip. Study 2 was a set of observations of driver-cyclist encounters across five real traffic scenarios to identify the messages and cues AVs should recognise and display in response. The road users frequently interacted, showing a clear need for interfaces once human drivers are no longer behind the wheel. There were some differences between scenarios; for example, interactions were more expressive at uncontrolled intersections to negotiate right of way but brief in lane merging scenarios, with drivers rarely using expressive social cues. Study 3 was a naturalistic study in which cyclists were equipped with eye-tracking glasses to record two home-office commutes. This identified potential interface placements that align with cyclists' natural behaviours. Results showed that cyclists looked at different vehicle sides and traffic control features, including road markings and traffic lights. Therefore, placing interfaces on the AV or surrounding environment is feasible. However, not all scenarios had the vehicle in the cyclist's view. Wearable devices may improve the interaction experience and reduce the need for shoulder checking.

RQ1 Answer

The cumulative findings of these studies show that acceptable AV-cyclist interfaces must facilitate the exchange of awareness and intentions between AVs and cyclists across traffic scenarios, regardless of the level of traffic control or AV position. AVs must use a combination of explicit signals displayed on the interface and implicit cues through their driving behaviours for clear communication, and these studies showed how human drivers use these so AVs can act in a more familiar manner. Interfaces should be viewable from anywhere around the vehicle. However, there is room for improving current interaction by incorporating optional wearable devices to enhance usability.

Even though Study 1 participants were hesitant to use wearable devices, these are more acceptable if used alongside on-vehicle or environment interfaces. This led to the introduction of HACIs. A HACI is defined as *"an interconnected ecosystem of AV-cyclist interfaces aware of each other's states and presence. Interfaces within a HACI work together to facilitate interaction collectively. HACIs comprise a baseline interface on the AV or environment and other devices that may use different placements"*. HACIs are an acceptable solution because they allow AVs to interact with all cyclists, regardless of the devices they own. However, they leave room for additional support, similar to how cyclists currently use devices such as rearview radars [14].

7.1.2 RQ2: What features enable AV-cyclist interfaces to be versatile, supporting interaction across diverse traffic scenarios?

This was answered in Chapter 4. Studies from Chapter 3 showed that driver-cyclist interaction behaviours differ between scenarios. This established versatility as a key AV-cyclist interface design challenge. Interfaces must consistently facilitate interaction throughout a cyclist's journey, regardless of traffic control or AV position [12]. HACIs were shown to be an acceptable solution. However, these need a baseline interface on the vehicle or environment for interaction with all cyclists in all scenarios. Therefore, the research answering RQ2 focused exclusively on eHMIs. eHMIs are promising versatile solutions because they are placed on the vehicle itself, which Study 3 showed is a familiar area that aligns with cyclists' natural behaviours. eHMIs are also more suitable than stationary on-environment interfaces for interaction during dynamic scenarios, which may occur anywhere on the road, such as lane merging [67].

Approach

Three studies were conducted to address RQ2. Study 4 used participatory design with AutomotiveUI researchers and cyclists collaborating to design eHMIs around real vehicles. Results showed that eHMIs must primarily use visual cues and be viewable from all angles around the vehicle to communicate AV intentions. Three new eHMIs were synthesised by combining the most popular features between participant designs. They used distinct placements on the vehicle and had different approaches to communicating AV intentions: Safe Zone used red/green road projections, Emoji-Car displayed emojis on the roof, and LightRing used animated cyan lights on the vehicle's body.

These were implemented in VirtuRide, a VR cycling simulator developed for evaluating the eHMIs in Study 5. Participants used VirtuRide to interact with AVs using each eHMI across five traffic scenarios. Results showed that all eHMIs were versatile, but participants preferred red/green signals to communicate AV intentions. All designs were revised accordingly and evaluated outdoors using a Ghost Driver [109] setup in Study 6. This followed the same structure as the VR study. Designs were still versatile after revision, but participants preferred eHMIs placed on larger vehicle surfaces, such as its main body, rather than the roof. LightRing was the most positively evaluated eHMI.

RQ2 Answer

The overall findings of the three studies showed that eHMIs are suitable, versatile interfaces that can act as a baseline in HACIs. They should consistently communicate AV intentions in a simple, binary manner (i.e., AV-yielding or not yielding) to maintain versatility across traffic scenarios. The studies showed that red/green colour-coded signals were useful for binary AV intentions, as distinguishability is key. These may be complemented using secondary signals for enhanced recognisability, such as speed-based animations (e.g., pulsing for yielding and flashing for not yielding). eHMIs must be placed on large surfaces around the vehicle to work in scenarios with varying AV positions.

7.1.3 RQ3: What are the cultural differences in cyclist use and perceptions of AV-cyclist interfaces?

This was answered in Chapter 5. The research in this chapter began to investigate HACIs, which bring a large combination of devices, messages and modalities. The displayed messages can be more comprehensive than in individual interfaces like eHMIs. This maximises the potential cultural differences between how cyclists use and perceive HACIs, so testing them in one setting is insufficient [108].

Approach

Two studies were conducted to address RQ3. Study 7 used participatory design with HCI researchers and cyclists designing HACIs around real vehicles instrumented with the LightRing eHMI as a baseline interface. Results showed that HACIs can be multimodal, using a combination of visual, auditory, and haptic signals to display messages. Participant designs displayed the AV's intentions to reiterate LightRing and the AV's location in case of a blindspot. Three new HACIs were synthesised from these designs for cross-cultural evaluation. All incorporated additional multimodal wearable devices to the LightRing eHMI: Locator used wearables to communicate AV locations, Mirror reiterated AV intentions, and FullIntel combined both messages.

The HACIs were implemented in CycleARcade, an AR cycling simulator that projects virtual objects onto the real world so cyclists can ride in augmented physical space. A cross-cultural user study was conducted across Stockholm, Sweden (high cyclist segregation from vehicles), Glasgow, UK (some segregation), and Muscat, Oman (no segregation). Participants in all cities used CycleARcade to interact with AVs using each HACI across different traffic scenarios. Results showed that all cyclists preferred FullIntel. However, those accustomed to greater segregation in Stockholm preferred AV location cues to validate intention signals with AV driving behaviour, while Muscat cyclists preferred AV intention signals for fast-paced interaction. Those in Glasgow adapted the signals depending on the scenario.

RQ3 Answer

The overall results show that HACIs are an acceptable and highly usable solution for AV-cyclist interaction. It is feasible to design HACIs that communicate comprehensive messages that are adaptable between regions to promote cultural inclusivity. However, these signals must be developed around a universally understood baseline, which in this case was LightRing. Some alterations may be needed to suit local norms, but these should be on wearable devices to avoid disrupting the cultural inclusivity of baseline interfaces.

7.1.4 RQ4: How can AV-cyclist interfaces facilitate interaction between an increasing number of AVs and cyclists to support scalable communication?

This was answered in Chapter 6. The HACI design sessions in Study 7 showed that they overcome ambiguity in multi-cyclist encounters [47]. However, displaying information from multiple AVs remained challenging [123]. For example, it is difficult to synchronise smartwatch vibrations with multiple eHMIs. Therefore, two studies were conducted to investigate scalable AV-cyclist interaction in a scenario with three AVs. AVs approached from different directions and were governed by distinct traffic control features, so they had different intentions.

Approach

Two studies were conducted to address RQ4. Study 9 used participatory design with HCI researchers and cyclists collaborating within CycleARcade to design scalable HACIs. They spawned multimodal design objects directly into the AR scene and experienced them in the three-AV scenario for rapid iterative design. Opinions diverged on whether visual information should be placed on the environment or handlebar and the type of information scalable HACIs should present: direct information on AV intentions or indirect signals that simply widen a cyclist's field of view. Three new HACIs were developed from participant designs to capture these differences: RoadAlert used AR road projections to display AV intentions and spatial audio to communicate the proximity of out-of-view AVs, Gem used a handlebar display to display AV intentions and smartwatch vibrations to alert cyclists of approaching AVs, and reARview was an AR HUD showing live footage of any AVs behind the cyclist. Study 10 evaluated the three HACIs to form a consensus on participant perceptions. Participants used CycleARcade to test each HACI in the three-AV scenario. They preferred RoadAlert. Therefore, results showed that visual displays should be integrated into the environment, and HACIs should communicate direct feedback showing AV intentions to make informed decisions. Non-visual signals should communicate more detailed information rather than simple alerts to be viewed as useful.

RQ4 Answer

These studies show that HACIs are feasible solutions for AV-cyclist interface scalability. They overcome multi-cyclist ambiguity by using wearable devices to assure cyclists that messages are for them, and can centralise multi-AV information to reduce the workload when multiple AVs are present. However, multi-AV scenarios impose a high cognitive demand on cyclists. Therefore, it is critical to maintain cyclist attention on the road using on-environment and non-visual signals rather than handlebar displays. Cyclists also successfully processed multimodal signals communicating distinct information in multi-AV scenarios, such as audio cues for AV proximity and visual cues for AV intentions. Scalable HACIs do not need to direct cyclists to all nearby AVs. They can alert them only to non-yielding or out-of-view vehicles to avoid being overloaded with information.

7.2 Thesis Limitations and Future Work

This thesis investigated four design challenges to prepare AV-cyclist interfaces for real-world use. However, some more subtle challenges must still be addressed. This section discusses how future research should use the findings from this thesis to investigate these factors.

Two-way AV-cyclist communication

The research in this thesis primarily explored how interfaces can present AV information to cyclists. However, Chapter 3 showed that driver-cyclist communication is two-way. This means that AVs must recognise cues from cyclists to negotiate the right of way and be equipped with the required sensors to recognise subtle cues, such as hand gestures and facial expressions. Compelling cyclists to carry new devices to send their intentions to AVs may not be acceptable, as shown in Chapter 3. However, HACIs still leave room for incorporating wearable devices;

this is key because some participants from the design sessions in Chapter 5 did not trust AVs to recognise their social cues. Instead, they proposed on-handlebar directional indicators and smart bells connected to AVs via V2X.

Future research should explore two-way AV-cyclist communication in more detail [134]. This could take two directions. First, the research could investigate the sequence of signals exchanged between the road users to ensure that two-way communication maintains familiarity and predictability. This may depend on the traffic scenario. For example, Chapter 3 showed that drivers only responded to lane merging cyclists after cyclists established eye contact and used hand gestures. It could also depend on the cultural setting. For example, Chapter 5 showed that cyclists in Muscat make potentially unsafe decisions purely based on AV intention signals; these may be better informed if they were only displayed after cyclists conveyed their intentions. The other research direction is to investigate new types of signals cyclists can communicate to AVs. For example, participants in Chapter 5 proposed a smart bell that conveys how hurried cyclists are in their commutes.

Investigating the nuances of AV-cyclist interaction

While the four design challenges are key for ensuring AV-cyclist interface acceptability and usability, some factors could still influence AV-cyclist interface design. Interfaces should operate regardless of the weather or lighting conditions to ensure reliability [37]. This was partially addressed in the thesis. For example, results from Study 6 showed that road projections are not clearly visible in sunny conditions, and LED lights are a more reliable alternative. Study 7 also showed that HACIs allow devices to offer a failsafe for eHMIs, which would be useful when eHMIs are not visible due to extreme weather. However, this was not explicitly tested across varying weather conditions. Future research should investigate the solutions contributed by this thesis under different weather and lighting conditions. This is important as AV driving behaviours may vary; for example, AVs may drive more cautiously under heavy snow [14].

The solutions in this thesis were designed and tested around city cars: 2019 Citroen C3s. This is because findings from Chapter 3 showed that cyclists are more likely to encounter and interact with these vehicles. However, cyclists may encounter other types of vehicles, such as trucks and buses [100]. It is unknown how the solutions in this thesis generalise to these vehicles. For example, results showed that HACIs should focus on alerting cyclists to the most challenging encounters in multi-AV scenarios; it is unknown whether encountering larger vehicles that are yielding is perceived to be challenging in this context. Future research should test the solutions in this thesis with vehicles varying in size. The studies in this thesis focused primarily on urban rather than rural areas, as these have higher cycling traffic and an increased chance of AV-cyclist encounters [36]. Future research should investigate AV-cyclist interface use in rural traffic scenarios, as driving behaviours may be different [25].

Finally, the studies focused exclusively on SAE level 5 AVs; these require no human driver in all conditions [117]. All simulated vehicles in user studies had no visible driver behind the wheel. This was critical to provide a starting point for the research and identify the messages and types of signals AV-cyclist interfaces should display without the complexity of having a human driver. This provided a clear point of comparison on how interfaces can differ from traditional cues from drivers. It also provided comparability with prior work on AV-pedestrian interaction, which is dominant in the field and has mostly investigated SAE level 5 AVs [37]. Moreover, AVs with no human in the driver seat are starting to appear in the real world, such as Waymo taxis in San Francisco [23]. This made it critical to investigate SAE level 5 AVs, as cyclists do not have a fallback of social interaction. It is still important to investigate how the solutions in this thesis generalise to AVs with different SAE levels, as these may feature a visible human behind the wheel who is not in control [117]. This has the potential for confusion as the rider may think they are communicating with the driver, but if the vehicle is in autonomous mode, the person at the wheel does not have control [37].

Incorporating other road users

This thesis focused exclusively on cyclists, as previous research showed that they have unique requirements [66], and AV interfaces have so far mostly considered pedestrians [37]. It was critical to understand how interfaces can be designed according to cyclists' needs [16]. The next step in the research is to ensure that interfaces are inclusive of all road users, as it would be impractical to use different interfaces, particularly eHMIs, between road users. The studies in this thesis identified many promising overlaps between pedestrians and cyclists. For example, eHMIs are promising solutions [104], colour takes precedence over animation [39], and cyan is useful for communicating the AV state [37]. Interface designers can use these overlaps to develop and test inclusive solutions. The research findings in the thesis could also generalise to drivers, motorcyclists and e-scooter riders because these road users are also likely to encounter vehicles across a range of traffic scenarios and be exposed to different vehicle sides [66]. Future work should explore the solutions in this thesis with these road users. Study 7 showed that HACIs could adapt to different road users and traffic scenarios, so any wearable devices could be adjusted to suit different road user types.

Conducting cross-cultural design sessions

Chapter 5 explored the cultural inclusivity of HACIs. The research approach involved designing and synthesising new HACIs in Glasgow before testing them in Stockholm, Glasgow and Muscat. This was because the research required a systematic comparison of how cyclists from different cultures use and behave around the same interfaces. However, designing the interfaces in a single cultural setting may have introduced some bias in the outcome interfaces, as they may cater to the local needs of Glasgow cyclists. Measures were still taken to mitigate this; sessions were conducted in Glasgow because cyclists in that area fall between those in Stockholm and Muscat, as they are accustomed to riding in segregated and mixed traffic. This was also evident in the evaluation study, where results for Glasgow cyclists were commonly a middle-point. This suggests that while the interfaces were developed in a single location, they may have incorporated elements relevant across contexts.

Moreover, participants in the evaluation study were asked about what they would change about the interfaces and how they might be better adapted to local needs, helping to surface culture-specific feedback despite the shared design origin. The study revealed novel insights about the cultural inclusivity of HACIs. For example, interfaces could communicate comprehensive messages that cyclists can adapt according to their local needs, similar to how Stockholm cyclists prioritised AV location information over intentions. However, the study also showed key local challenges within each culture. Therefore, future research can conduct localised design sessions that are better informed about the challenges to consider, such as fostering trust for Stockholm cyclists.

7.3 Contributions to Knowledge

The research presented in this thesis significantly contributes to the field of AV-cyclist interaction and the broader HCI domain. These contributions include novel AV-cyclist interface concepts and a comprehensive set of design guidelines to inform their implementation. The research also introduced and employed novel replicable methodologies that enabled data collection in more immersive and ecologically valid environments than typically seen in prior work [14, 37].

These contributions are essential for ensuring the successful global deployment of AVs [14]. They also support the continued rise of cycling as a sustainable mode of transport by addressing cyclist' needs and enhancing their confidence and safety around AVs [67]. This allowed the thesis to have a strong societal impact, directly contributing to the United Nations' Sustainable Development Goals (SDGs) [129], including SDG 3 (Good Health and Wellbeing), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

7.3.1 AV-Cyclist Interface Concepts

The design sessions in this thesis resulted in new concepts from participants; they were developed based on the ideas of researchers and cyclists. This provided insights into their pragmatic qualities from researchers and real-world usefulness from cyclists [70]. Participant designs informed the development of new concepts for evaluation. The concepts in Chapter 4 were the first AV-cyclist interfaces developed to be versatile. They were also the first eHMIs designed according to cyclists' needs [37]. The concepts were revised following two stages of evaluation in VR and outdoor settings, and this brought them closer to real-world use [28].

The concepts in Chapter 5 were the first HACIs introduced in the research domain. They used emerging technologies to facilitate interaction, including AR displays, spatial audio and

V2X. Their practical usability and guidance for implementing them in real-world settings were discussed. The concepts were evaluated across different cultural settings to ensure cultural inclusivity, so these are also feasible to support the large scale deployment of AVs [108]. Chapter 6 also contributed the first scalable HACIs and tested them in outdoor settings to deduce the design features that support their real-world use [47].

7.3.2 AV-Cyclist Interface Design Guidelines

The contributions were not limited to the concepts; each experimental chapter synthesised novel design guidelines for overcoming the respective design challenge that was investigated. This is critical for helping designers make informed decisions based on empirical evidence to adhere to the needs and requirements of cyclists [67]. The design guidelines were as follows:

- **Guidelines for Acceptability:** A set of 9 design guidelines in Chapter 3. For the first time, these show how AV-cyclist interfaces can be acceptable for cyclists and match their needs and requirements. These guidelines were based on cyclist perceptions and natural behaviours collected through real-world studies. The guidelines provide the AV-cyclist interaction domain with the necessary foundation to advance the field in a similar manner to AV-pedestrian interaction research [104];

- **Guidelines for Versatility:** A set of 7 design guidelines in Chapter 4. These address the versatility design challenge, which is crucial for AV-cyclist interfaces. For the first time, these guidelines show how interfaces can be designed to consistently facilitate AV-cyclist interaction between traffic scenarios, regardless of traffic control or vehicle positions;

- **Guidelines for Cultural Inclusivity:** A set of 3 design guidelines in Chapter 5. These are the first design guidelines that show cultural differences in how cyclists interact with AVs, and how AV-cyclist interfaces can be culturally inclusive and adapt to their local norms and needs. They are based on the perceptions and behaviours of cyclists from different cultural settings who directly interacted with AVs. Chapter 5 also contributes 3 lessons learned from conducting cross-cultural research to inform and motivate similar studies;

- **Guidelines for Scalability:** A set of 4 design guidelines in Chapter 6. These novel guidelines show how interfaces can scale to facilitate clear communication between an increasing number of road users without overwhelming cyclists with signals.

7.3.3 Research Tools and Simulators

The research in this thesis also introduced new types of simulators. VirtuRide was the first VR cycling simulator developed to assess interfaces in a range of traffic scenarios and inform

AV-cyclist interface versatility. Traffic scenarios were modelled based on real footage of driver-cyclist encounters collected in the eye-tracking study from Chapter 3. Any traffic control features, such as road markings, were based on the UK Highway Code [128]. Versatility is a crucial requirement, not just for AV-cyclist interfaces but for other road users likely to encounter AVs across a range of traffic scenarios, including human drivers and motorcyclists [66, 96]. VirtuRide's environment can be customised to support testing interfaces for these road users.

CycleARcade was the first AR cycling simulator that used passthrough technology on mixed-reality headsets to increase immersion. Previous AR simulators were deployed on HoloLens headsets with a narrow field of view and projected translucent AR objects [87, 88]. CycleARcade also featured multi-user features, allowing interface evaluation and prototyping with multiple road users. It had participatory design features, so its use cases go beyond interface evaluation. CycleARcade is a useful tool for future research in the AutomotiveUI and cycling HCI domain.

7.3.4 Methodological Contributions

The studies in this thesis employed novel methodologies to enhance ecological validity and immerse participants into designing and testing any interfaces. The design sessions in Chapter 4 and Chapter 5 were the first AutomotiveUI or cycling HCI design sessions to be conducted outdoors around real vehicles and bicycles. This allowed participants to contemplate their concepts to scale in a representative setting, which was shown to be effective as the study outcomes were aligned with later evaluations. For example, road projections were positively evaluated, and AV locations and intentions were shown to be suitable messages communicated by HACIs. Deducing versatile concepts by combining overlapping features between designs for individual traffic scenario categories was also shown to be an effective approach in Chapter 4. This is a significant contribution as it was previously unknown how to design versatile interfaces without providing participants with a scope that was too broad [67, 70]. The CycleARcade design sessions in Chapter 6 were the first participatory design sessions conducted in AR. These facilitated rapid iterative design with participants designing, experiencing and refining high-fidelity prototypes in a representative setting. Resulting designs were closer to their final versions, as participants did not highlight any areas for refining basic design features, such as colours, following evaluation. This method is useful when there is a specific scenario to design for, such as the three-AV scenario used in the study. This is a significant contribution to the HCI research domain, as rapid iterative design is useful beyond AutomotiveUI and cycling HCI [28, 70, 91].

Even though the Ghost Driver [109] approach was previously used to assess AV-HRU interfaces, previous work only tested one single type of display, such as LED lights [44] or a screen on the bumper [96]. The study in Chapter 4 was the first to assess multiple interfaces in a single Ghost Driver study. This was achieved by using velcro to attach any displays between conditions. This is useful for informing future research attempting to evaluate interfaces in real-world settings. The cross-cultural evaluation study in Chapter 5 was the first of its kind, with participants in multiple cities experiencing the same interfaces and AV driving behaviours while riding in real physical space. This method employed CycleARcade to centralise the apparatus into a single platform, which was useful for study replication. Conducting a user study rather than an online survey between cultures proved beneficial as it provided insights into cycling behaviours, and any perceptions were based on direct interaction [28]. Perceptions and behaviours were found to be correlated in this case. For example, Glasgow participants reported high anxiety when interacting with AVs, and their behaviours aligned with this as they cycled slower and conducted more shoulder checks. This shows the value of conducting cross-cultural user studies to gain a holistic view of interface performance [88].

7.4 Overall Discussion and Closing Remarks

The AV-cyclist interaction problem has been widely documented in prior work [16, 82, 97, 101, 120]. This thesis presents new ways to facilitate clear communication between AVs and cyclists. This section discusses the design guidelines and interfaces presented in the thesis to demonstrate how they can be applied in practice.

7.4.1 Actioning the Design Guidelines

The research produced comprehensive design guidelines to inform the design of AV-cyclist interfaces. This section abstracts these design guidelines into four actionable points that can be viewed as a framework for developing acceptable and usable HACIs.

Designers can base their interfaces on the current driver-cyclist interaction

Chapter 3 showed that acceptability is closely tied to maintaining the current cycling setup and allowing cyclists to interact with AVs with a minimal learning curve. It is essential to emphasise that clear communication is not limited to explicit signals, but rather the appropriate combination of implicit AV driving behaviours and explicit signals displayed on interfaces [82]. Observations from Chapter 3 showed that AV implicit cues must be familiar, e.g. acceleration when the AV is not yielding. Explicit signals on the interface must align with implicit ones and not contradict them to ensure clear communication. Designers can also consider how cyclists currently interact to understand the type of interface to design. Cyclists rely on social cues from drivers for clear communication; future interfaces can be eHMIs, using AVs as a placement. This way, cyclists can receive signals from a familiar location without needing any extra equipment [49]. This enhances acceptability and allows new interfaces to align with the natural gaze behaviours and expectations of cyclists, ultimately minimising the learning curve. However, the online survey in Chapter 3 showed that cyclists in current traffic also use devices, such as bike computers and rearview radars, for navigation or receiving alerts of potentially dangerous encounters. Therefore, while baseline interfaces can compensate for human drivers, designers can also focus on grouping these with wearable or bike-mounted devices as part of a HACI.

Designers should start by developing baseline interfaces before additional ones

The purpose of baseline interfaces is to compensate for human drivers and support cyclists who may not carry additional devices. Therefore, baseline interfaces should support all cyclists throughout their journeys, being versatile and working across traffic scenarios [12]. Designers should develop their baseline interfaces as the first step in their HACI; this is to ensure that these displays are uncompromised and can support the widest possible range of cyclists. Messages from the baseline interface must adhere to cyclist requirements, being easy to distinguish and perceive from around the vehicle. Chapter 4 identified the design features that support the versatility and usability of baseline interfaces, including communicating AV intentions in a binary manner using colour changes.

Designers can add wearable or bike-mounted devices that communicate additional signals to baseline interfaces

HACIs can expand on baseline interfaces to communicate more comprehensive messages, such as AV locations, in addition to intentions. This improves current interaction by introducing new signals that enhance cyclists' situational awareness. Chapter 5 showed that this also promotes cultural inclusivity because it helps cyclists adapt comprehensive information according to their local needs. For example, AV locations may be more helpful in some traffic environments than AV intentions. Designers should ensure that these messages are easy to distinguish and separate so cyclists can adapt them easily. For example, FullIntel from Chapter 5 presented AV intentions as road projections and AV locations as AR traffic signs. There may be some local challenges that HACIs can address, such as communicating AV awareness more explicitly in certain regions. These additions should be on wearable or bike-mounted devices rather than baseline interfaces to ensure that cyclists from different cultures have a common ground.

Designers can use multimodality to manage cyclist attention

The placement of AV-cyclist interfaces was found to be a key factor in managing cyclist attention. Visual interfaces must be placed on areas that align with the natural behaviours of cyclists because cyclists move at higher speeds and must be able to process signals while moving quickly [66]. The eye-tracking study from Chapter 3 showed the areas where cyclists naturally look, including vehicles and the surrounding environment. This was later corroborated in Chapter 6, where cyclists preferred interfaces placed on the road (environment) over bicycle handlebars. However, Chapter 4 showed that visual displays must not be overloaded with signals, as their signals must be quick to comprehend. Non-visual signals, such as spatial audio, were found

Figure 7.1: The LightRing eHMI: LED strips around the AV that use colour-coded red/green signals to communicate AV intentions (not-yielding/yielding). LightRing is green in this figure, meaning the AV is yielding.

to be useful for communicating complementary information without overloading visual ones. These maintain cyclist attention because they do not require cyclists to divert their focus from the road ahead. Chapter 6 also showed that cyclists can interpret distinct information from visual and non-visual cues without increasing cognitive load. This demonstrated that HACIs are not only acceptable for AV-cyclist interaction but highly usable as they can use multimodal signals to manage cyclist attention effectively.

7.4.2 Effectiveness of the Final Solutions

This section presents some of the final interfaces developed in the thesis and uses them as a case study to discuss how they incorporate the design guidelines and research findings.

LightRing: the ideal eHMI?

Chapter 4 concluded that LightRing (see Figure 7.1) is the best performing eHMI tested in the studies. LightRing requires a low workload and minimal attention from cyclists to interpret its signals. It is versatile and communicates binary AV-yielding/not yielding signals throughout traffic scenarios. This consistent set of signals simplifies today's interaction behaviours, where drivers communicate different messages between scenarios, as shown in Chapter 3. Therefore, LightRing requires a minimal learning curve between scenarios. LightRing's placement around the vehicle aligns with the design guidelines from Chapter 3. This helped it to be usable between traffic scenarios regardless of the AV's position. LED lights made it practical and straightforward to implement, as they require no expensive hardware compared to more sophisticated displays and road projections. LEDs are also easy to recognise, even in sunny conditions. LightRing's messages are highly distinguishable; this was a key factor outlined in the guidelines from Chapter 4. It uses contrasting colours: green lights for yielding and red for not yielding.

Figure 7.2: RoadAlert: Incorporates AR road projections and spatial audio from the helmet to LightRing. Projections point to non-yielding and out-of-view AVs; audio communicates the proximity of AVs behind the cyclist. This figure shows RoadAlert as implemented in CycleARcade.

LightRing's message distinguishability was further enhanced through speed-based animations of the lights (flashing or pulsing) to support colour-blind cyclists and provide some redundancy to colour-coded signals.

Colour changes and animations were found to be culturally inclusive across the regions tested in Chapter 5; participants had no issues understanding LightRing's messages. Some required additional information to AV intentions, especially in Stockholm. However, this can be achieved through additional HACI devices. One particular advantage of LightRing was that its design language was straightforward to extend to other modalities, e.g. synchronising smartwatch vibrations with speed-based animations. This makes it a suitable baseline for HACIs and aligns with Chapter 5's design guidelines, which recommend building culturally inclusive HACIs around a suitable baseline. LightRing is also scalable in multi-AV encounters, as participants in Chapter 6 did not alter it in the design sessions. Its placement around the vehicle allows it to be adapted to support multi-cyclist encounters. For example, only the side the cyclist is on can be active, and this can be further segmented by only displaying the AV's intentions in a smaller portion of the lights according to the cyclist's location. This was proposed in prior work to communicate AV awareness through eHMIs [15, 43]. LightRing may also generalise to other road users beyond cyclists. Red and green signals for AV intentions were found to be effective with pedestrians [80] and human drivers [105]. Its placement around the vehicle makes it viewable from the front for pedestrians [104] and anywhere around the vehicle for drivers, motorcyclists and other road users who may encounter AVs across different scenarios [66].

RoadAlert: the ideal HACI?

LightRing was incorporated into HACIs in studies in Chapter 5 and Chapter 6. Cyclists appreciated additional multimodal devices and were not overwhelmed with the signals. This shows that there is room for additional support from AV-cyclist interfaces, beyond compensating for human drivers. HACIs consistently outperformed baseline conditions with just the eHMI in Chapter 5 and Chapter 6. Chapter 6 concluded that RoadAlert (see Figure 7.2) was the best performing HACI of those evaluated. This may be considered the most effective interface contributed in the thesis. RoadAlert adheres to the design guidelines throughout the thesis. It is highly acceptable because it compensates human drivers and communicates AV intentions through LightRing. It also incorporates additional AR and spatial audio signals to improve the current interaction experience and enhance situational awareness. Findings from Chapter 3 showed that the road is a suitable placement for AV-cyclist interfaces as it offers a large surface that adheres to cyclists' natural gaze behaviours. However, Chapter 4 showed that eHMI road projections are challenging to implement between weather conditions and road textures. RoadAlert overcomes these issues by using AR road projections.

AR projections were also found to be successful in previous research [140]. However, there was no baseline interface to support acceptability; RoadAlert features LightRing to overcome these issues. Including AR projections and an eHMI to communicate the same message allows the displays to act as failsafes for each other; cyclists can still receive AV intentions through the AR display if the eHMI is damaged or not visible [9]. RoadAlert is likely to generalise well between cultures because it is a scalable variation of FullIntel, which was positively evaluated across all cultures in Chapter 5. It also only projects the intentions of non-yielding AVs onto the road. This could be suitable for cyclists from Stockholm who placed more value on AV driving behaviours, so they would not be overwhelmed with intention signals beyond the eHMI. Simultaneously, it can also help cyclists from Muscat make faster decisions, as they will only receive additional signals when AVs do not yield, and more negotiation is required. RoadAlert uses spatial audio to communicate the proximity of out-of-view AVs. This helps cyclists minimise shoulder checks and lowers the workload, particularly in multi-AV encounters where it is critical to manage cyclist attention effectively, as shown in Chapter 6. These factors suggest that RoadAlert is suitable for real-world use.

Transitioning from mixed to automated traffic

LightRing and RoadAlert also generalise to more complex traffic situations. For example, they could help cyclists adapt to the transition from manually driven to fully automated vehicles. Chapter 3 showed that cyclists are already accustomed to receiving signals from vehicles (through directional indicators) and drivers. LightRing uses always-on cyan to inform cyclists whether the vehicle is autonomous and should expect any signals from the eHMI; this would be helpful for interaction if the AV is SAE level 3 or 4, featuring a potential human driver [117].

This always-on cyan feature may be temporary until SAE level 5 AVs have a high presence in traffic, meaning the LightRing eHMI could only rely on red/green signals when cyclists are accustomed to interacting with AVs. Chapter 5 also showed that HACIs can help cyclists transition to the increasing presence of AVs in traffic, such that additional wearable devices can act as "training wheels" until cyclists are accustomed to interacting with AVs. Therefore, some cyclists may use AR and spatial audio for extra support until they are comfortable using only the LightRing eHMI.

Chapter 5 showed that HACIs can be modular, with cyclists customising the devices connected to the eHMI. This would help them receive signals on cyclist-specific scenarios, such as dooring [137], using a similar design language to what they are accustomed to in road interactions. For example, RoadAlert can use road projections and spatial audio to alert cyclists of an AV whose door is about to open. This could minimise the learning curve because cyclists do not need to learn new signals for such scenarios. In addition, this modularity allows HACIs to adapt to cultural variations and the technology adoption of cyclists. Cyclists will have LightRing as a common ground, but the wearable or bike-mounted devices can depend on the local challenges they face in their traffic environment or the availability of such devices.

7.4.3 Closing Remarks

In conclusion, this thesis shows that AVs must communicate clearly with cyclists to achieve large-scale adoption [67, 97, 101]. The research focused on how to design interfaces that support this communication by addressing four key interface design challenges: acceptability, versatility, cultural inclusivity, and scalability. The results highlight that AV-cyclist interfaces are essential for safe and unambiguous interactions. Interfaces must clearly communicate the AV's intentions to give cyclists sufficient information to resolve space-sharing conflicts. They must also avoid disrupting and complicating the current cycling setup to be acceptable and usable on a large scale. Optional wearable interfaces may also be used for added support. For example, these may be adapted to local norms between cultural settings or be used to centralise information from multiple AVs around a cyclist. The thesis contributes new interfaces and design guidelines responding to the four challenges. These contributions are important for ensuring cyclist safety and supporting the global deployment of AVs in future traffic.

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Appendix A

Study Materials

All data resulting from the studies in this thesis can be found at: `zenodo.org/records/15569938`

A.1 Example Information Sheet

The following two pages contain an example Information Sheet from a study in this thesis.

Sharing the Road: Cyclists and Automated Vehicles

INFORMATION SHEET

We, the researchers at the University of Glasgow, invite you to take part in a design session. This study will involve you developing the design of an interface that facilitates interactions between cyclists and autonomous vehicles (AVs). Please read the following information carefully and discuss it with others if you wish. Ask us if anything is unclear or if you would like more information.

What is the purpose of the study?

This study is part of a larger research project investigating the interaction between cyclists and autonomous vehicles (AVs). Cyclists often share the road with motorised vehicles. As cyclists are vulnerable road users, they rely on social interactions with other protected road users to navigate traffic safely. These interactions typically happen through eye contact, hand gestures and subtle head movements.

AVs will be on the road soon; the currently established interactions will change, and cyclist-vehicle interaction will shift from interpersonal to human-machine. This work aims to contribute techniques that facilitate AV-cyclist interaction.

This co-design study aims to contribute novel designs of interfaces that facilitate AV-cyclist interaction. The interfaces should use the vehicle as a design space. In other terms, they should be external Human-Machine Interfaces (eHMIs). This study is a first step toward contributing eHMI designs that are catered toward cyclists' needs.

What will I be required to do?

You will be part of a team of one HCI expert and one cyclist. We expect you to collaborate and brainstorm with your partner to design at least one eHMI. You will be briefed about the user requirements before the study. The study will be conducted outdoors in a parking lot, and you will be required to stick sheets of paper on a car to illustrate your eHMI design.

Why have I been chosen?

You were chosen because you are an adult (18+) cyclist or HCI expert, and your knowledge can be used to design a novel eHMI.

Do I have to take part?

You do not have to participate and have the right to stop participating during the study.

Are there any risks?

There are no risks. You will be tasked with brainstorming design ideas around a parked car and sticking sheets of paper on the car to illustrate your concept.

Will my taking part in this study be kept confidential?

Yes, all data collected from you will be treated confidentially, will be seen in its raw form only by the experimenters, and, if published, will not be identifiable as coming from you.

What will happen to the results of the research study?

The results of the study may appear in research publications. The results may also be presented at scientific meetings or in talks at academic institutions. Results will always be presented in a confidential format where anonymity is preserved.

How can I get in contact with the researcher?

If you have any questions or issues, feel free to get in touch with the researcher at any time.

Researcher: Ammar Al-Taie
Email: XXXXXXXX@student.gla.ac.uk

Supervisor: Professor Stephen Brewster
Email: stephen.brewster@glasgow.ac.uk

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee (Application Number:).

A.2 Example Consent Form

The following page contains an example Consent Form from a study in this thesis.

eHMI DESIGN SESSION - CONSENT FORM
University of Glasgow

I understand that Ammar Al-Taie is collecting data in the form of completed questionnaires, video footage, photographs, interviews and design sketches for use in an academic research project at the University of Glasgow.

I give my consent to the use of data for this purpose on the understanding that:

1. I have read and understood the information about the study provided earlier, and the researchers have answered any questions I might have about the study.
2. I confirm that I have read and understood the Information Sheet, understand how the researchers will handle my data, and have had the opportunity to ask questions.
3. I understand that all data collected from me will be anonymous and treated confidentially.
4. Only the researchers will see the data in its raw form, and it will not be identifiable as coming from me if published.
5. I understand that participation in this study is voluntary, and I may withdraw consent at any time and for any reason.
6. The researchers can archive all captured data in online repositories such as Enlighten: Research Data: http://researchdata.gla.ac.uk/.
7. I understand that any designs I contribute to are experimental data that may be used as part of a scientific publication.
8. I confirm that I am 18+ years old.

Signed by the participant: ___________________________ Date:

Researcher: Ammar Al-Taie
Email: a.al-taie1@research.gla.ac.uk

Supervisor: Professor Stephen Brewster
Email: stephen.brewster@glasgow.ac.uk

Appendix B

Questionnaires

B.1 Example Demographics Survey

Participant demographics were collected using the questions in Table B.1.

Survey Question	**Response Option**
How often do you cycle?	Once a year or less A couple of times a year At least once a month Once a week Multiple days a week Everyday
How long have you been cycling?	Less than one year One to two years Three to four years More than four years
Where do you often cycle?	Mostly urban areas Mostly rural areas Urban and rural areas equally
Gender	Male Female Non-binary / third gender Prefer not to say
Age	Free text input
Why do you cycle?	Sports/leisure Commuting Job (e.g. delivery) Other
In which country and city do you mostly cycle?	Free text input

Table B.1: Demographics survey study participants answered.

B.2 Post-Scenario Questionnaire

Statement	Response Scale
NASA-TLX	
How mentally demanding was the task?	0–21
How physically demanding was the task?	0–21
How hurried or rushed was the task?	0–21
How successful were you in accomplishing what you were asked to do?	0–21
How hard did you have to work to accomplish your level of performance?	0–21
How insecure, discouraged, irritated, stressed, and annoyed were you?	0–21
Perception of the AV	
The AV was aware of my presenc.	Strongly disagree – Strongly agree
I was confident in the AV's next manoeuvre (Intentions)	Strongly disagree – Strongly agree

Table B.2: The post-scenario questionnaire.

B.3 Post-Track Questionnaire

Statement	Response Scale
Cycling Performance	
The system would be useful while cycling.	Strongly disagree – Strongly agree
Using the system enables me to accomplish my goals more quickly.	Strongly disagree – Strongly agree
Using the system increases my cycling performance.	Strongly disagree – Strongly agree
If I would use the system I will reach my destination safely.	Strongly disagree – Strongly agree
Anxiety	
I have concerns about using the system.	Strongly disagree – Strongly agree
I think I could have an accident because of using the system.	Strongly disagree – Strongly agree
The system is somewhat frightening to me.	Strongly disagree – Strongly agree
I fear that I do not reach my destination because of the system.	Strongly disagree – Strongly agree
I am afraid that I do not understand the system.	Strongly disagree – Strongly agree
I am confident that the system does not affect my riding.	Strongly disagree – Strongly agree
Perceived Safety	
I felt safe using the interface while riding.	Strongly disagree – Strongly agree
Trust	
I trusted the interface.	Strongly disagree – Strongly agree
Usability (UEQ-S)	
Obstructive – Supportive	1–7 scale
Complicated – Easy	1–7 scale
Inefficient – Efficient	1–7 scale
Clear – Confusing	1–7 scale
Boring – Exciting	1–7 scale
Not interesting – Interesting	1–7 scale
Inventive – Conventional	1–7 scale
Usual – Leading edge	1–7 scale

Table B.3: The Post-Track Questionnaire.

B.4 Online Survey from Study 1

Questions from the Study 1: Online Survey in Chapter 3 are shown below.

Table B.4: Questions from Study 1 — Block 1.

Block 1 - Interaction Behaviour	*Five-Point Likert (Never - Always)*
I interact with drivers when cycling in their presence	
Establishing eye contact with drivers makes me feel safer	
I use hand gestures to interact with drivers	
I conduct shoulder checks when cycling around motorised vehicles	
I feel safer when motorised vehicles use turn signals and brake lights	
Turn signals and brake lights (when used by the driver) are a reliable way to know the driver's intent	
I can tell what the driver's next manoeuvre is just by looking at their driving behaviour	
I understand what drivers mean when they use horns and flashing lights	
I feel that drivers understand the messages I communicate to them when I am cycling	
I interact with drivers to communicate positive messages such as thanking them	
I interact with drivers to communicate my intent when cycling, for example indicating that I will turn left	
I interact with drivers to communicate negative messages, for example yelling at them if they make me feel unsafe	
It is important for me to know if a driver has seen me when I am sharing the road with them	
It is important for me to know what the driver's next manoeuvre is when I am sharing the road with them	
Please describe your experiences interacting with drivers, including any social signals and messages you exchange.	*Open Question*

Table B.5: Questions from Study 1 — Block 2.

Block 2 - Perception of Traffic Scenarios	*Ranking (Most to Least Dangerous)*
Crossing the road	
Me overtaking a car	
Unexpected road repairs	
Cycling on a straight road with heavy traffic	
Straight road with parked cars on both sides	
Intersection with traffic lights	
A car overtaking me	
Roundabout	
Crossing a car's course when turning at a traffic light	
Intersection without traffic lights	
Cycling around larger vehicles such as buses or trucks	
Lane merging (You changing lanes)	
Cycle lane that suddenly merges into traffic	
Please justify your rankings and discuss your perceptions of different traffic scenarios; what makes a scenario dangerous? Are there any other scenarios you can think of?	*Open Question*

Table B.6: Questions from Study 1 — Block 3.

Block 3 - Perception of AVs	*Five-Point Likert (Strongly Disagree - Strongly Agree)*
Autonomous vehicles will enhance the overall transportation system	
Autonomous vehicles will make the roads safer	
Autonomous vehicles can correctly detect cyclists on the road	
I would feel comfortable if my loved ones cycle in the presence of autonomous vehicles	
I would recommend my family and friends to be comfortable while cycling alongside autonomous vehicles	
I would feel more comfortable doing other things (e.g., texting, listening to music) while cycling alongside autonomous vehicles	

Continued on next page

Table B.6 continued from previous page

Block 3 - Perception of AVs (continued)	*Five-Point Likert (Strongly Disagree - Strongly Agree)*
I would feel safe to cycle alongside autonomous vehicles	
It would take less effort from me to observe my surroundings while cycling if there are only autonomous vehicles involved	
I would find it pleasant to cycle alongside autonomous vehicles	
The traffic infrastructure supports the launch of autonomous vehicles	
Autonomous vehicles will be able to effectively interact with cyclists	
Autonomous vehicles are compatible with all aspects of the transportation system in my area	
I will interact with autonomous vehicles the same way I interact with conventional vehicles	
Autonomous vehicles will not affect my cycling habits	
I would use smart devices such as my phone or smartwatch while cycling if they will make it easier to interact with autonomous vehicles	
I need to know if autonomous vehicles are aware of my presence if I am cycling near them	
I need to know what the autonomous vehicles' next manoeuvre is if I am cycling near them	
Interacting with autonomous vehicles while cycling would not require a lot of mental effort	
Please discuss your perceptions and expectations of AVs	*Open Question*

Table B.7: Questions from Study 1 — Block 4.

Block 4 - Current and Future Device Use	*Five-Point Likert (Never - Always)*
If I had a bell on my bike I would use it to communicate with drivers	
I would buy smart devices that will help me interact with motorised vehicles	
Safety gear makes it easier to interact with car drivers	
I wear a helmet when I cycle	
I wear reflectors or high visibility clothes when I cycle at night	
I have front/rear bicycle lights	

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Table B.7 continued from previous page

Block 4 - Current and Future Device Use (continued)	*Five-Point Likert (Never - Always)*
I have a bike bell/horn on my bike	
My bike is equipped with smart devices that help keep me safe while cycling	
My bike is equipped with assisted cycling gear such as a rear-view mirror	
I carry my phone with me when I cycle	
I wear smart wearables such as an apple watch when I cycle	
I have ear/headphones on when I cycle	
I use my phone for non-cycling related tasks while cycling	
I use my phone for cycling-related tasks such as navigation when I cycle	
Please discuss any safety gear or smart devices that you use while cycling, and whether there is potential for these to display information about autonomous vehicles, including their intentions or awareness of you.	*Open Question*